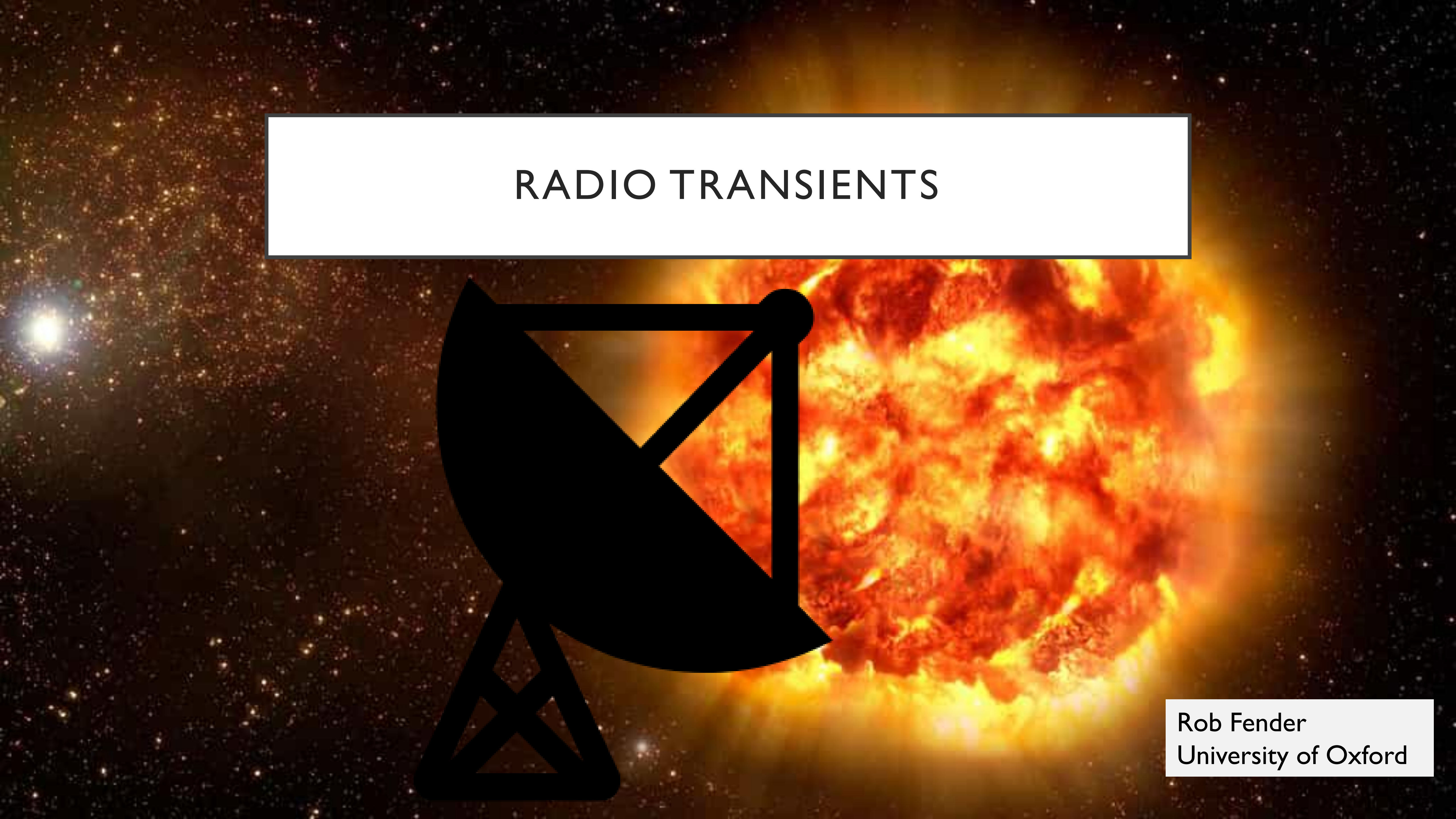


RADIO TRANSIENTS

Rob Fender
University of Oxford

RADIO ASTRONOMY

RADIO TRANSIENT ASTROPHYSICS

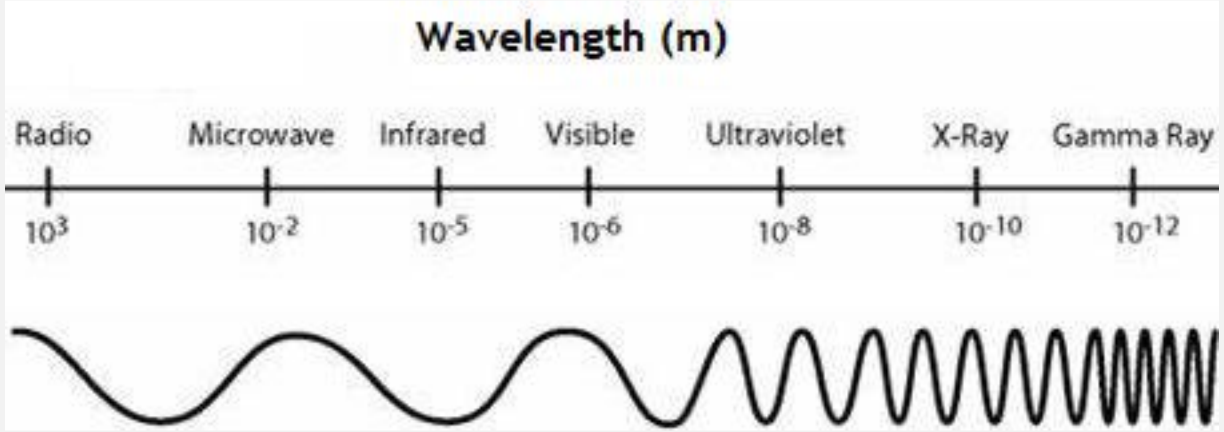
FUTURE FACILITIES AND PROSPECTS

RADIO ASTRONOMY

RADIO TRANSIENT ASTROPHYSICS

FUTURE FACILITIES AND PROSPECTS

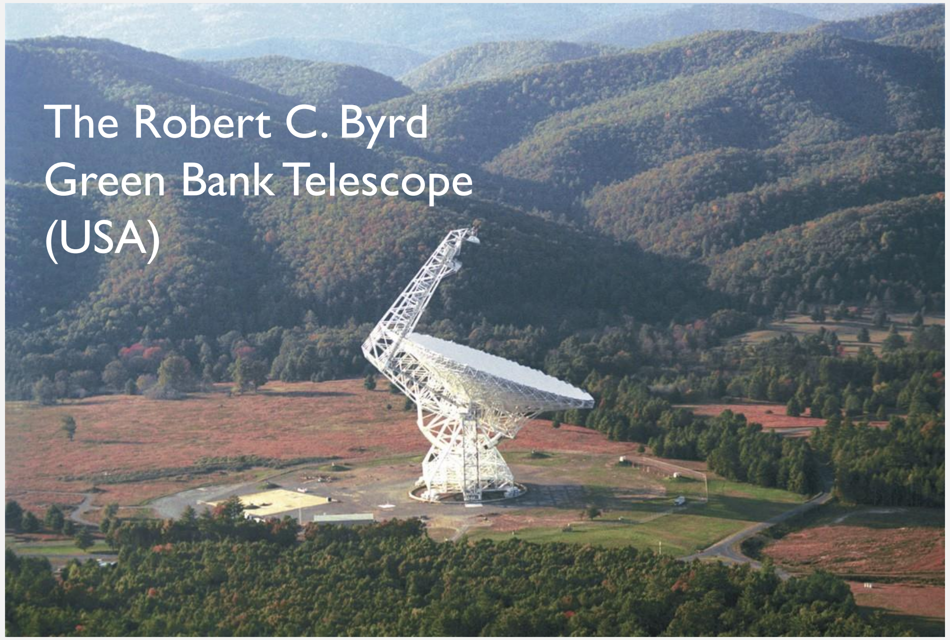
The very basics



The wavelengths of radio waves are **human sized**

The surface quality of a telescope needs to be about as good as the wavelength of the radiation, or better, so radio telescopes can be made with much less precision and expense than optical telescopes, and can even have gaps in.

The very basics: single dishes



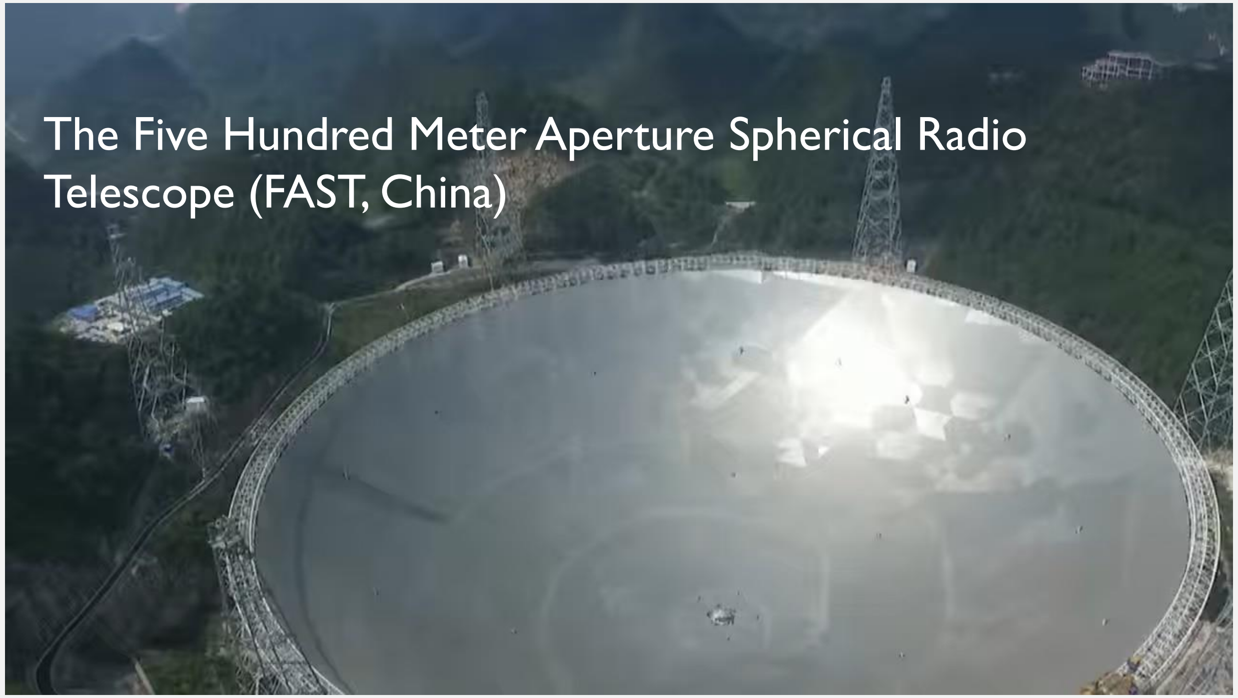
Angular resolution

$$\theta = \lambda / d$$

Since λ is large for radio astronomy, we need d to be large to get good resolution

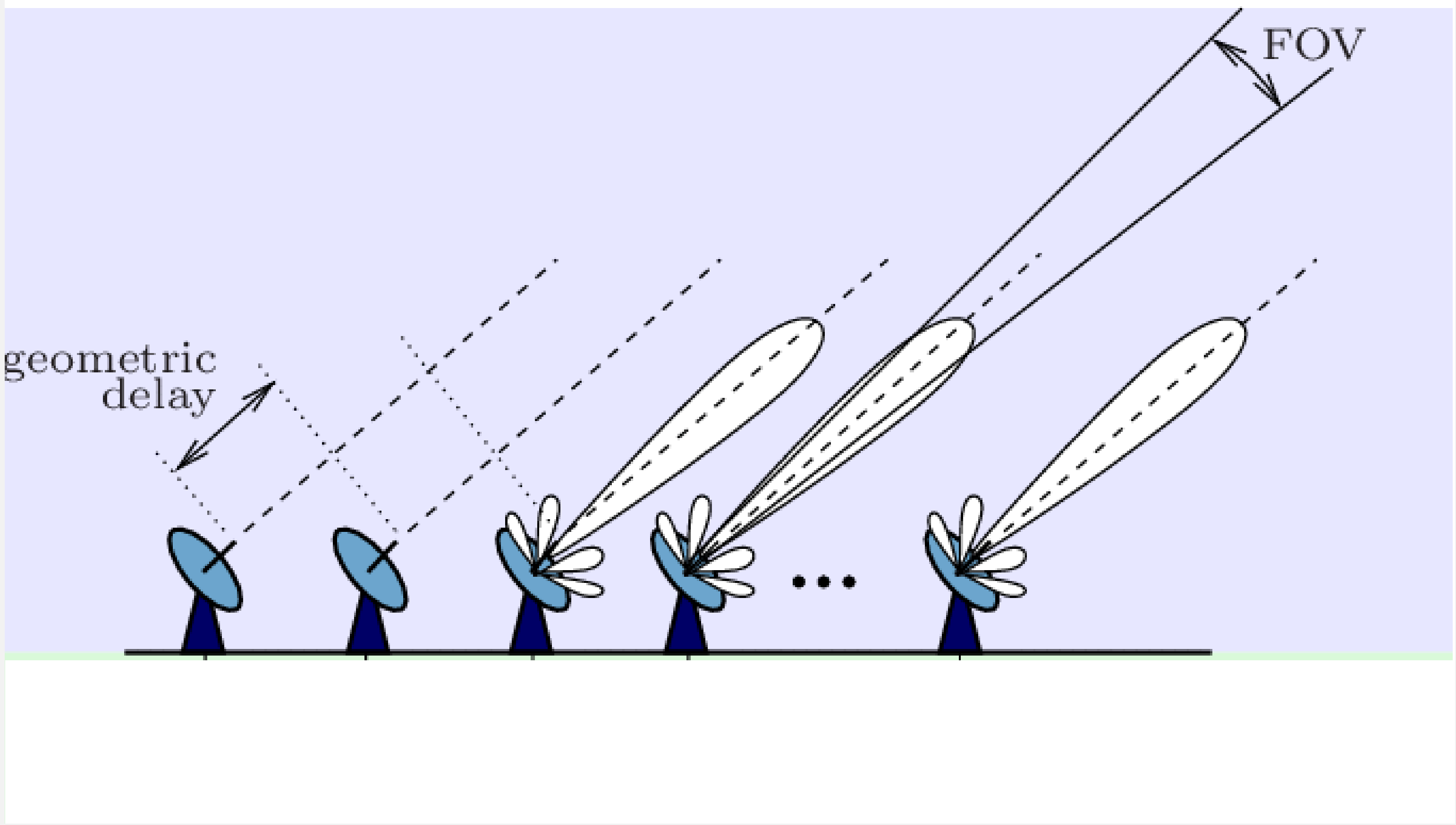
The Robert C. Byrd GBT (USA) is the largest steerable radio telescope in the world, with 100m diameter

The largest filled-aperture radio telescope is FAST (China) which cannot be steered, but has 500m diameter



The very basics: interferometers

Most radio data on transients is obtained with interferometers



If we combine multiple radio telescopes into an interferometer we have two different d for this equation:

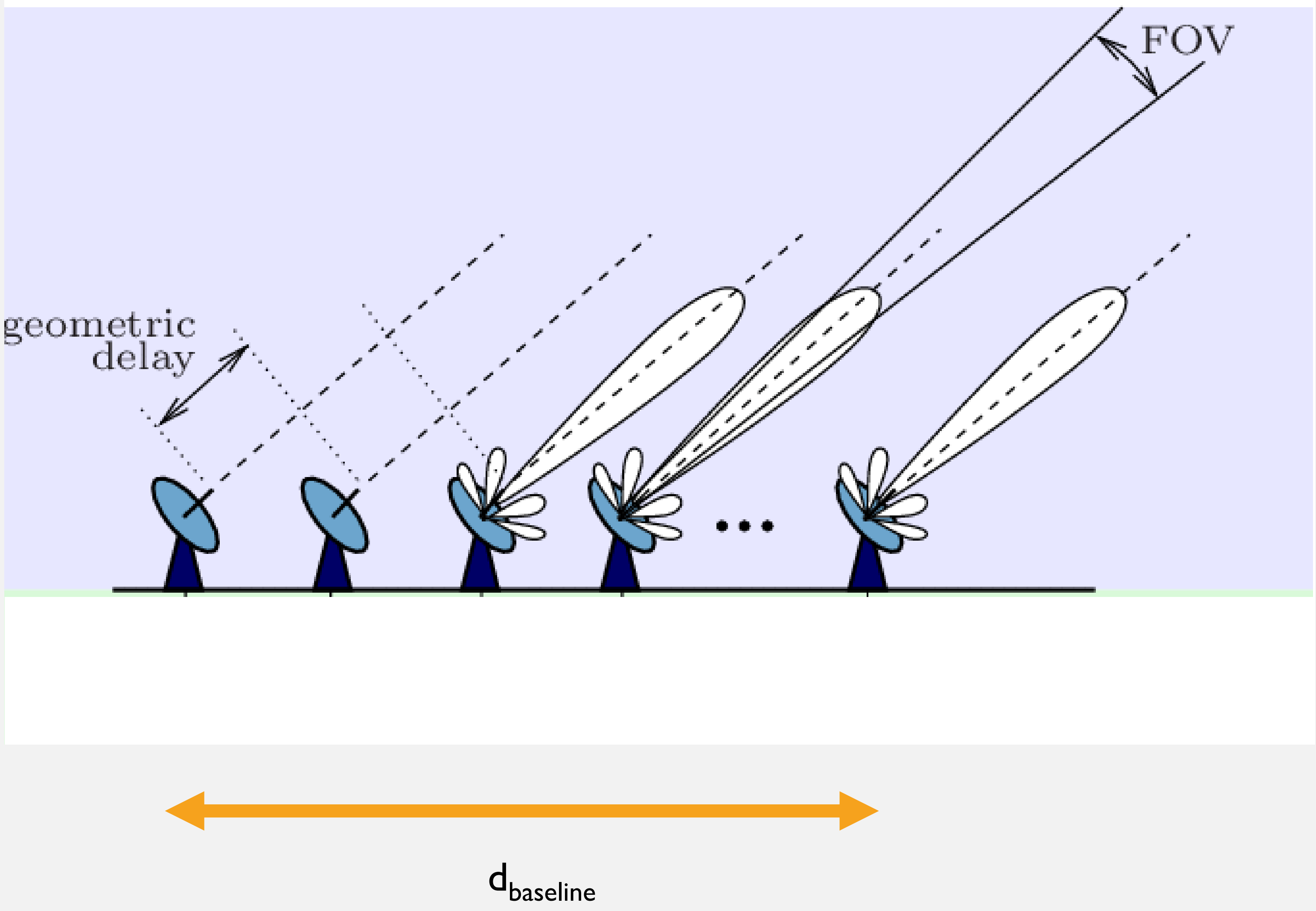
$$\theta = \lambda / d$$

Using the size of an individual dish we get

$$\theta_{FOV} = \lambda / d_{dish}$$

Which is the field of view (FOV) or 'primary beam'

The very basics: interferometers



Using the length of the longest baseline

$$\theta_{BEAM} = \lambda \,/\, d_{baseline}$$

Which is the angular resolution (~'synthesized beam')

∴ number of resolution elements across your image is

$$\theta_{FOV} \,/\, \theta_{BEAM} = d_{baseline} \,/\, d_{dish}$$

The very basics: interferometers

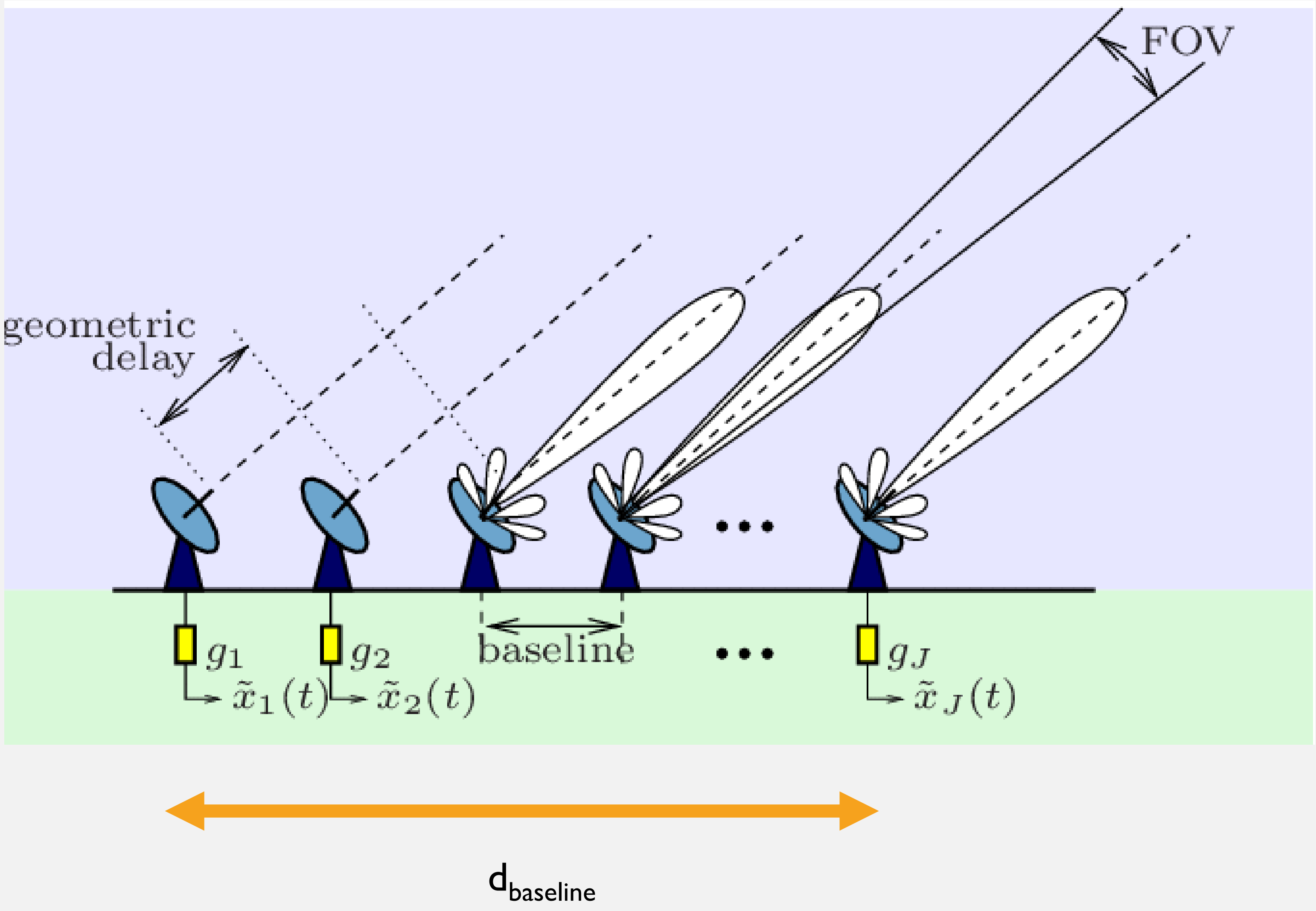
For the VLA, the longest baseline is 36 km, and the individual dishes are 25 m in diameter

∴

$d_{baseline} / d_{dish} \sim 1440$

Since we like to have images which look a bit smoother than our angular resolution we typically choose pixels about 1/3 the size of synthesized beam

The very basics: interferometers



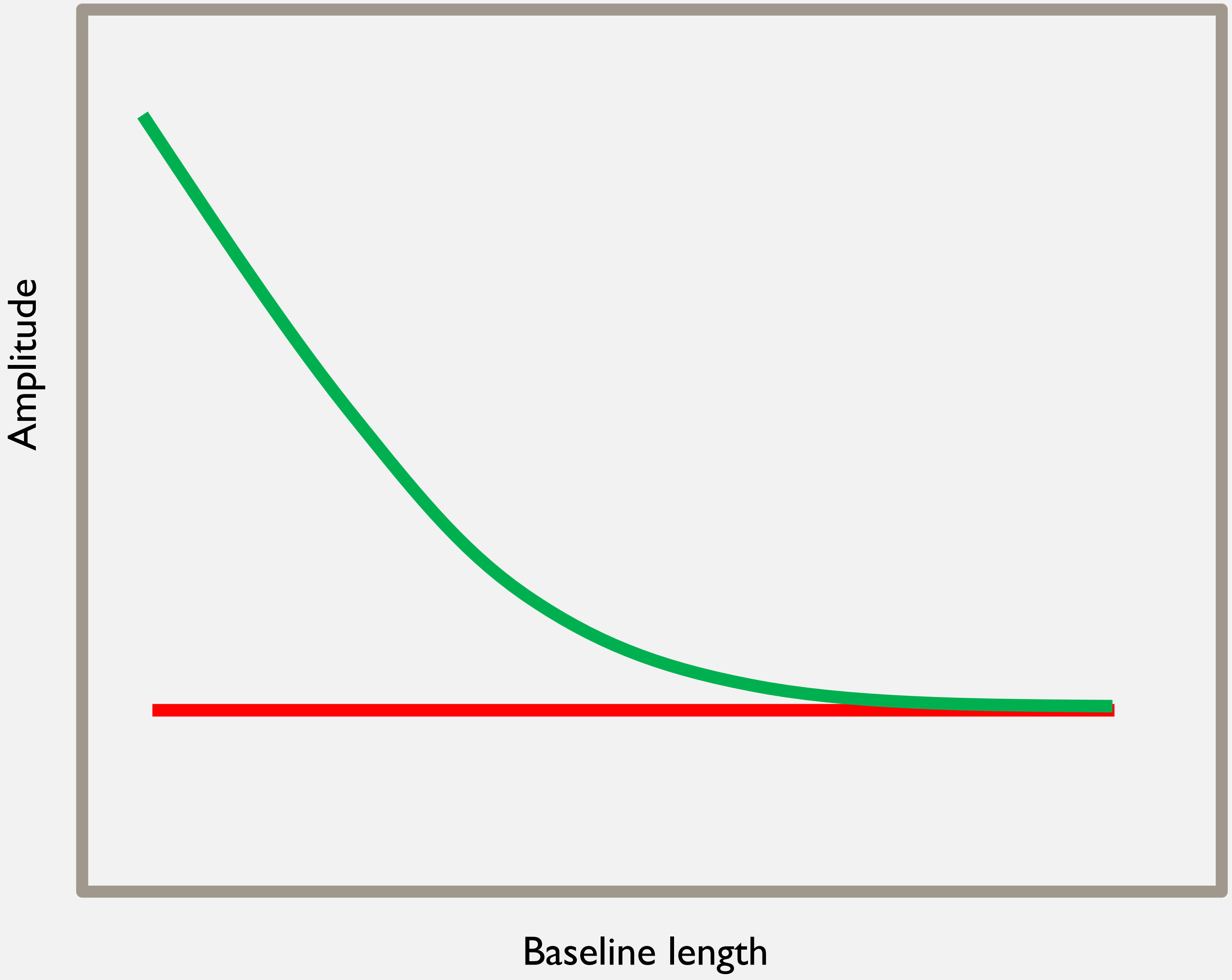
How do we make the images?

Each telescopes receives a radio wave signal from the source

If we **correlate** (multiply) the signal received at two different telescopes we measure an **amplitude** and a **phase** (the complex 'visibility')

The amplitude tells you about how bright the source is on that baseline and the phase tells you how offset the flux is from the phase centre, i.e. where the source is.

The very basics: interferometers



A baseline $d_{baseline}$ will measure flux from source of the corresponding angular size θ_{RES} *or smaller*

So, a 'point source' which is unresolved on all baselines will have constant amplitude as a function of baseline length

A 'resolved source' (e.g. supernova remnant) will be a appear brighter on shorter baselines

The very basics: (Earth rotation) aperture synthesis

A correlation ('visibility': amplitude, phase) is recorded for each baseline at each time step.

While the dishes track the target, the *array* does not, meaning the projection of the baselines onto the source varies with time as Earth rotates

This fills in the 'u,v plane' with tracks. The more filled in the u,v plane the more like a single filled aperture → images are **nicer** and **more accurate**

The larger the number of baselines, and the smoother their distribution, the better the images look.

Number of baselines

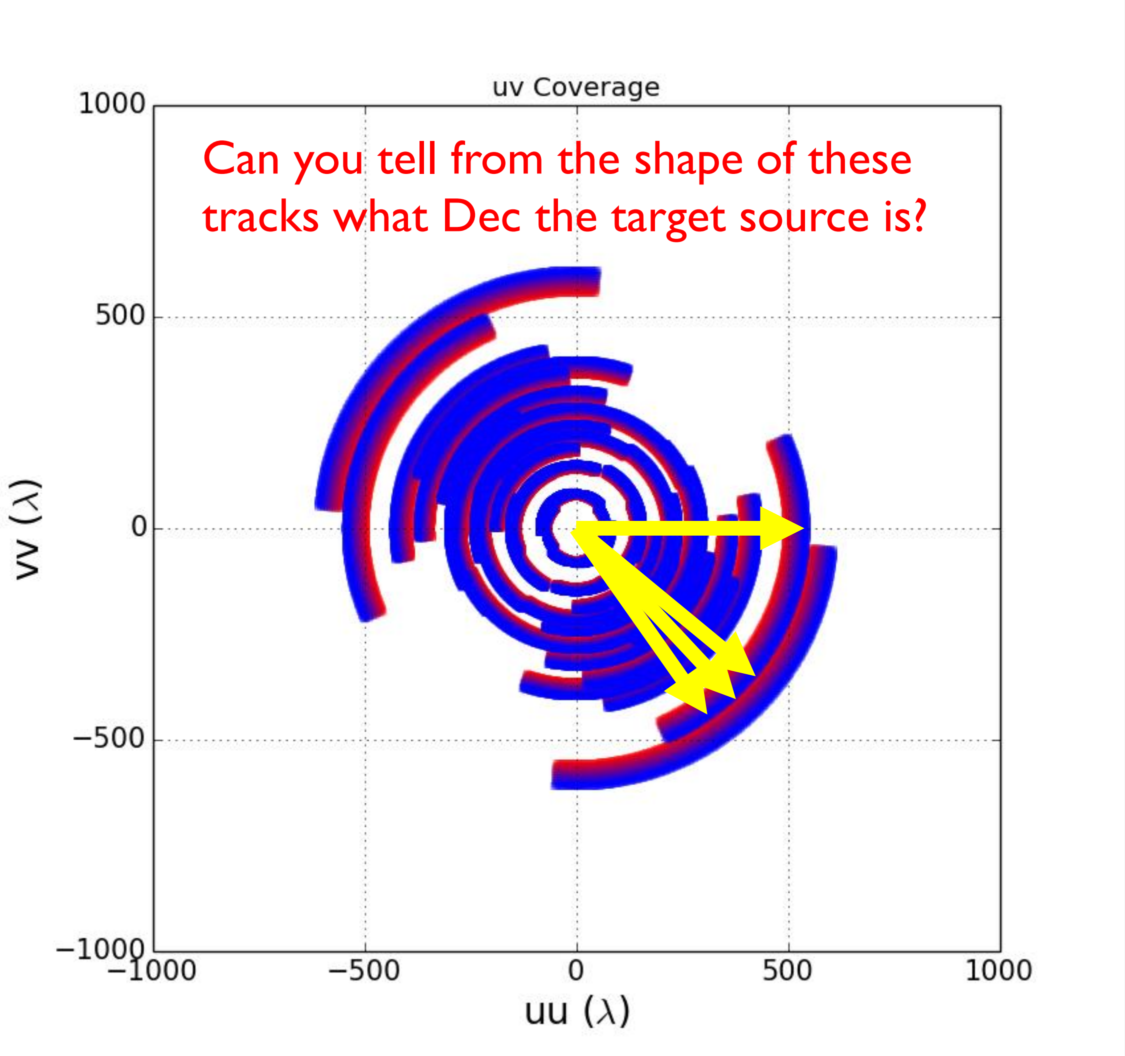
$N_{baseline} = N(N-1)/2$

Where N is number of antennas

Telescope	Dishes	Baselines
VLA	27	351
GMRT	30	435
MeerKAT	64	2016

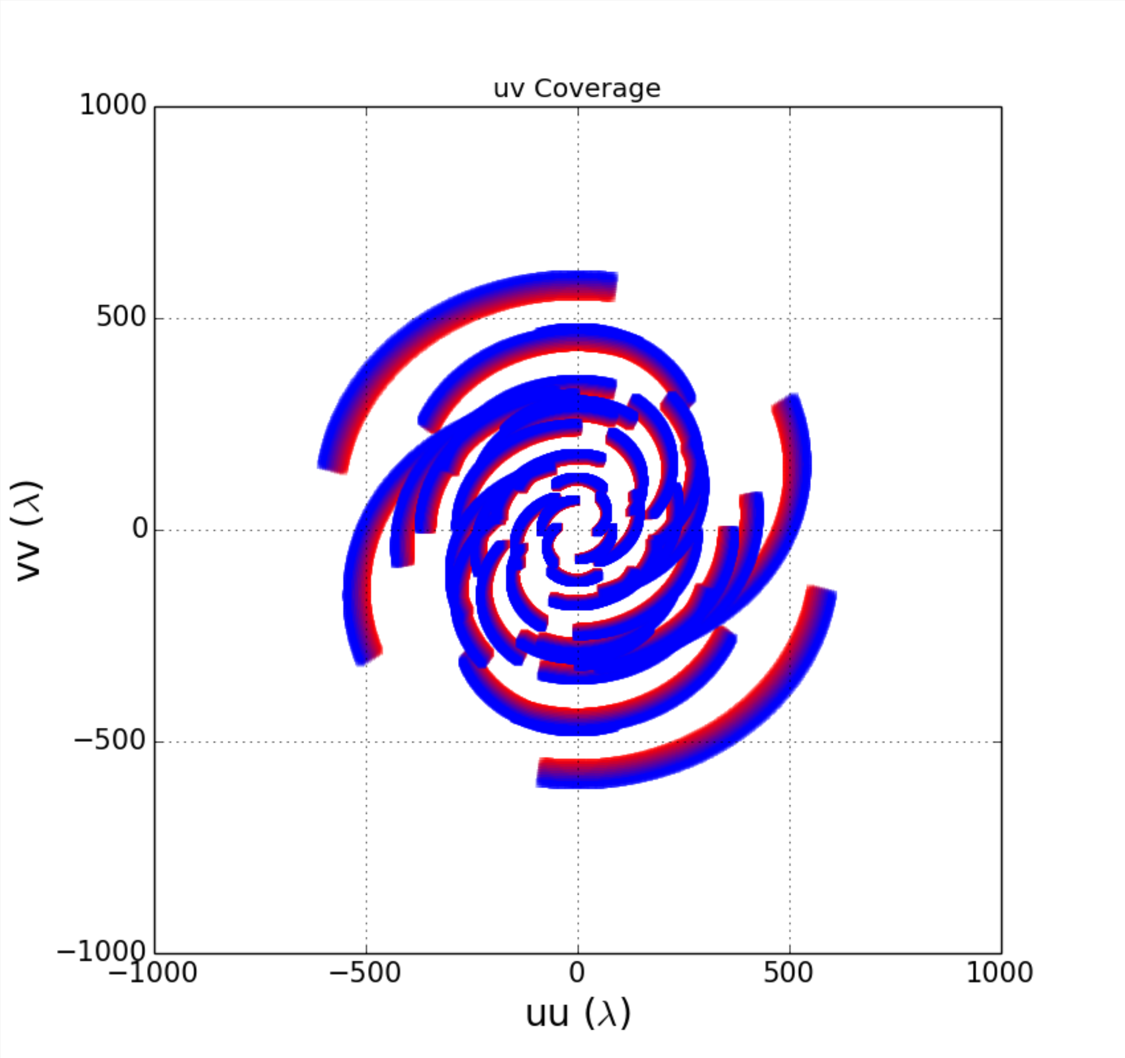
Source at **Dec -90**:
Circular tracks in (u,v) plane as Earth rotates.

KAT-7 (MeerKAT test array) South Africa
(21 baselines)



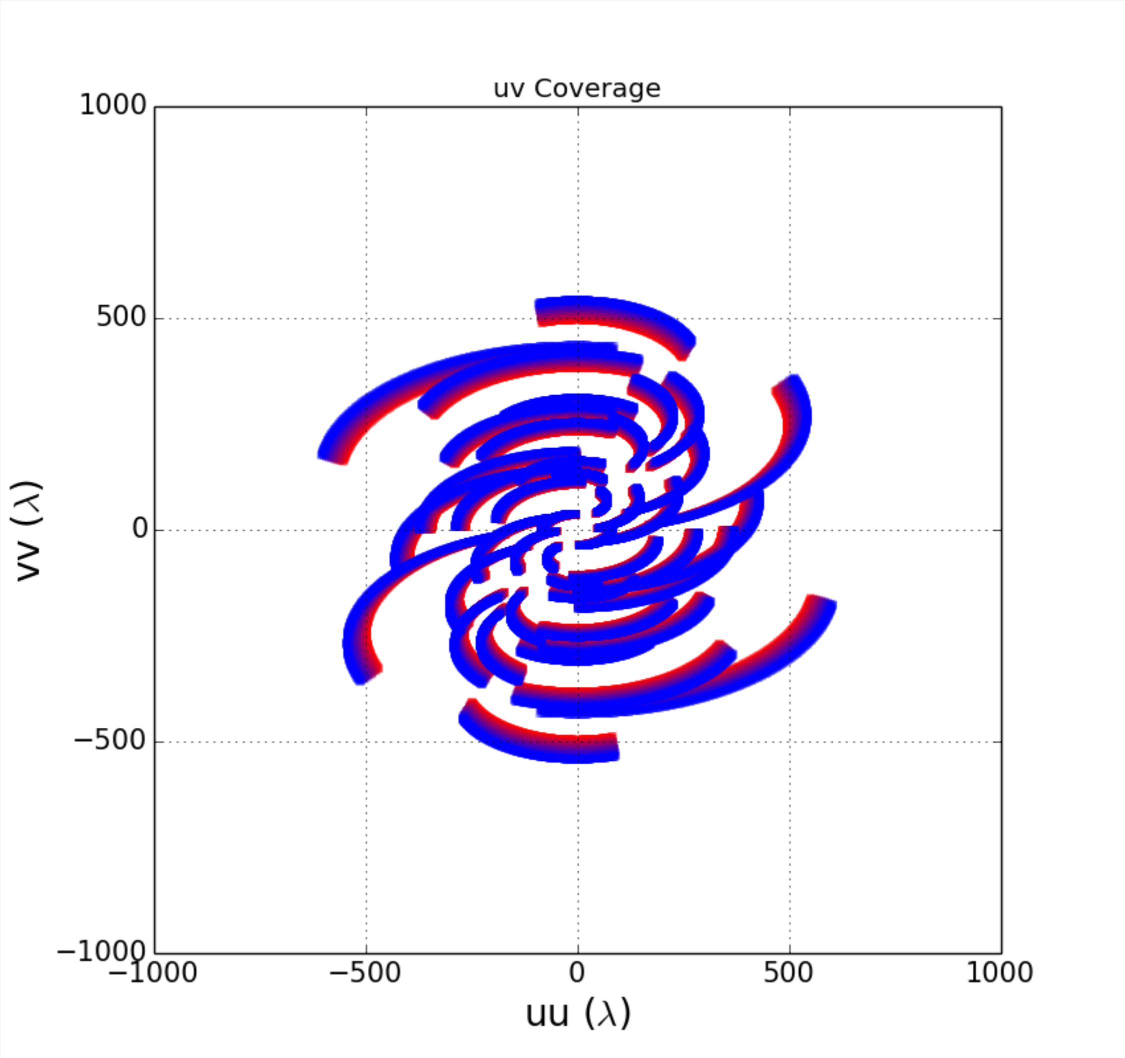
Radial distance of line from phase centre reflects baseline length
Orientation of baseline from projection onto the source
Azimuthal rotation due to (Earth) rotation of the array

Source at **Dec -60:** Projected tracks no longer circular



KAT-7 (MeerKAT test array) South Africa

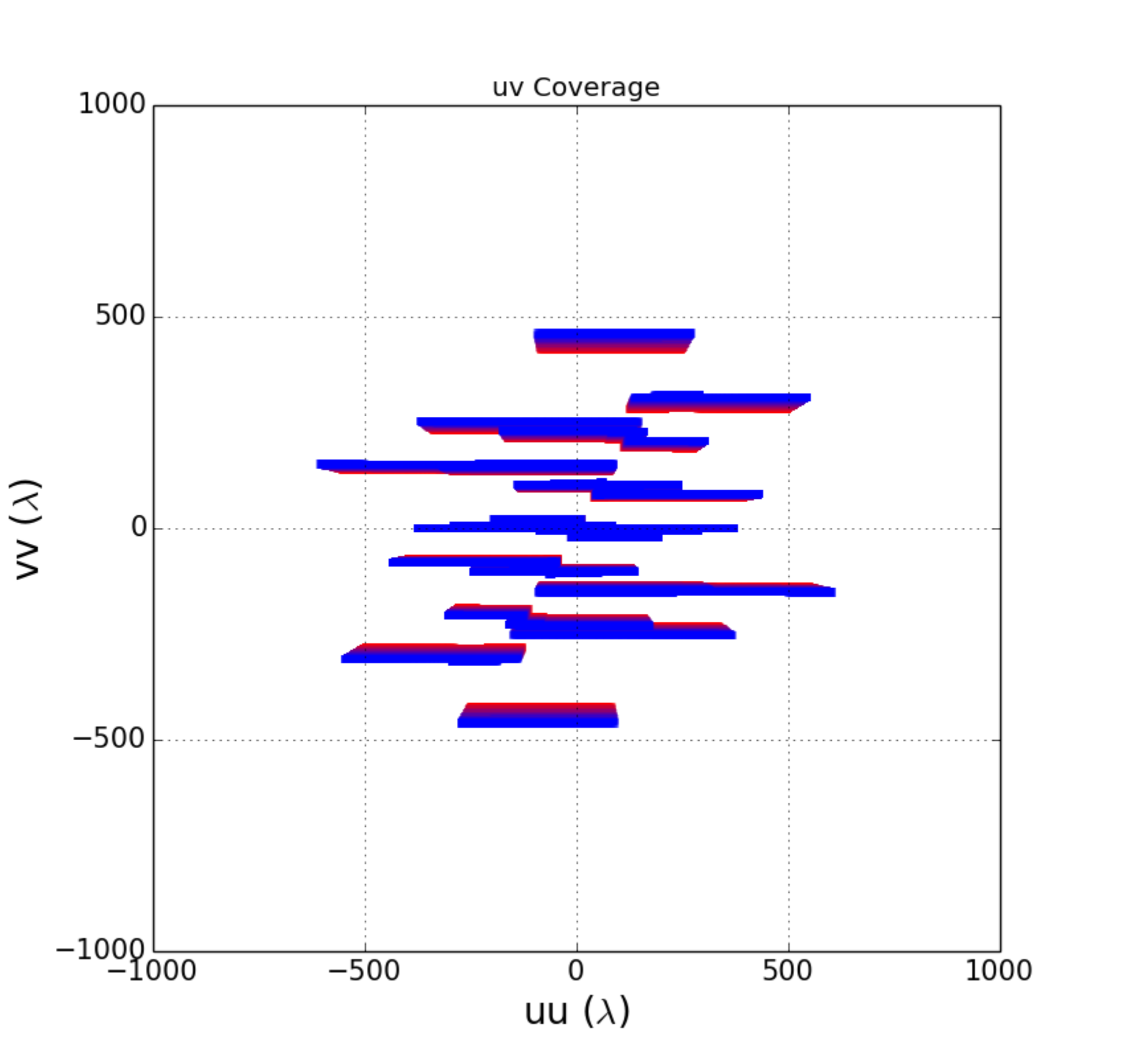
Source at **Dec -30**: Projected tracks no longer circular



KAT-7 (MeerKAT test array) South Africa

Source at **Dec 0**: projected tracks linear E-W

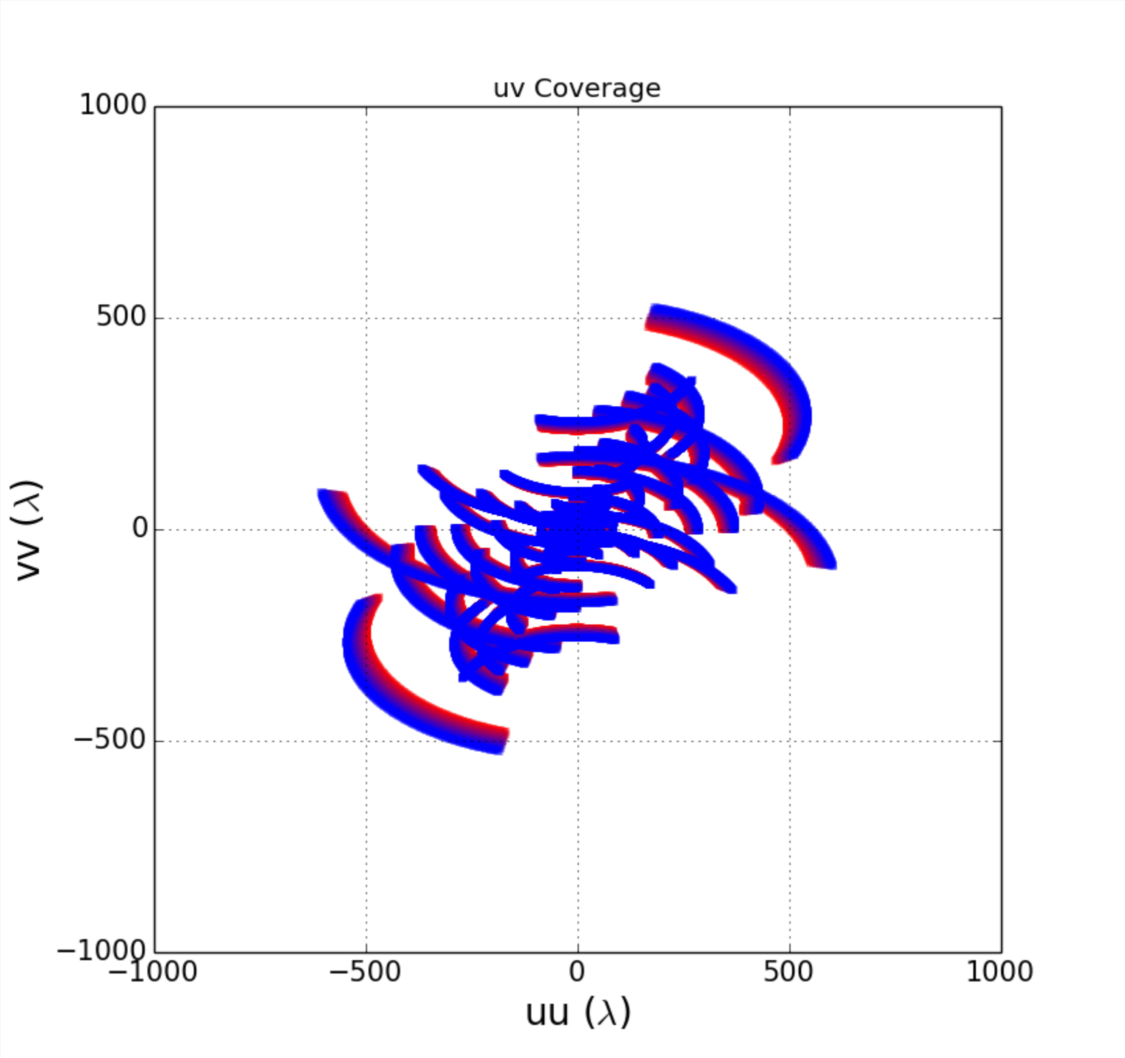
KAT-7 (MeerKAT test array) South Africa



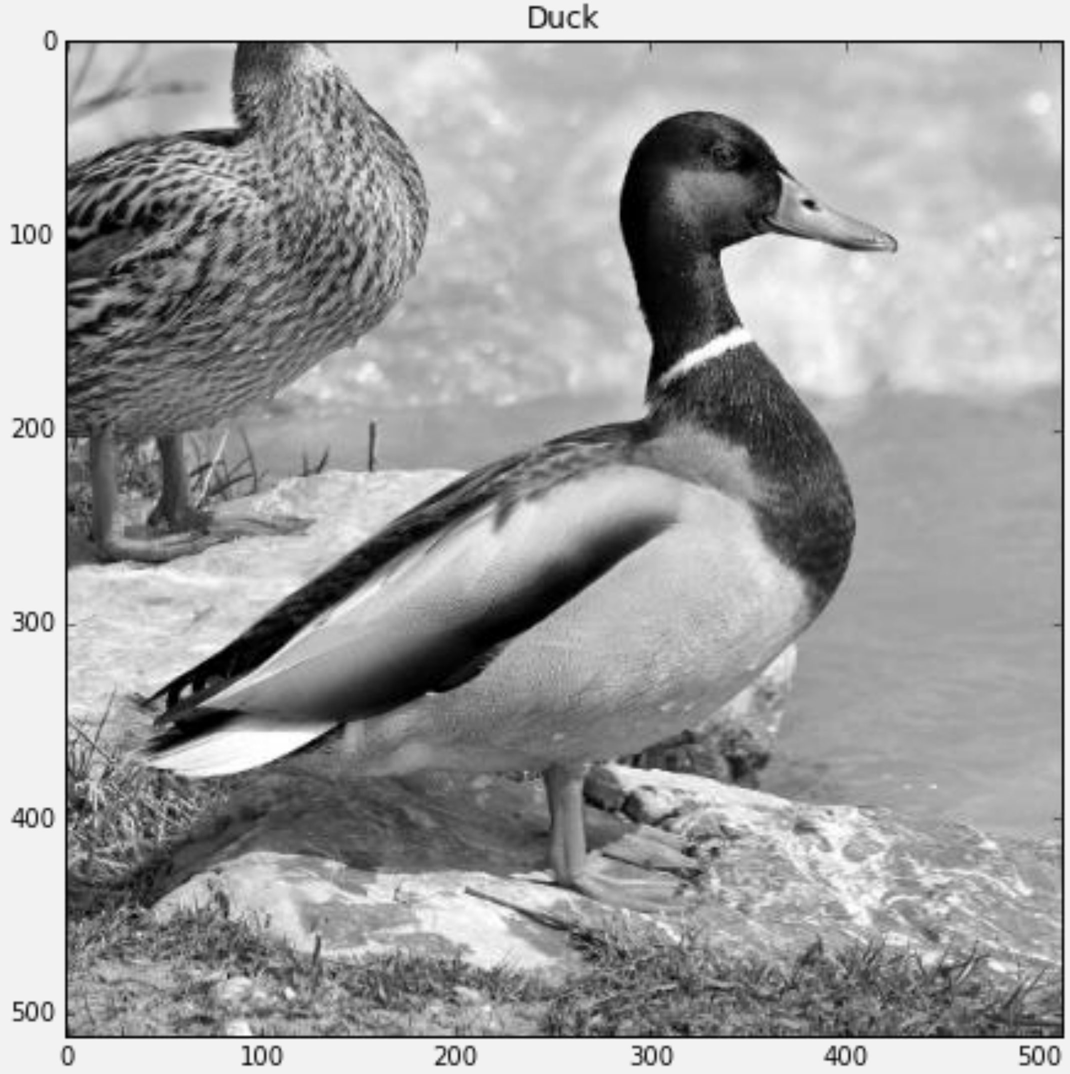
Imagine having an East-West only interferometer looking at a Dec 0 source

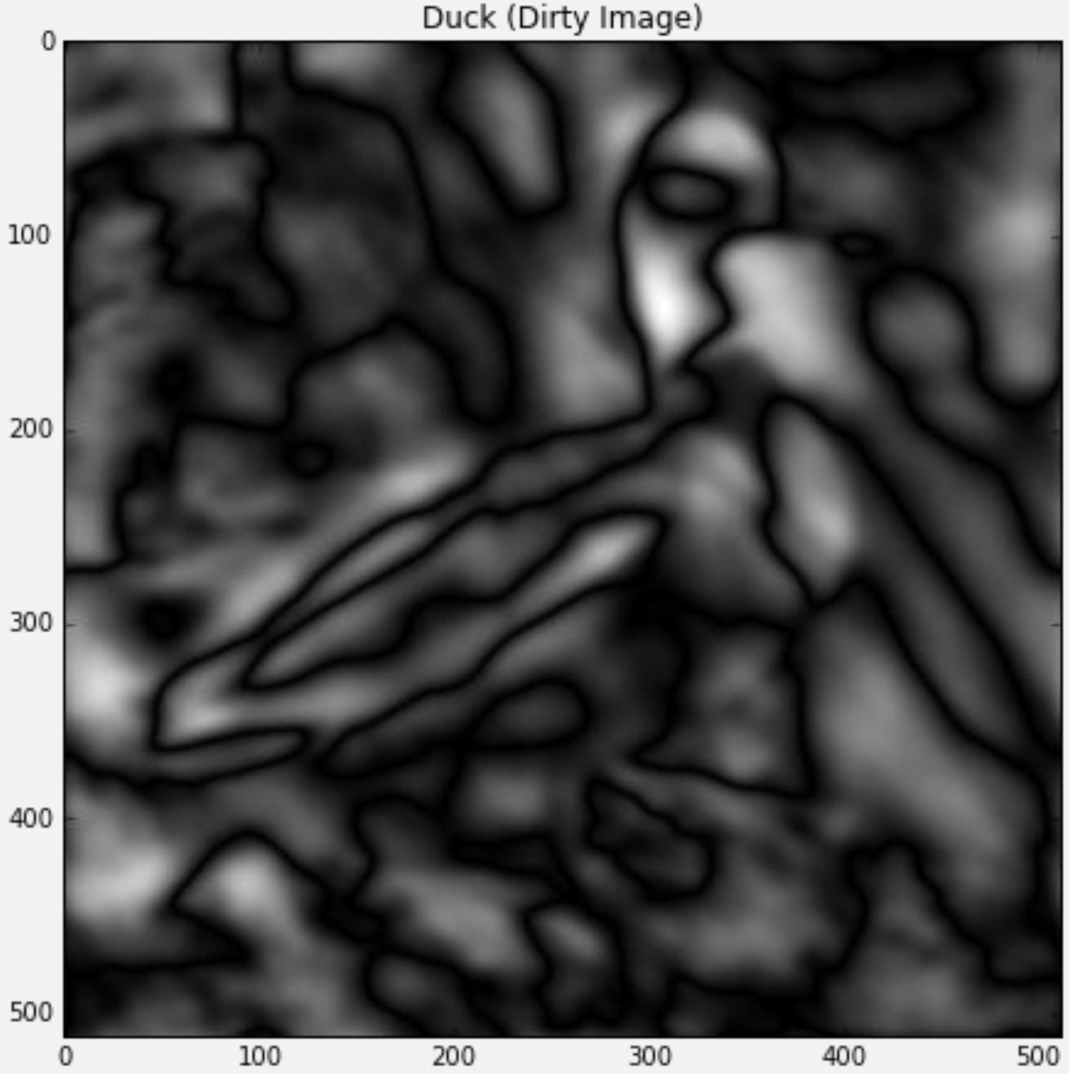
Source at **Dec +30**: Shorter tracks (horizon!)

KAT-7 (MeerKAT test array) South Africa



A celestial duck (at Dec -30, 6hr observation with KAT-7 [21 baselines])

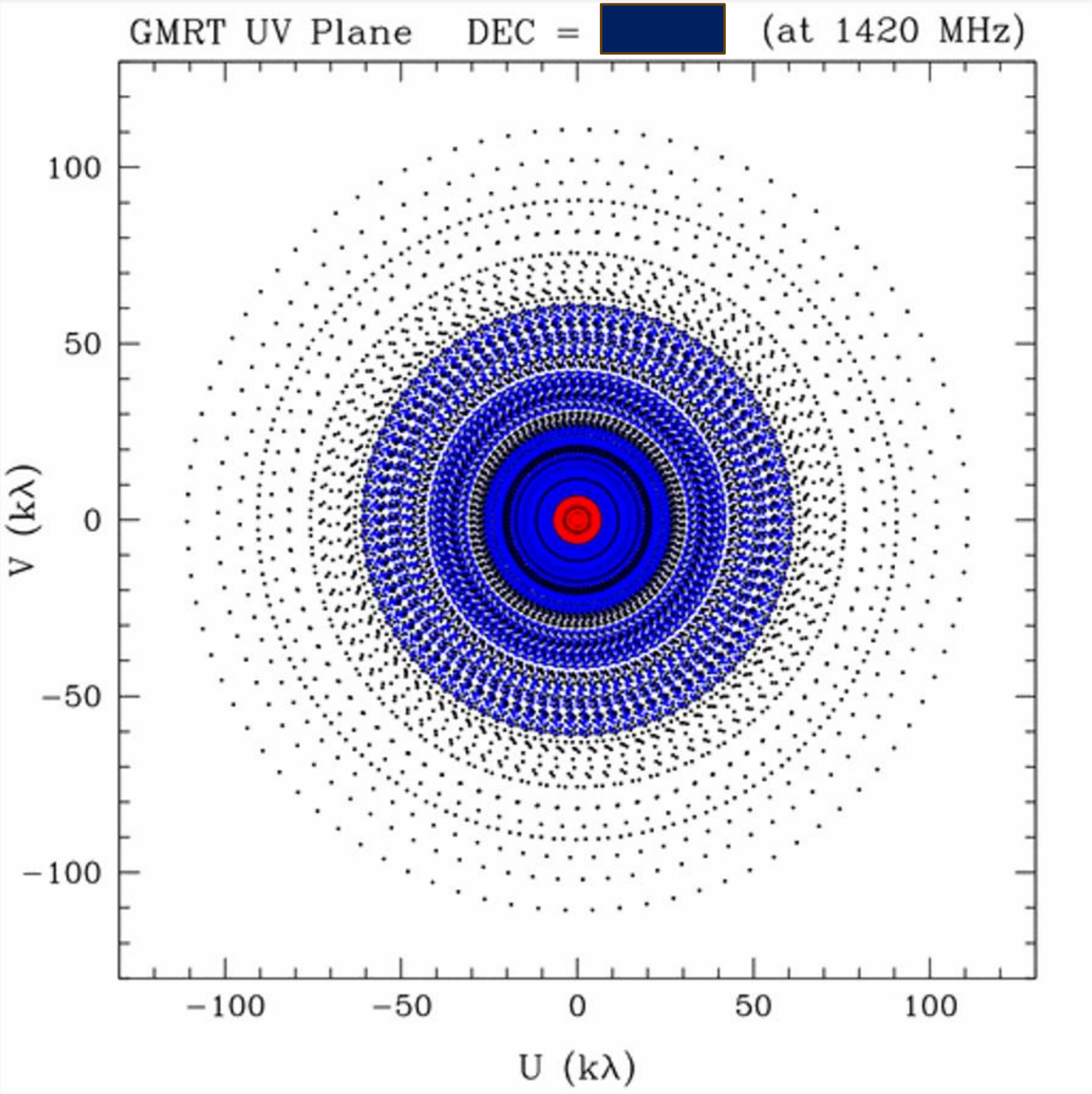




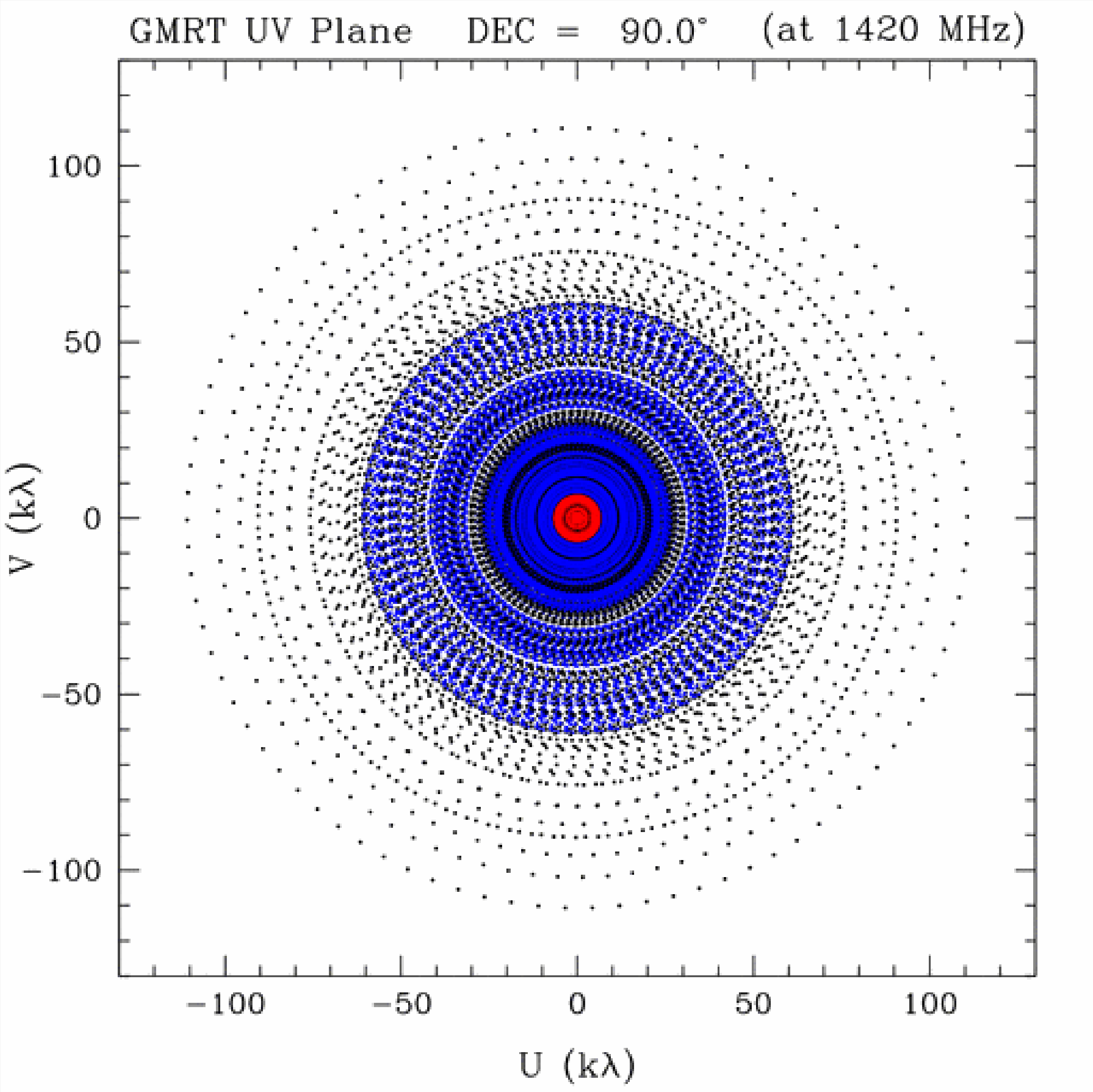
Imaging complex structures with sparse arrays is hard

The u,v plane: GMRT (435 baselines)

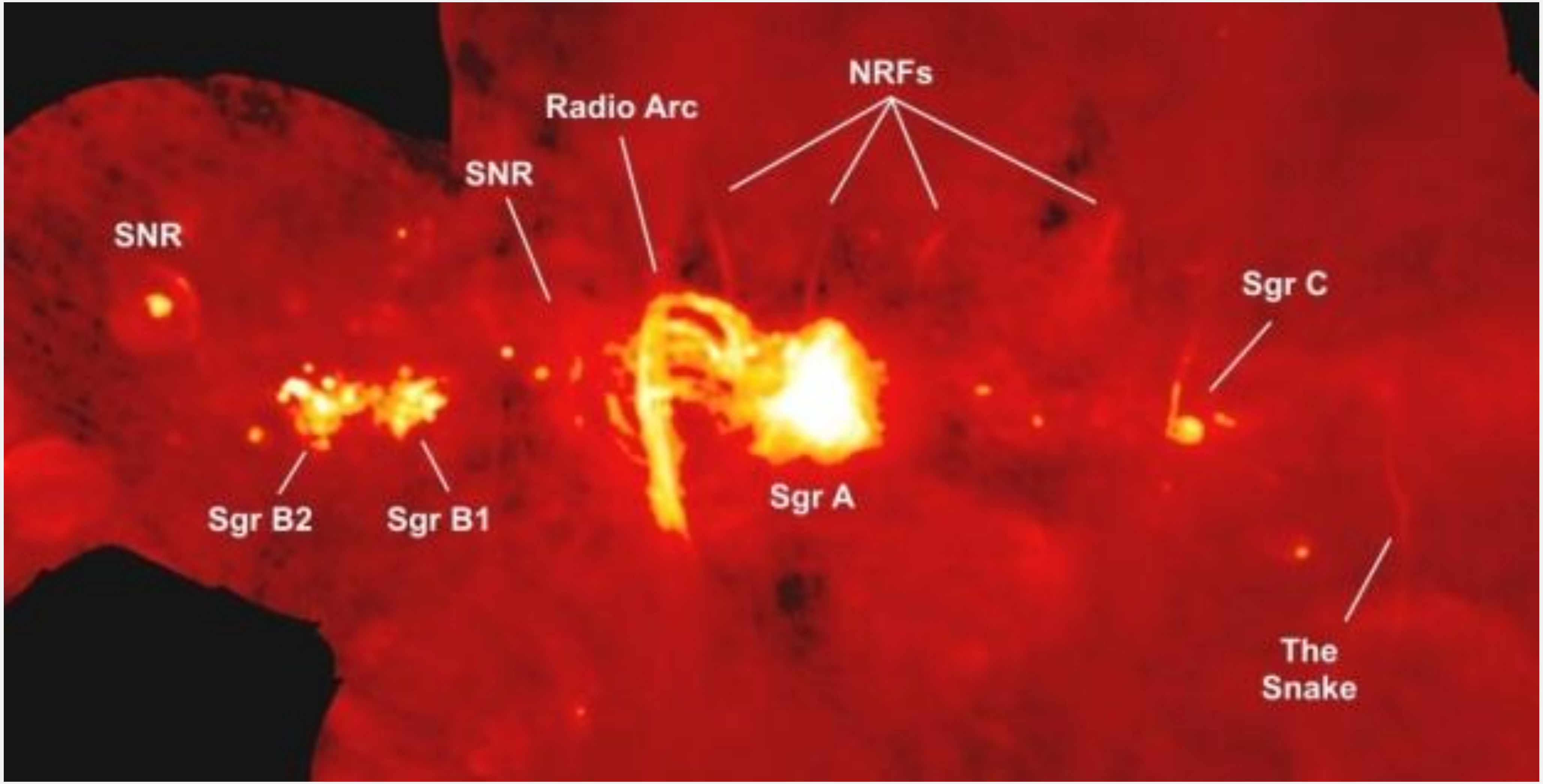
redacted



The u,v plane: GMRT

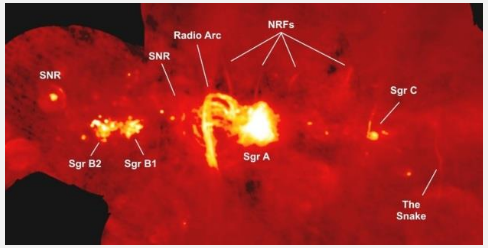


An example of the effect of more baselines: imaging the galactic centre

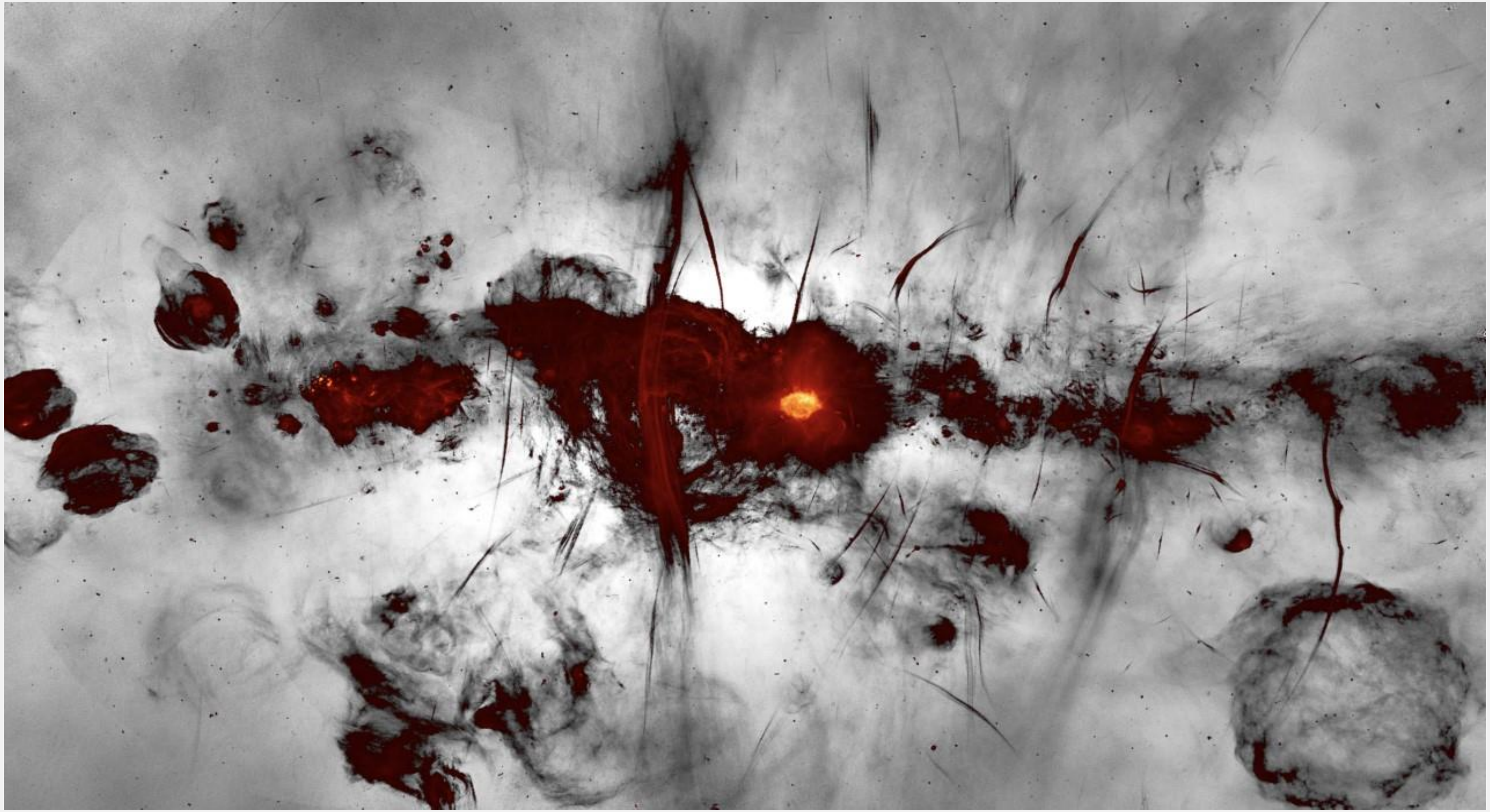


VLA (351 baselines)

An example: imaging the galactic centre

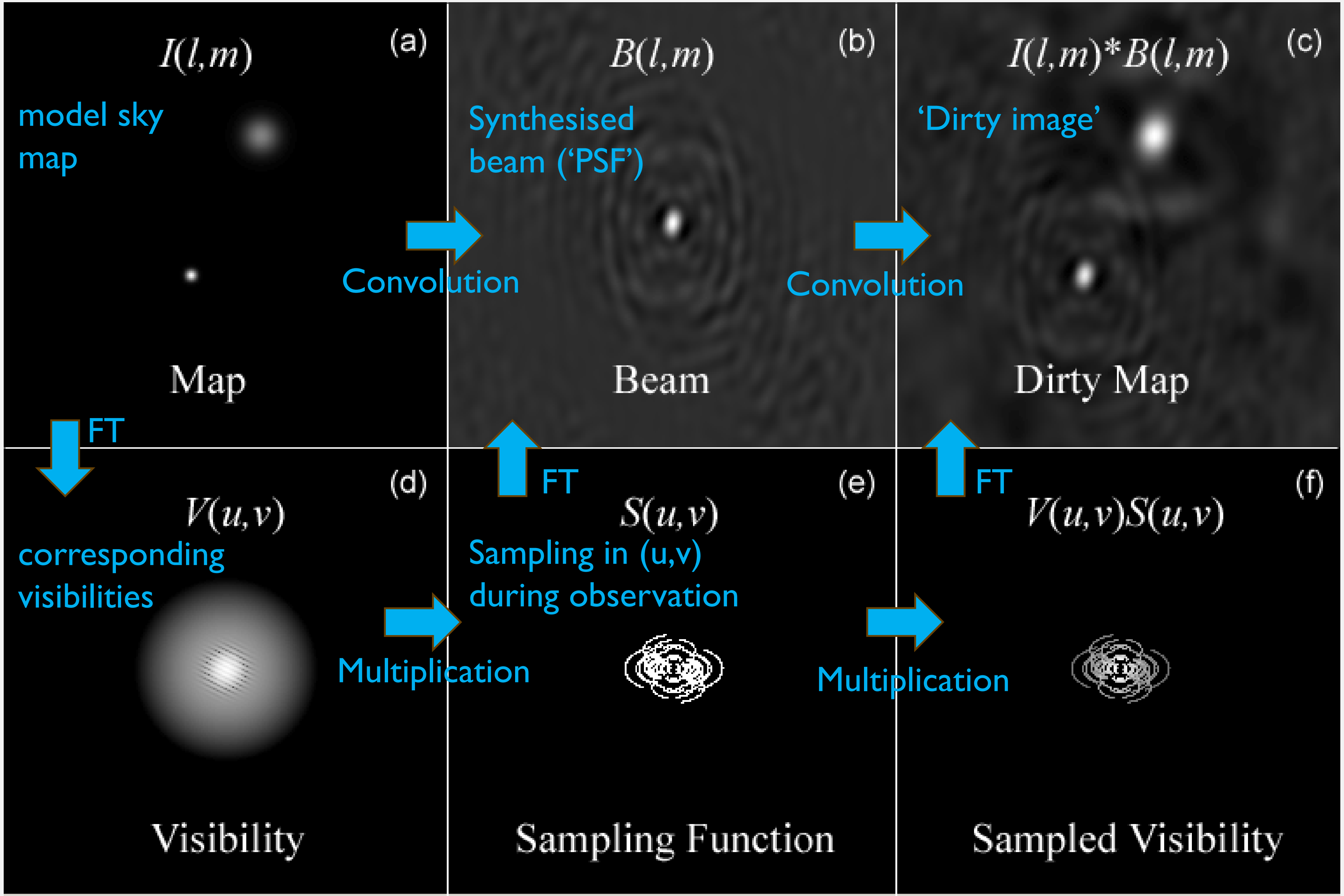


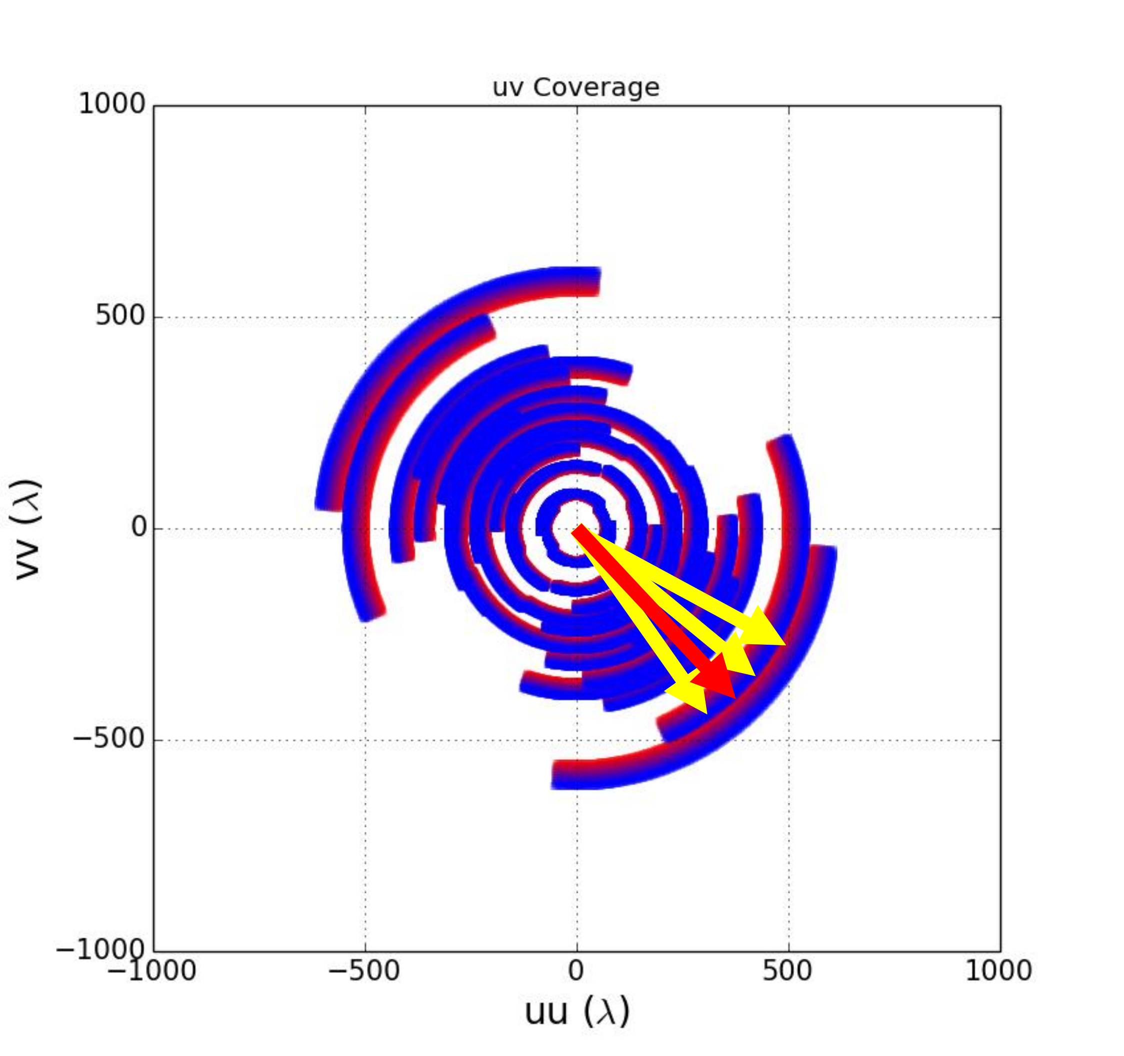
VLA (351 baselines)



MeerKAT (2016 baselines)

Now you understand why radio images (often) look so bad? Incomplete aperture!! Bad sampling!! Beware!!





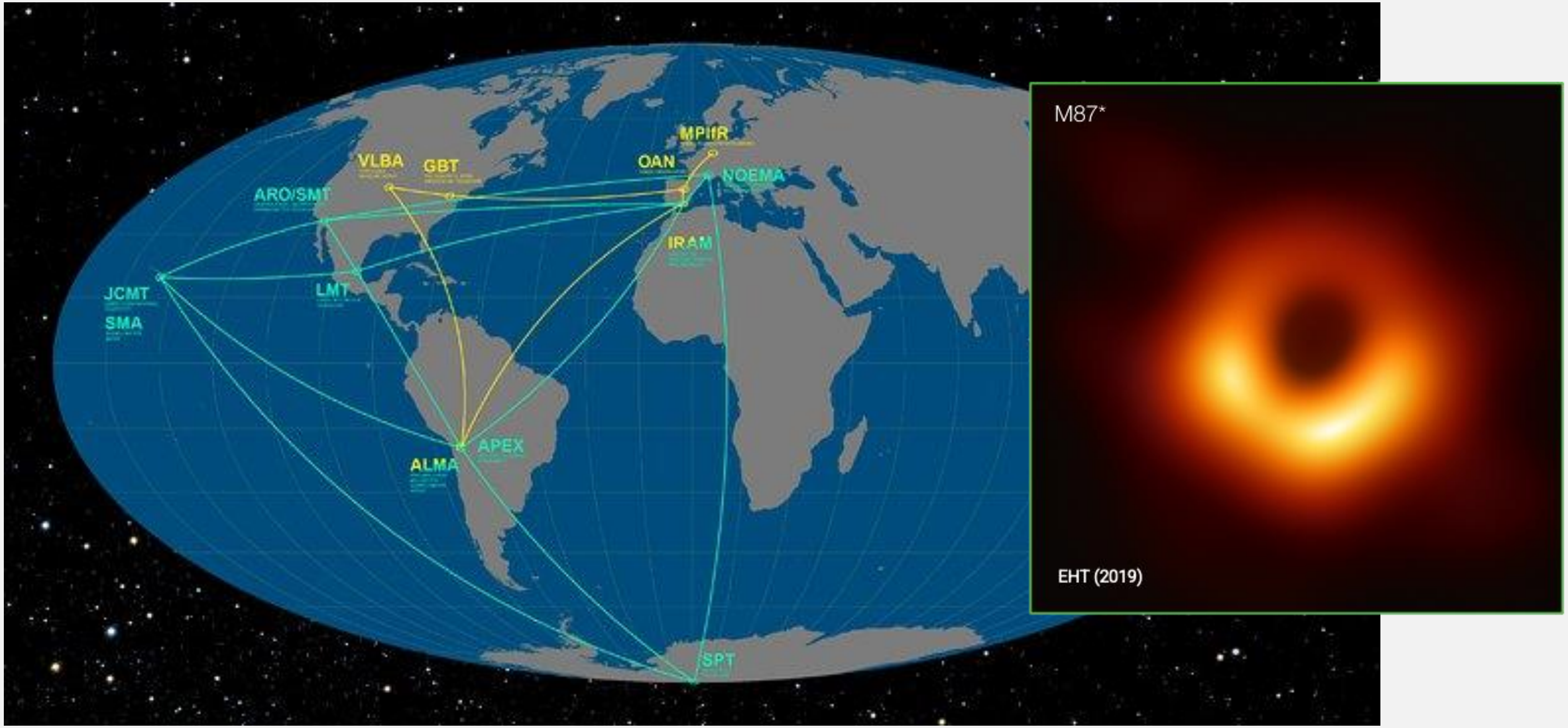
Most astrophysical **transients** are point sources

This means that sparse arrays and 'snapshots' (short observations with poor u,v coverage) can work

However, long observations of a source which is varying *during* the run will have artefacts: if the source is brighter for a few scans the (inverse) this is indistinguishable from more flux at that position angle and the FT can (often) produce an elongated structure at that angle.

Hence (perversely!) rapid variability from transients can produce artefacts which look like jets!!

VLBI: ironically the longest wavelengths give us highest resolution. How?
Because we can record and store the phases (and then ship them to a correlator)
So the highest angular resolution in astronomy comes from the highest frequency at which we can record phases: millimetre VLBI



EHT network

Down the rabbit hole…

We didn’t talk about **calibration**

Then you improve your ‘dirty’ image by applying the non-linear ‘clean’ algorithm

Maybe reconsider your **weightings?**

Finally you make a beautiful image which everyone trusts except you.

There are a lot of details in radio data reduction, but there are also a lot of experienced people out there and a lot of good resources. You can do it!

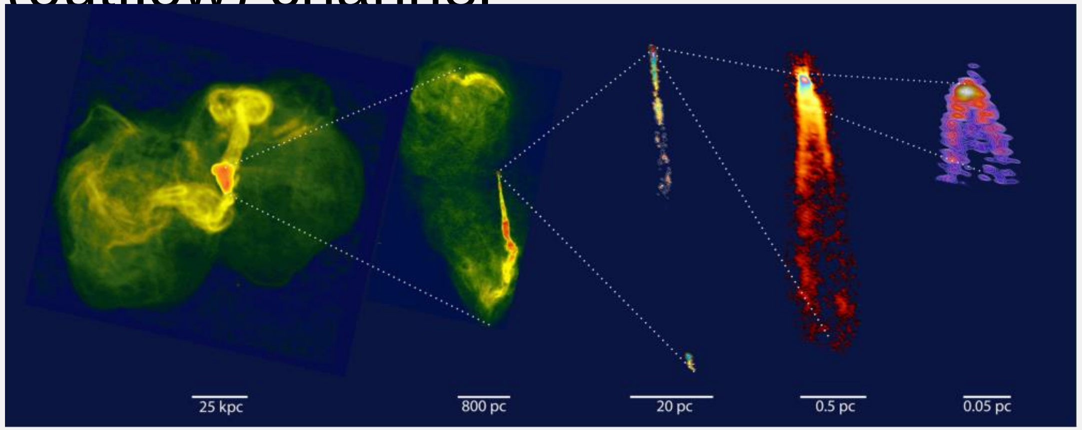
RADIO ASTRONOMY

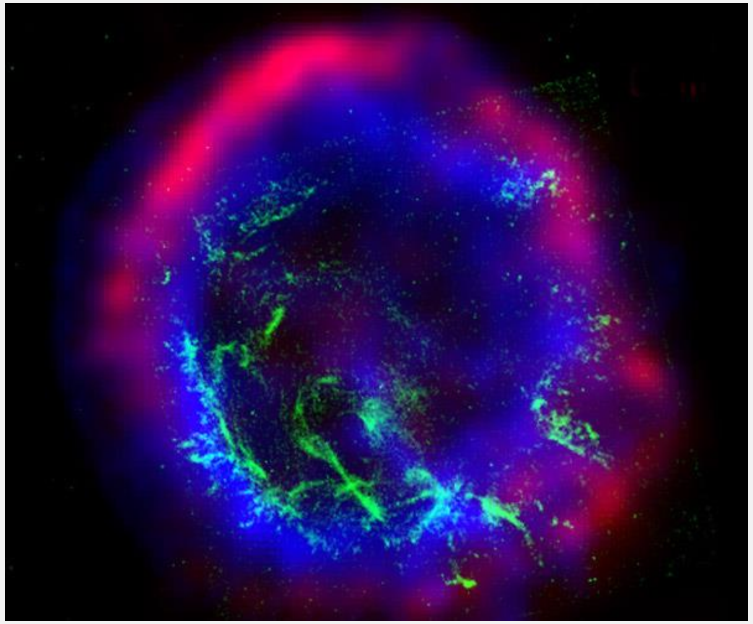
RADIO TRANSIENT ASTROPHYSICS

FUTURE FACILITIES AND PROSPECTS

Synchrotron (incoherent) transients are associated with **particle acceleration and kinetic feedback** from explosive events (all explosions except SN Ia so far…)

In most cases they are the **only** way to estimate the power from the event going into the kinetic energy (outflow) channel



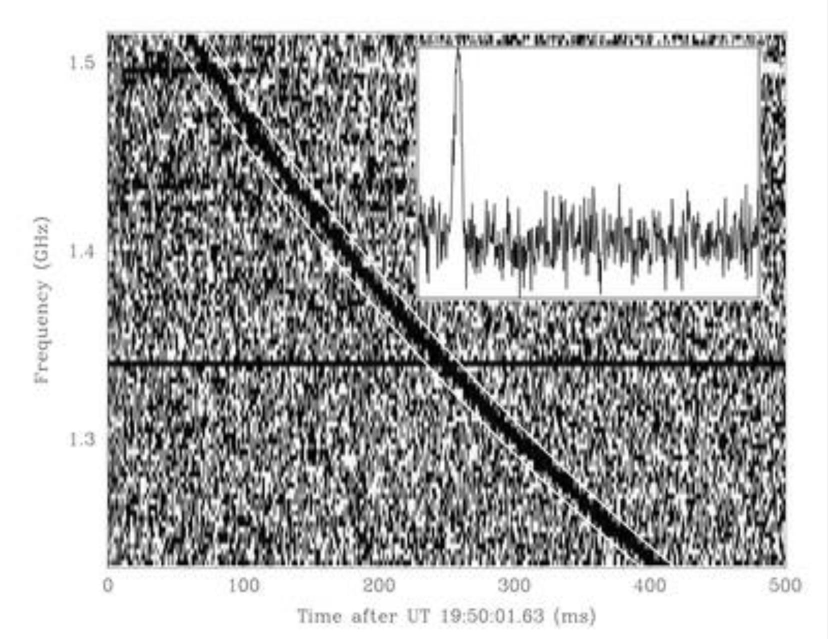


Radio arrays offer a **unique combination** of **very wide fields of view** and **high angular resolution**

However, for most astrophysical transients they are still sometimes less sensitive than X-ray telescopes for synchrotron sources

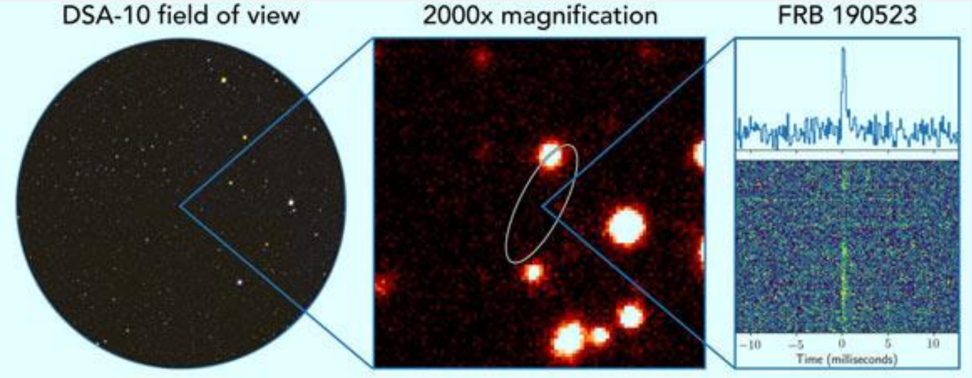
Coherent transients (FRBs and various flavours of pulsar) have short durations, and hence very high brightness temperatures

The underlying physics is unclear, but the intrinsic pulse narrowness means the observed profile tells us about properties of IGM/ISM

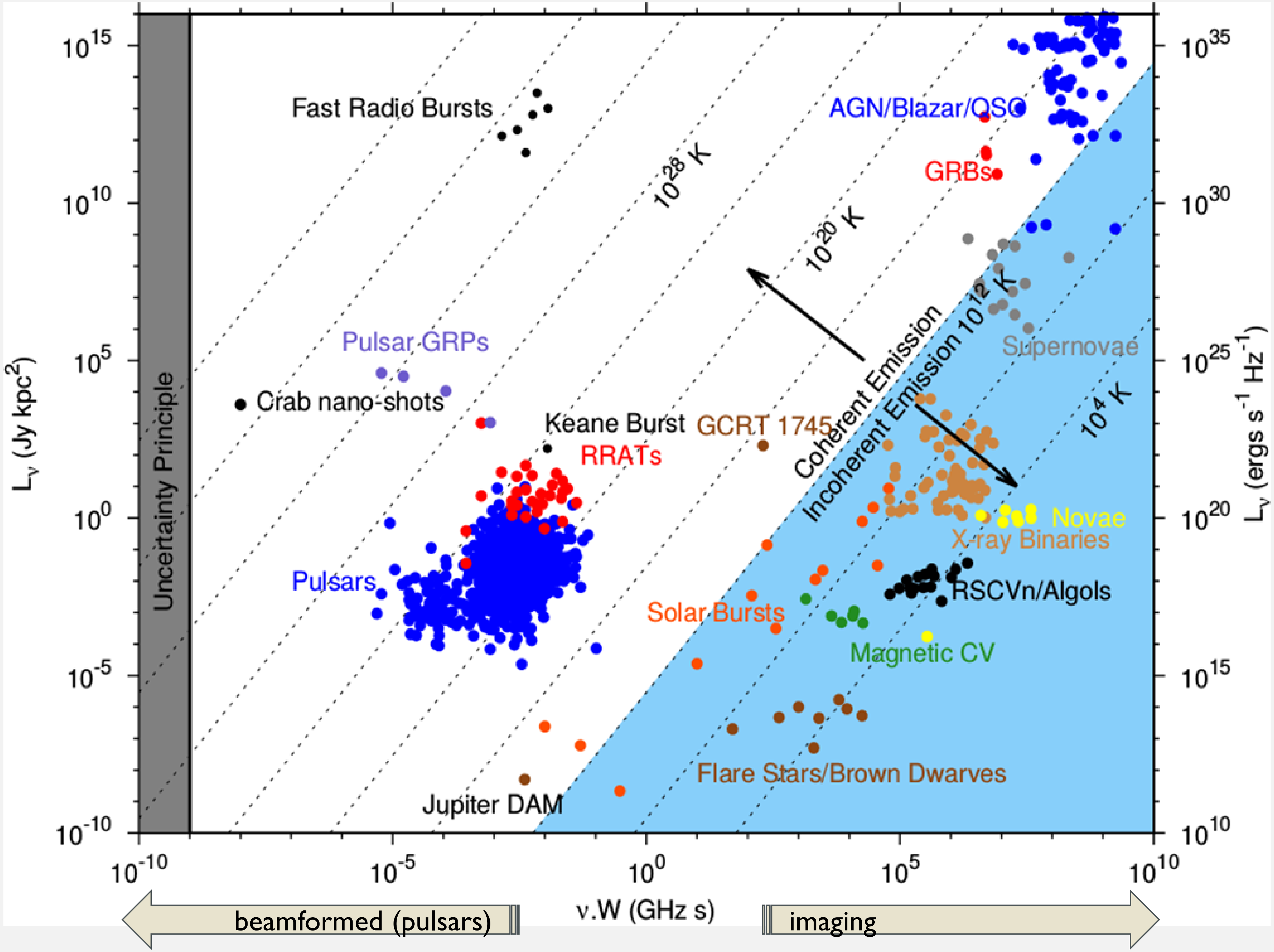


Radio telescopes are currently the **only** way to discover these sources

In some case - e.g. CHIME - large numbers are being found but with poor localisation (but see ASKAP)



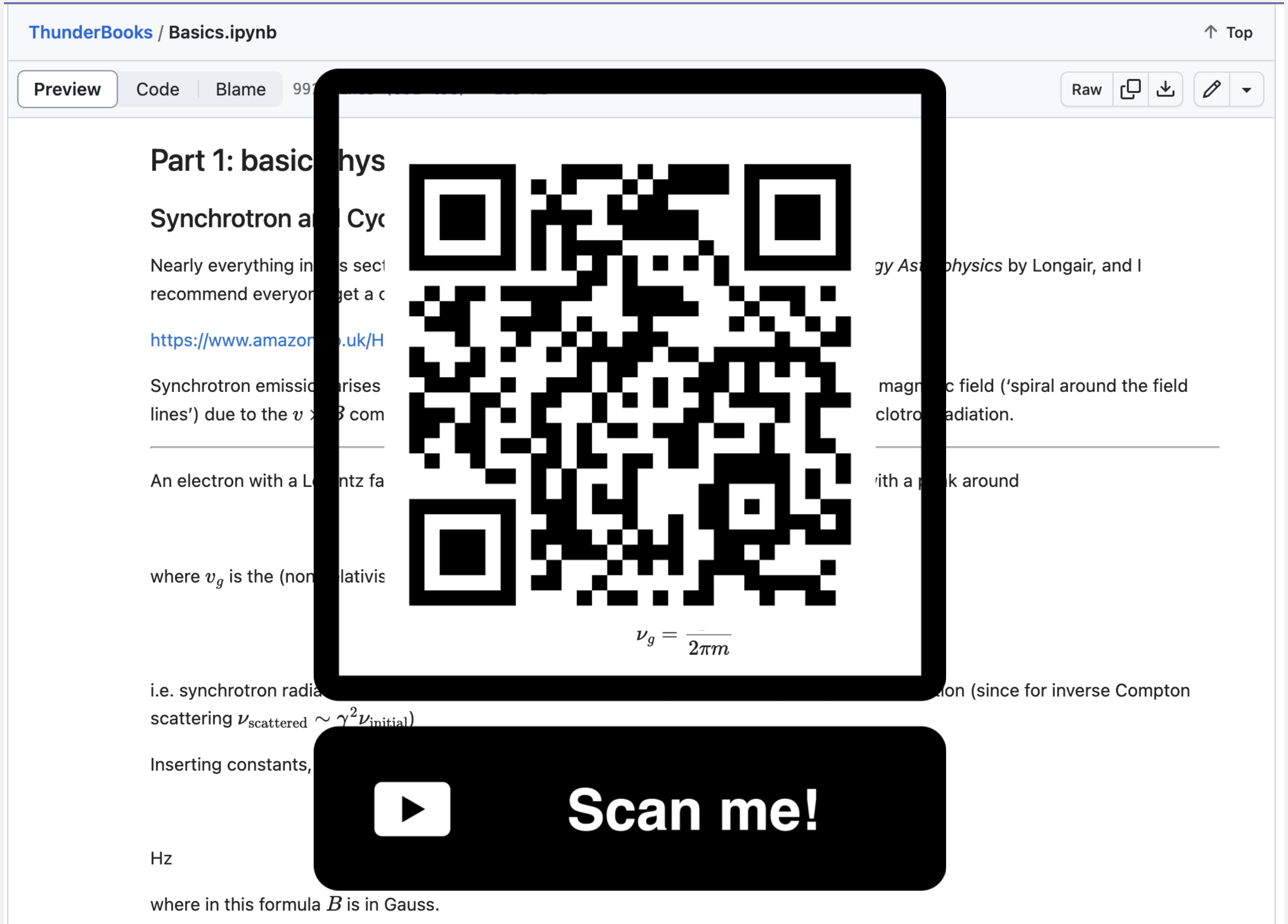
Multi-λ data are very sparse



Radio Transients luminosity - timescale parameter space

Pietka, Fender & Keane (2015)

https://github.com/robfender/ThunderBooks



Basics.ipynb

Equipartition analysis.ipynb

All the basic relations between electron energy, magnetic field, observed frequencies

How to calculate Brightness Temperature

Simplifield (and full) minimum energy calculations

Calculate full synchrotron spectrum (optically thick and thin) for an evolving, expanding blob

Synchrotron emission, simple things

Scan me!

Most of this is in the Jupyter notebook: https://github.com/robfender/ThunderBooks

Underlying electron energy distribution can be directly measured when source is optically thin

High brightness temperatures (T_B >10^8 K) rule out thermal emission in most cases.

However, there is a **maximum** brightness temperature **(**$T_{B,max}$~10^{12} K): above this you require relativistic beaming and/or interstellar scintillation and/or coherent (pulsar-like) processes. Invoking $T_{B,max}$~10^{12} K can be used to place a *lower* limit on the size of an emitting region.

Linear polarization measurements when optically thin tell you about orientation of magnetic field

Energy:

If you can measure the **luminosity** and **size** of synchrotron emitting region you can estimate the minimum energy content in magnetic fields and electrons. This is the main way to estimate kinetic energy feedback from transients.

This also gives you the corresponding magnetic field so you can estimate how energetic the electrons emitting at any frequency are.

Synchrotron emission

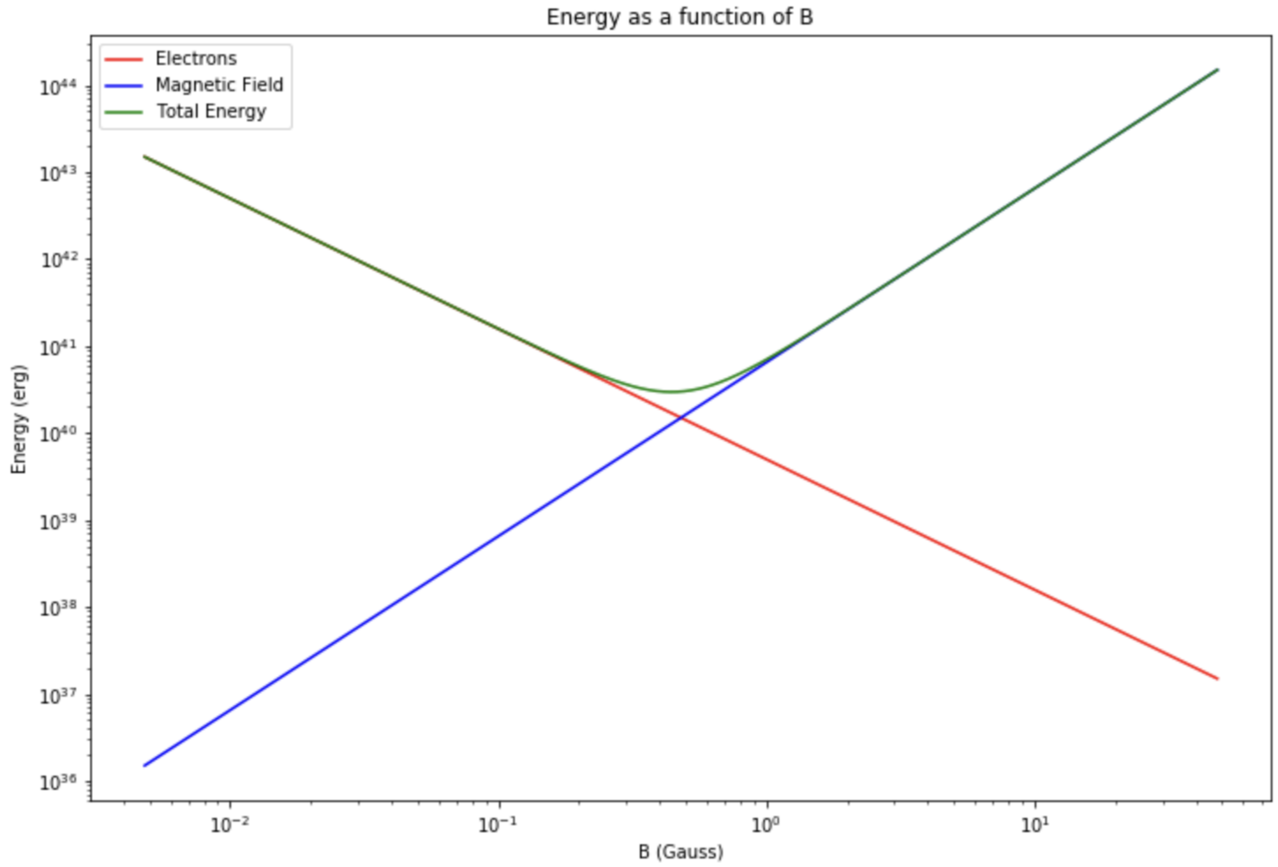
Energy:

If you can measure the **luminosity** and **size** of synchrotron emitting region you can estimate the minimum energy content in magnetic fields and electrons. This is <u>the</u> main way to estimate kinetic energy feedback from transients.

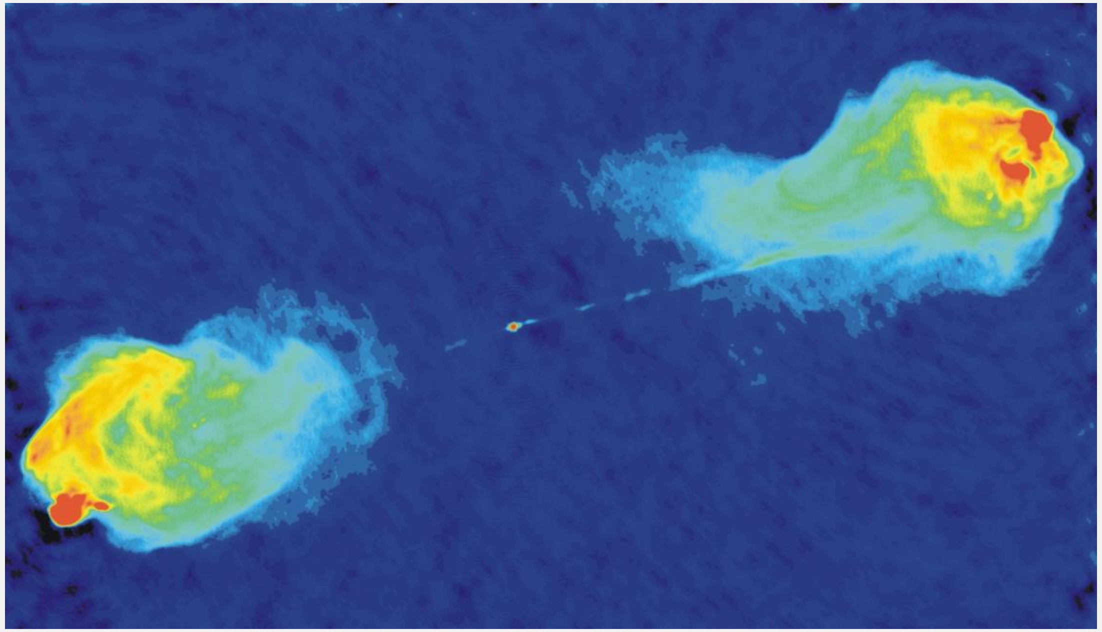
This also gives you the corresponding magnetic field so you can estimate how energetic the electrons emitting at any frequency are.

Note the radio emission 'glows' for a long time after energy injection (>10,000 yr for AGN)

```
Physical size and volume from timescale and expansion at speed 3.00e+10 cm/sec
t= 1.80e+03 sec, r= 5.40e+13 cm, V = 6.60e+41 cm^3
Calculated specific luminosity
L = 7.31e+21  erg / sec / Hz
Minimum Energy
E ~ 1.50e+40 erg
The corresponding magnetic field is
B ~ 4.80e-01 Gauss
And so the total energy in magnetic fields is
6.05e+39  erg
Lorentz factor of emitting electrons for this field is
8.48e+01
```

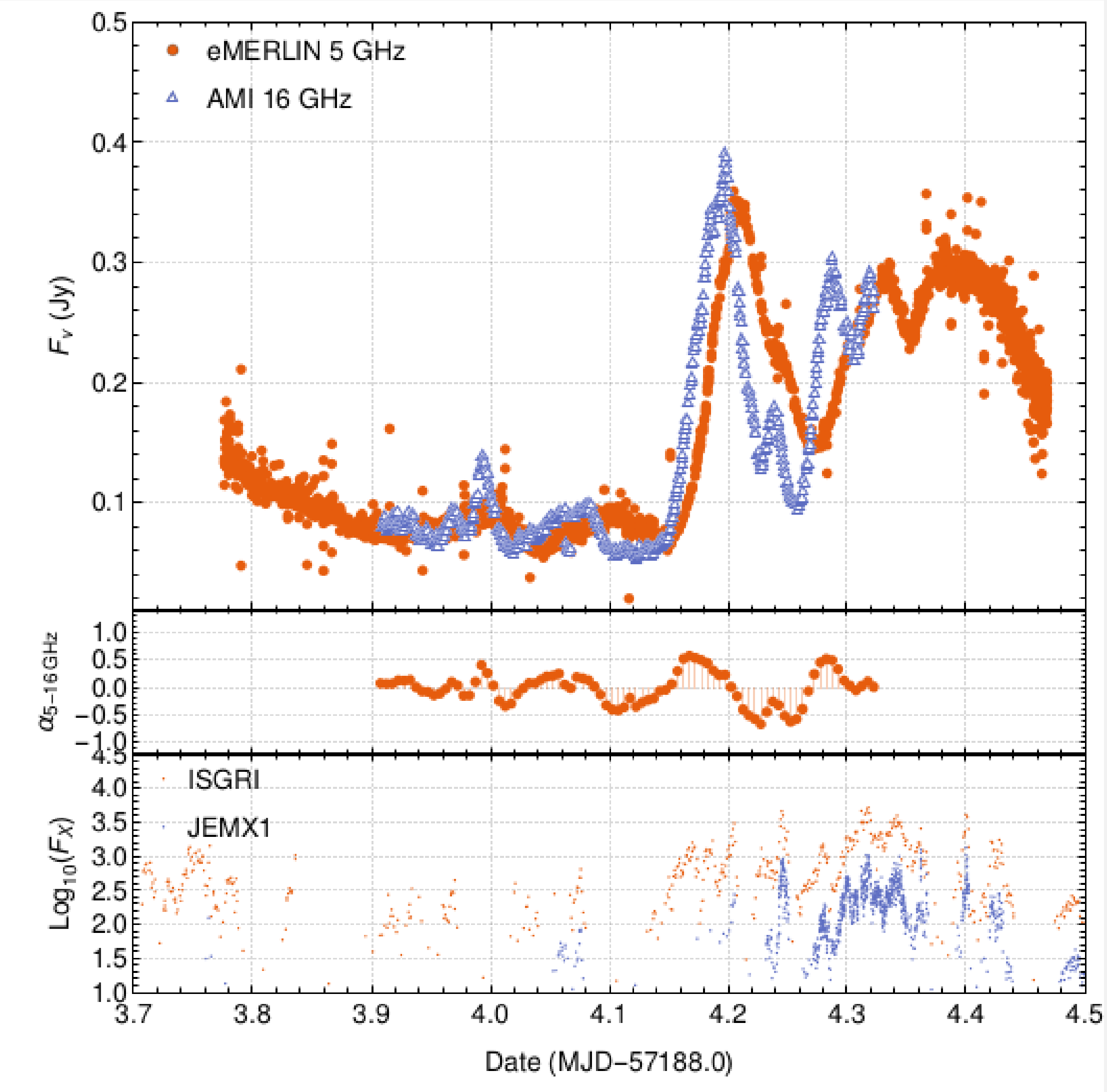


How do you measure the size?



Directly resolving the size of the emitting region is the most obvious way.

This is what Burbidge did in 1958, for AGN, in the first use of the minimum energy / equipartition approach.



For an *unresolved* source, you can measure the size if you know the frequency of the self absorption peak (see Fender & Bright 2019 for application to XRBs)

ThunderKAT

MeerKAT and galactic radio transients

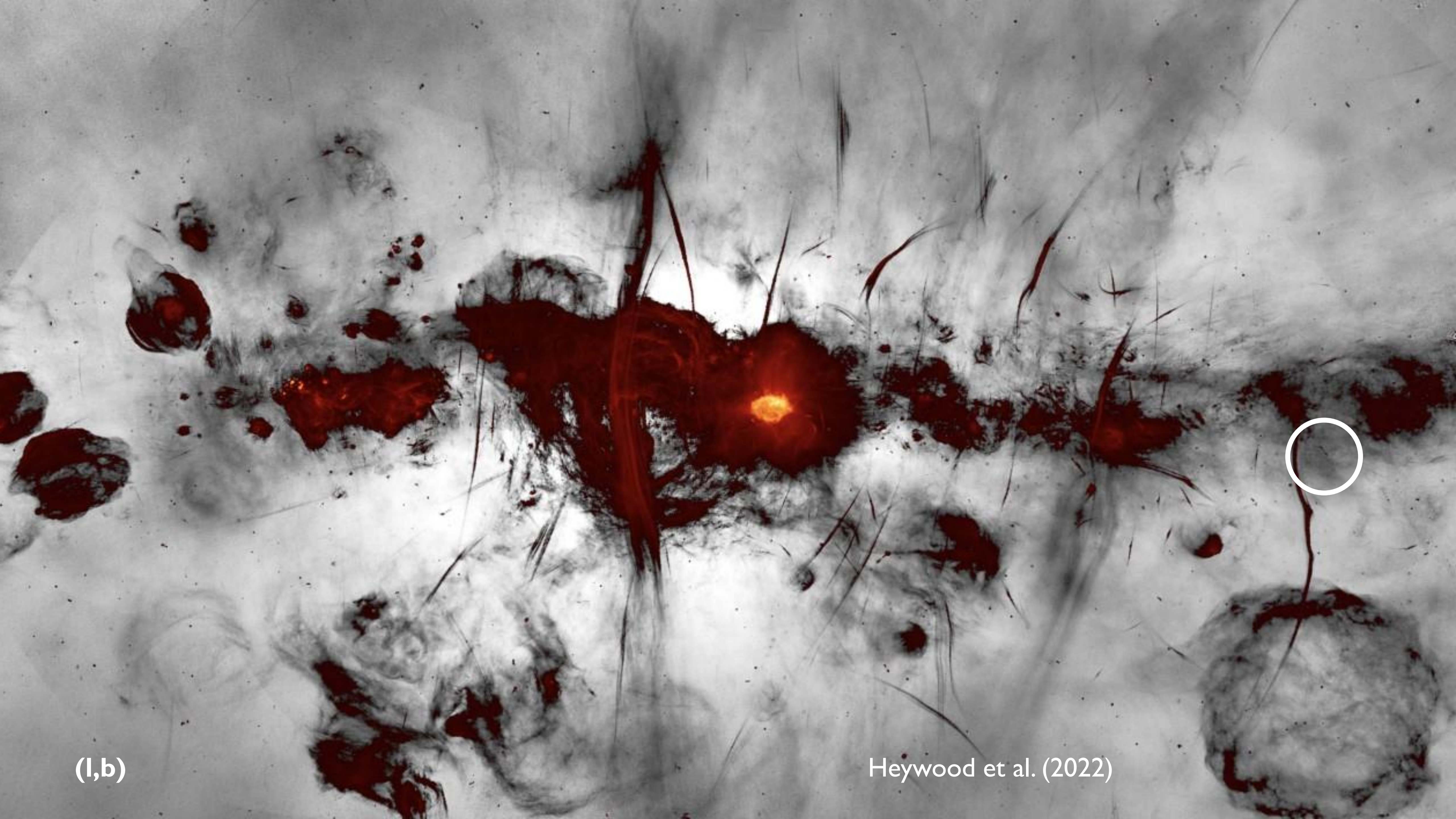
Since 2018
64 13.5-m dishes
(preceded by KAT-7 test array, succeeded by SKA1-MID)

National Research Foundation

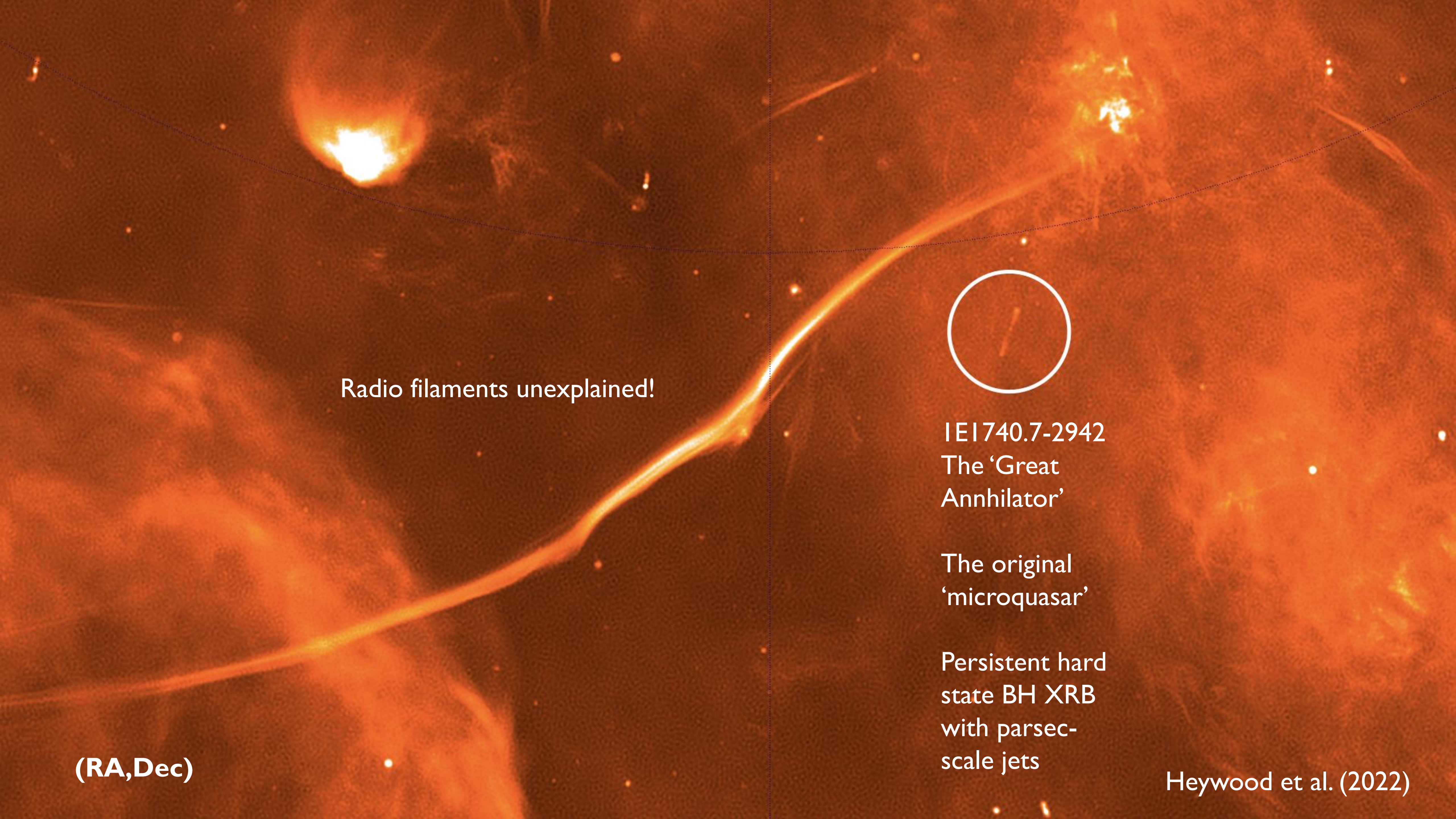
SARAO South African Radio Astronomy Observatory

SKA AFRICA SQUARE KILOMETRE ARRAY

Other telescopes are available

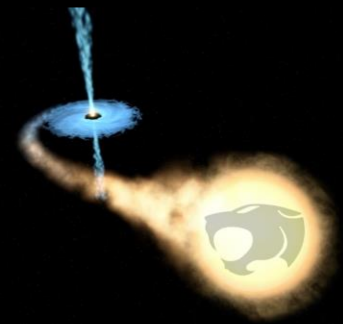

(l,b)
Heywood et al. (2022)


1E1740.7-2942
The 'Great Annhilator'
The original 'microquasar'
(RA,Dec)
Heywood et al. (2022)



Radio filaments unexplained!
1E1740.7-2942
The 'Great Annhilator'
The original 'microquasar'
Persistent hard state BH XRB with parsec-scale jets
(RA,Dec)
Heywood et al. (2022)

Weekly monitoring of all active XRB (15-minute blocks,1.4 GHz band)

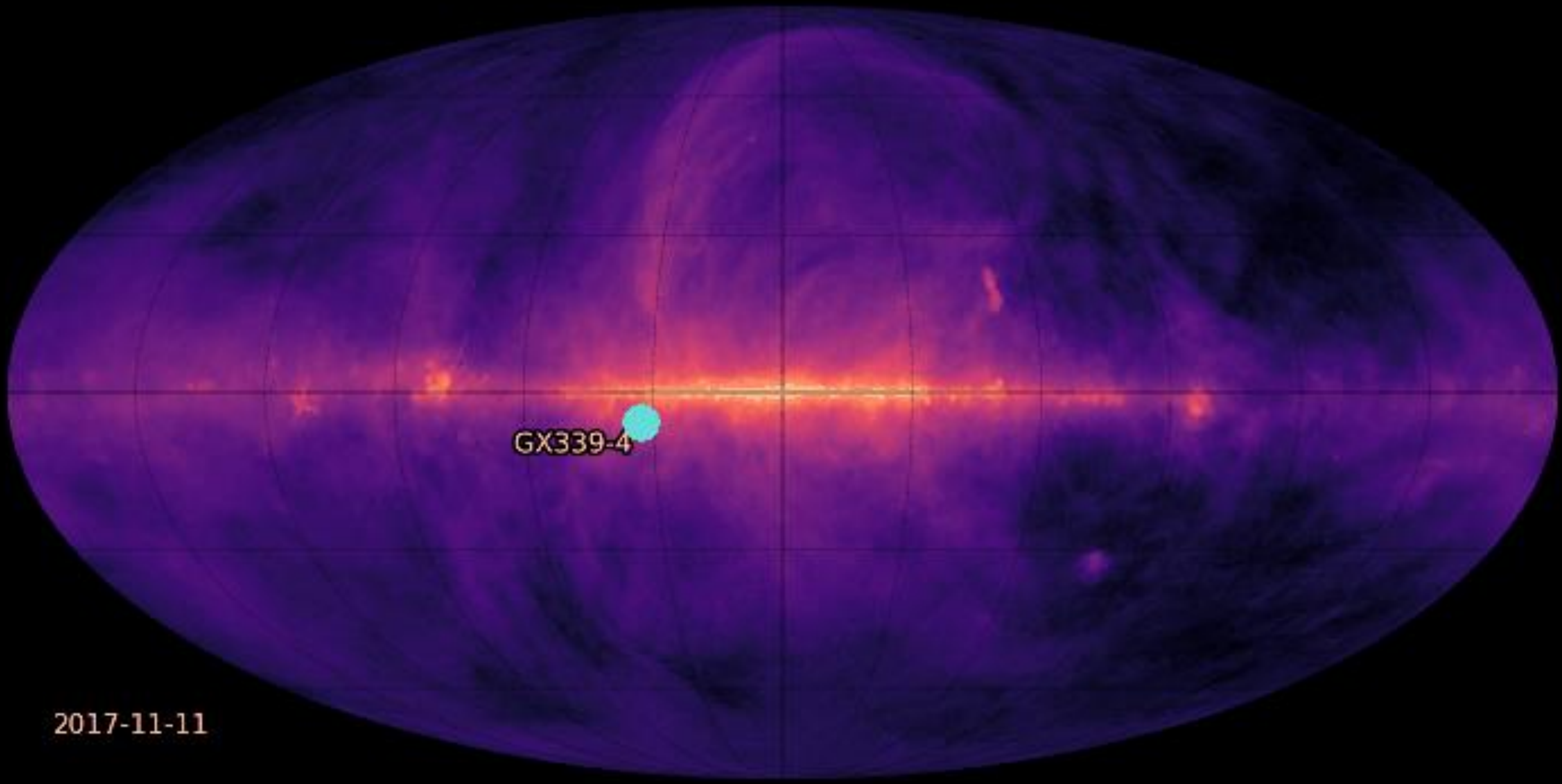


ThunderKAT

Fender & Woudt

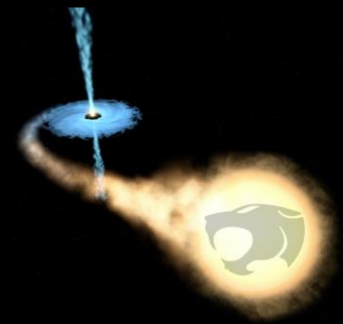
(see also VAST programme on ASKAP)

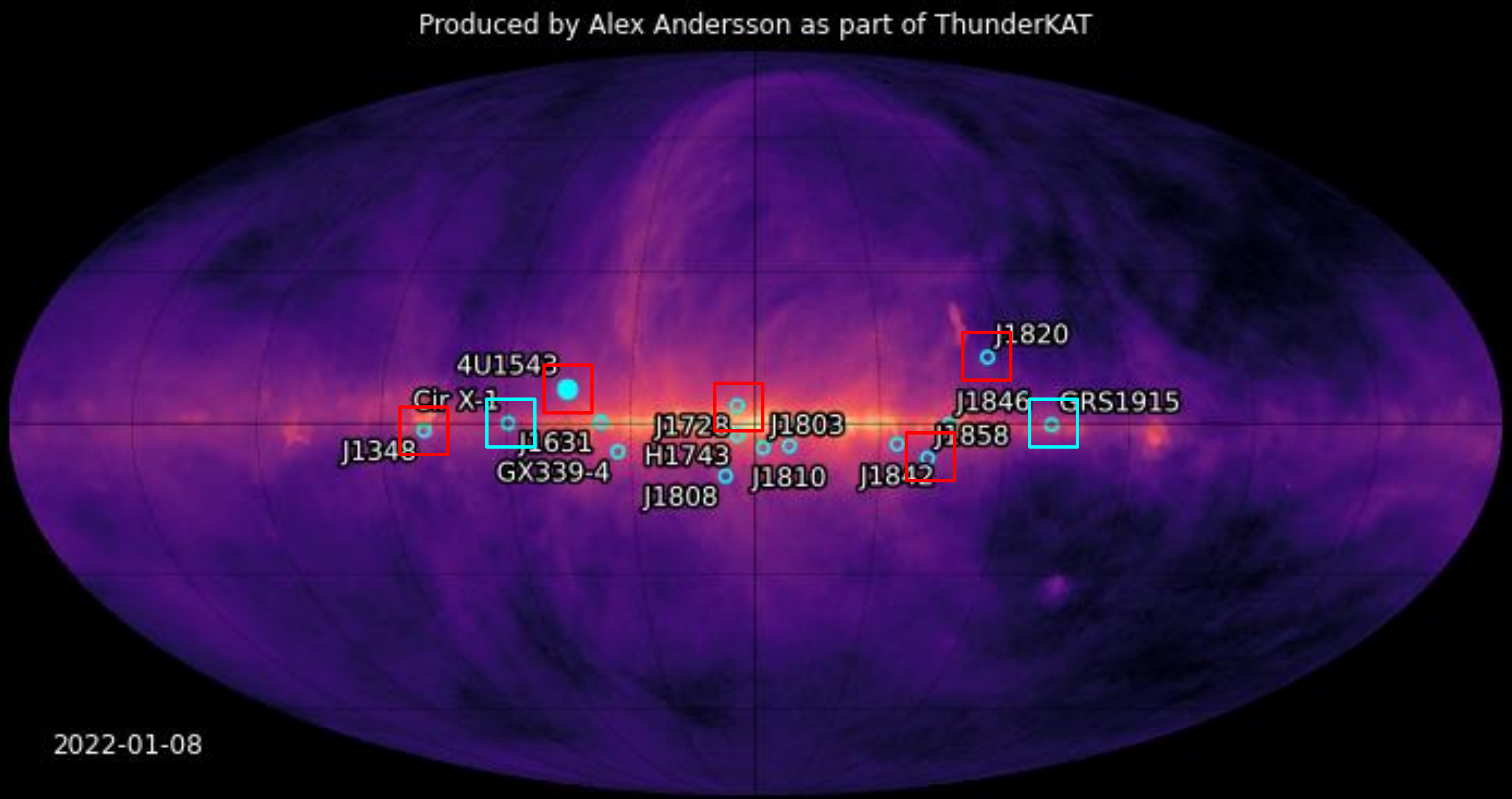
MeerKAT large survey project



Movie credit Alex Andersson

ThunderKAT has found **lots** of jets and jet-related structures, old and new





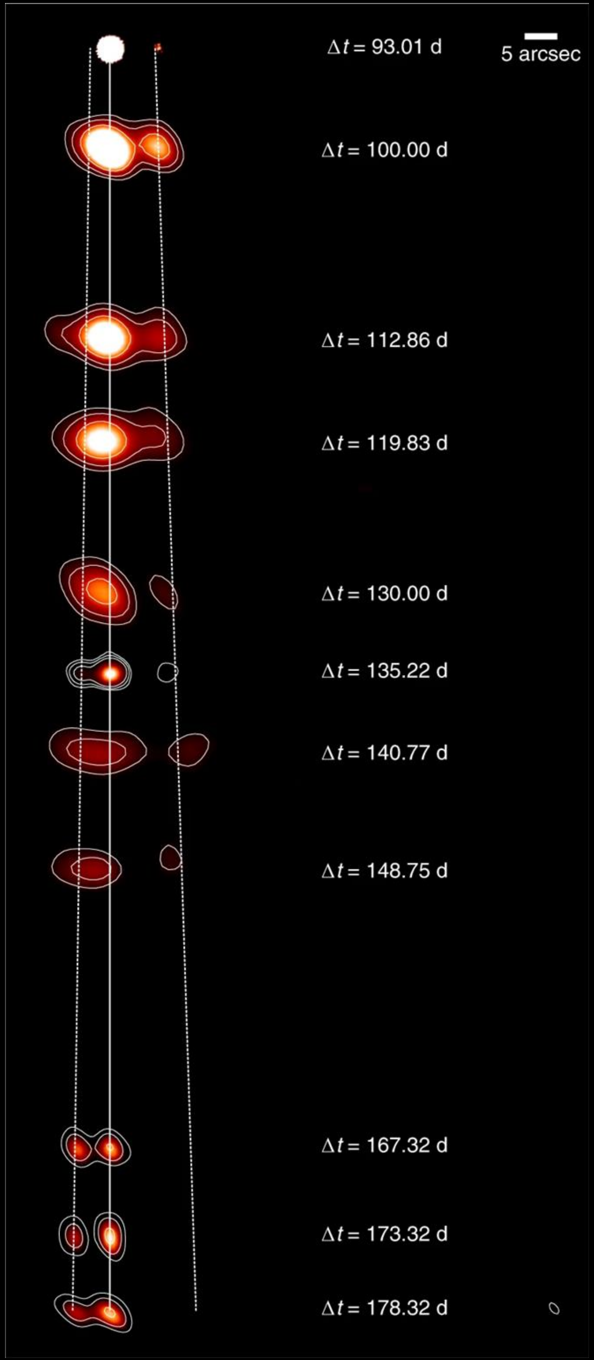
ThunderKAT

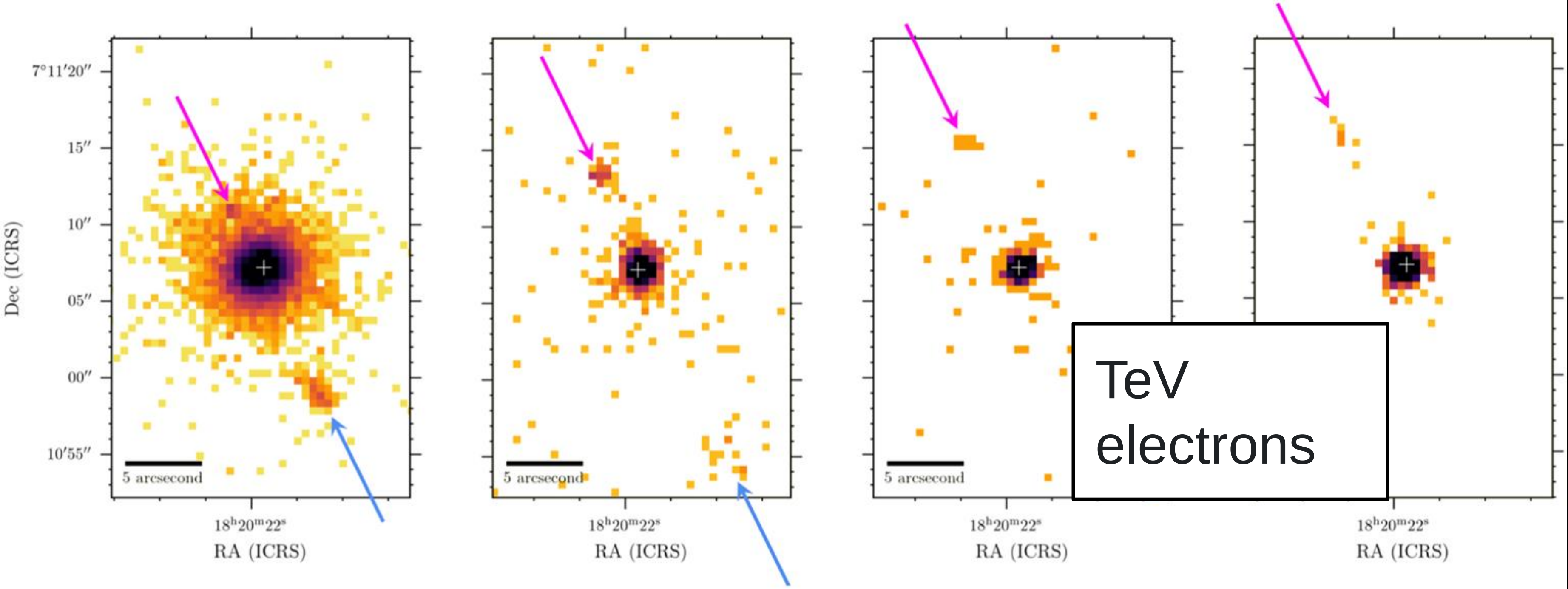
Fender & Woudt

MeerKAT large survey project

☐ = previously unknown large-scale jets (or jet-related structures)

☐ = previously known large-scale structures





MAXI J1820+070

Bright et al. (2020)

Espinasse et al. (2020)

Jets tracked for over half a year as they propagate to nearly a light year from BH

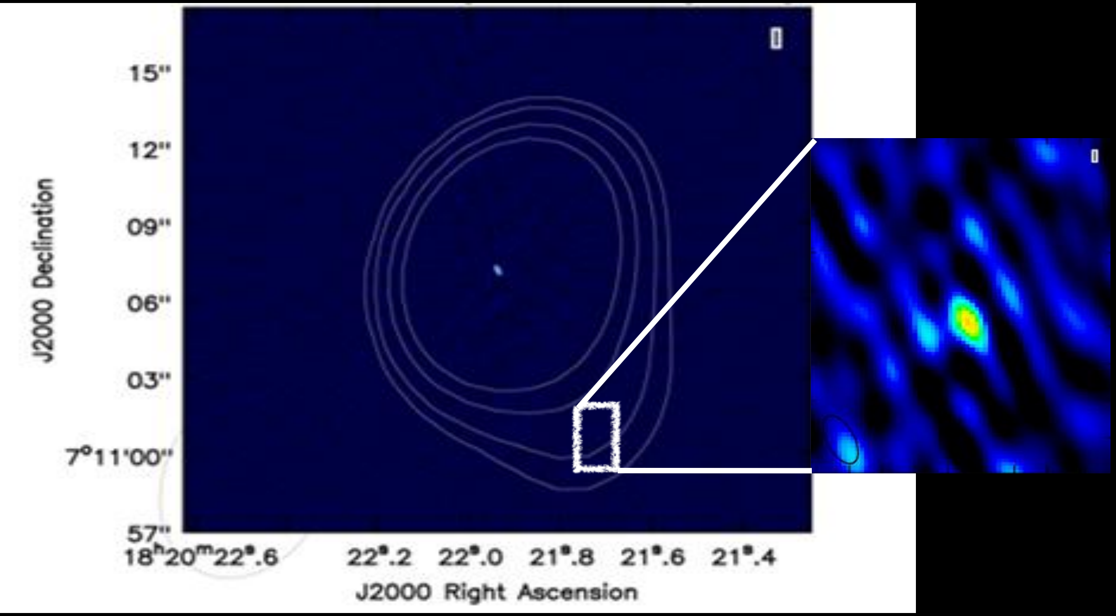
Highly accurate launch time connected to fluctuating accretion disc.

Very large estimates of ejection power

E(Δt=90d) $\gtrsim 10^{42}$ erg [!!]

Bright et al. (2020)

Size from direct imaging



Size + flux → minimum (equipartition) energy

This gave us

$E(\Delta t=90d) \gtrsim 10^{42}$ erg [!!]

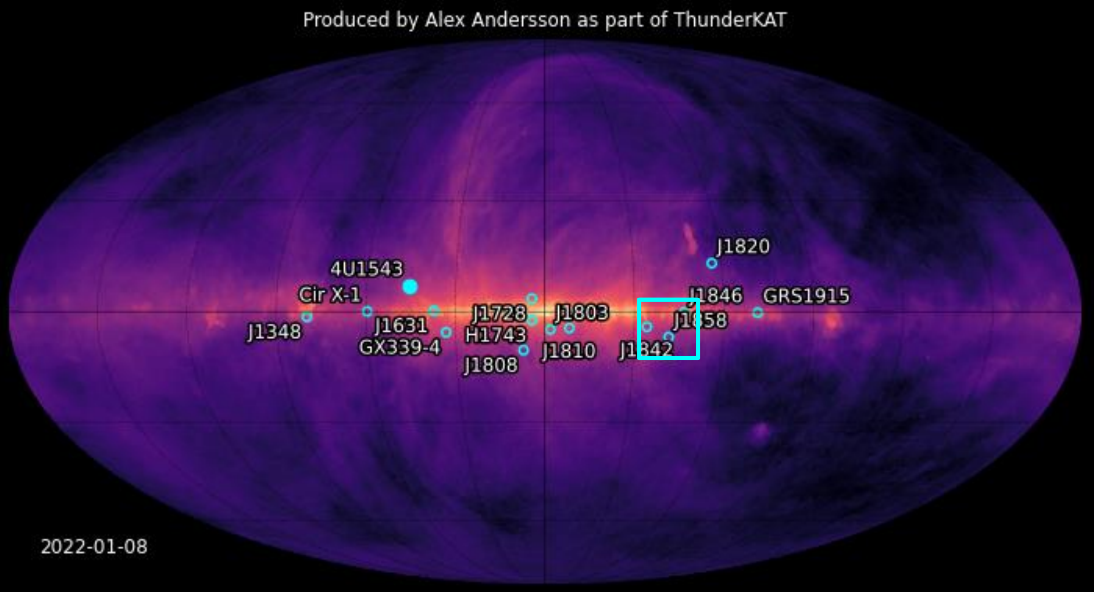
(**and** ejecta still moving superluminally at this stage so **total** jet power much larger)

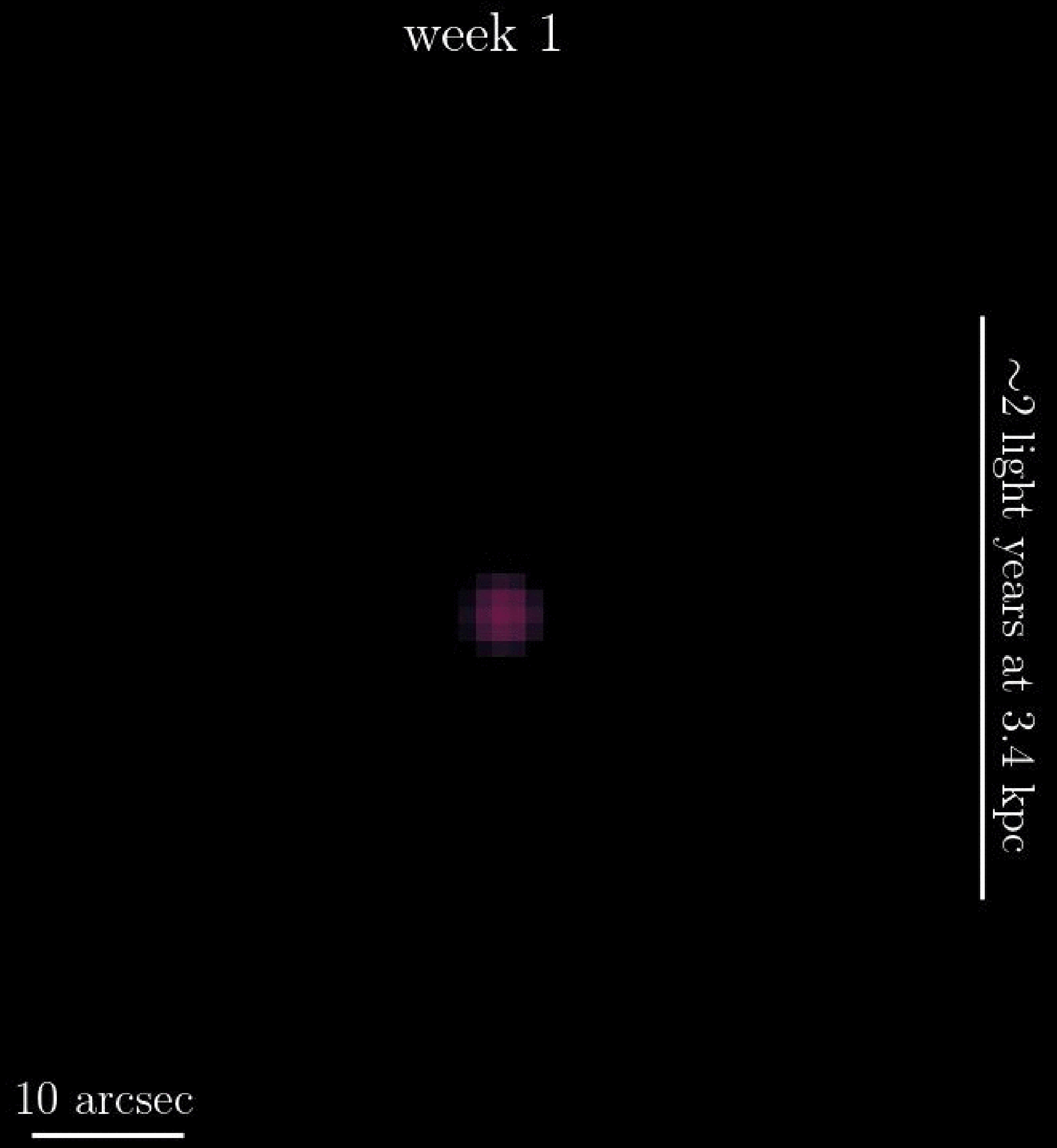
~2 arcsec (MeerKAT, unresolved

~0.1 arcsec (eMERLIN)

THE AMAZING LARGE-SCALE JETS OF MAXI J1848 (IN A GLOBULAR CLUSTER)

BAHRAMIAN ET AL. (2023)

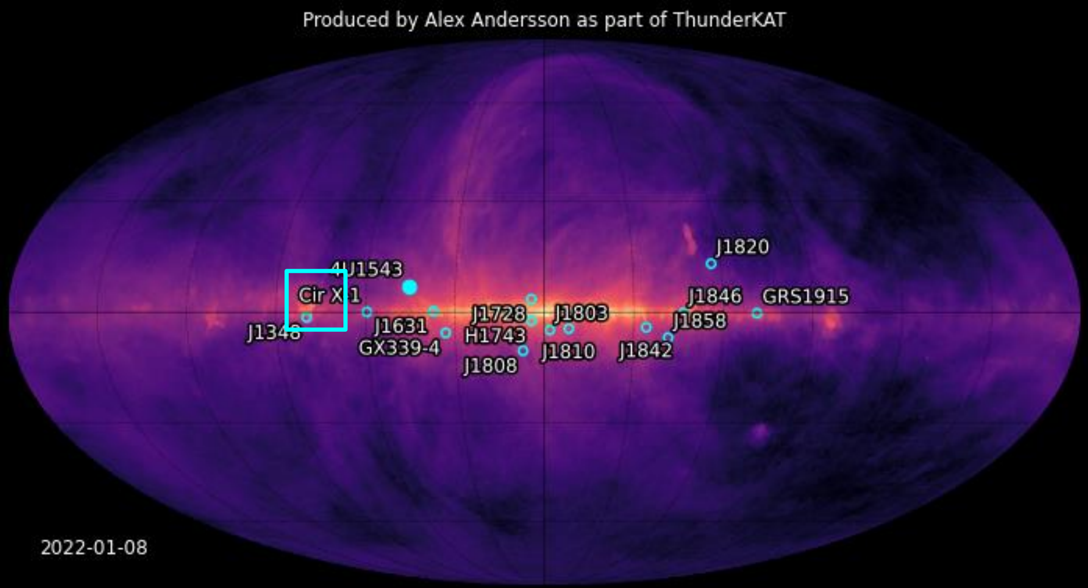


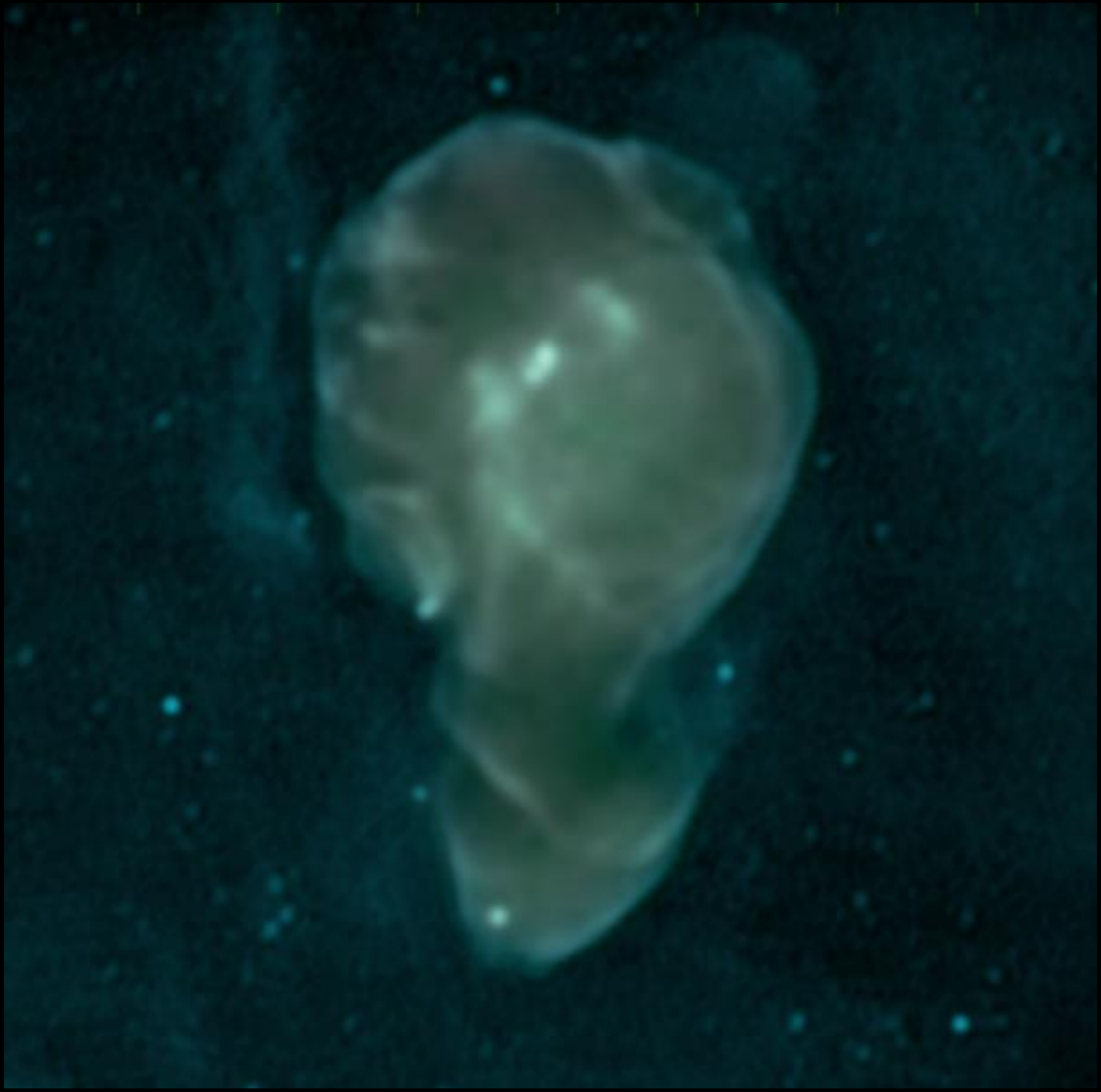


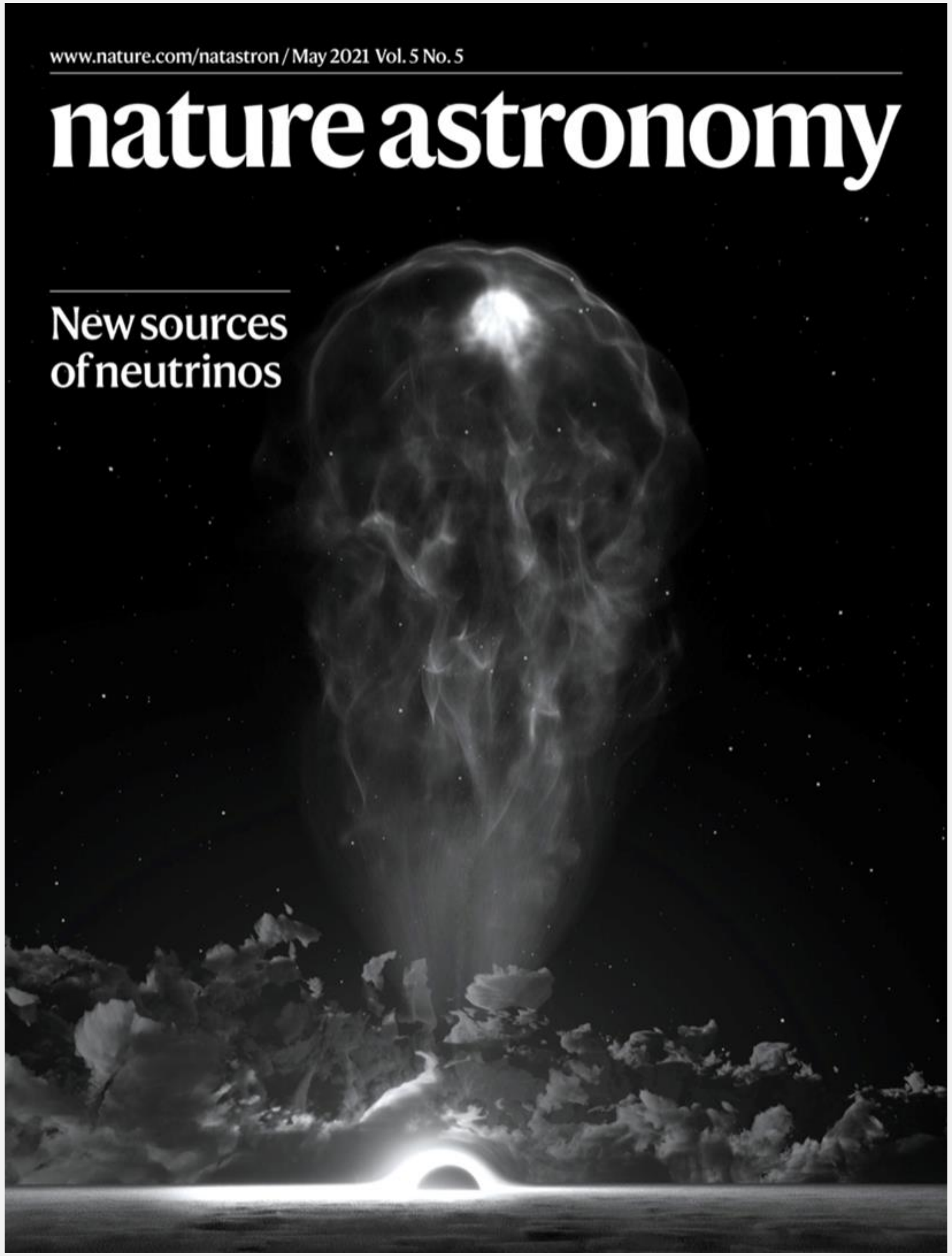
JET-POWERED
NEBULA AROUND
NEUTRON STAR
CIR X-1

A SOUTHERN SS433

GASEALAHWE ET AL.
(IN PREP)

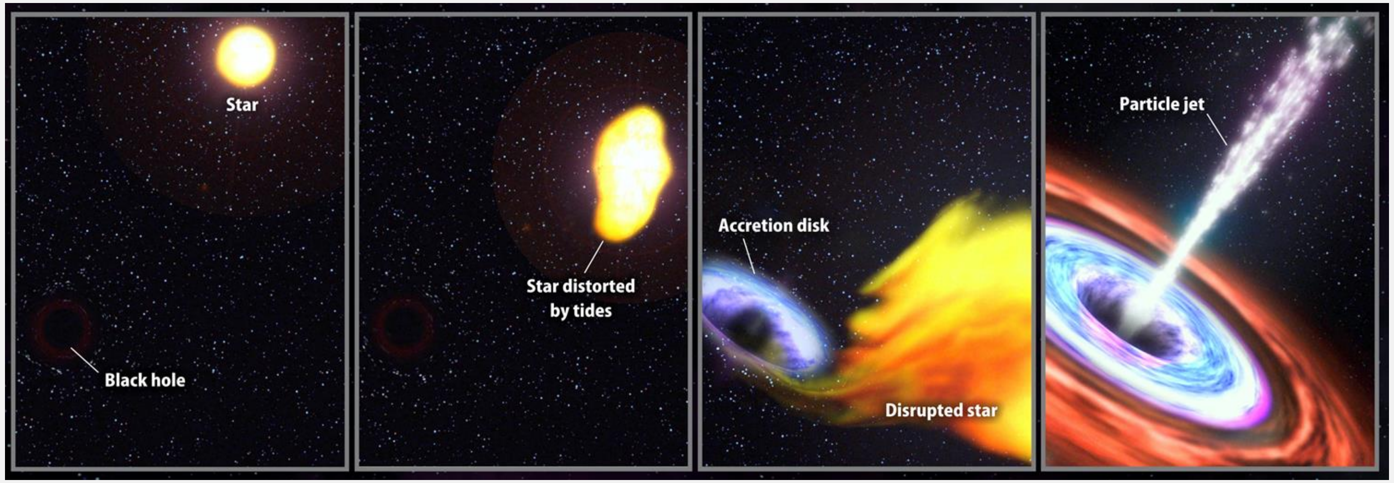






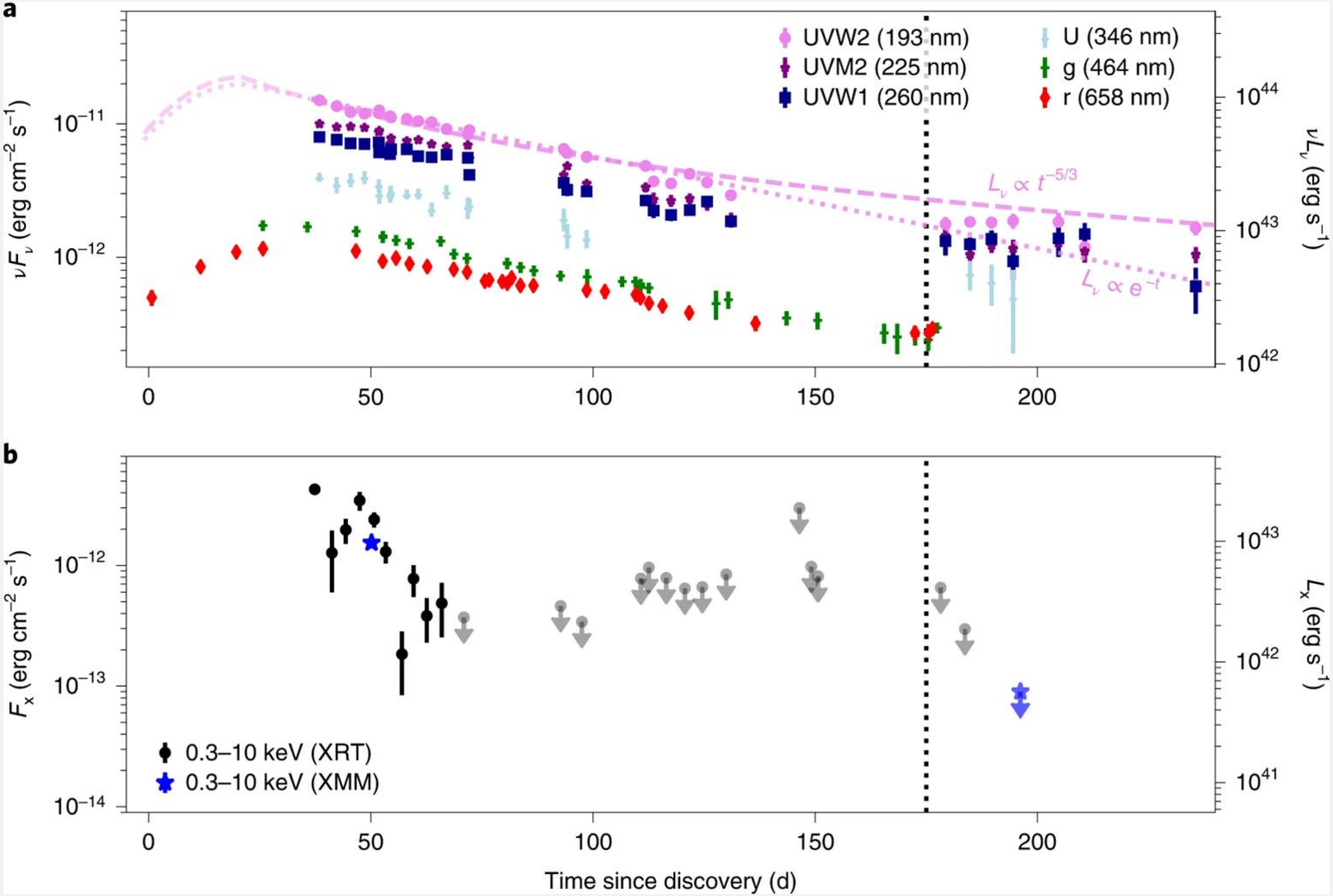
Radio emission from extragalactic transients

Possible detection of a 0.2 PeV **astrophysical neutrino** coincident with strong jet from late-time Tidal Disruption Event



Icecube detection of a probable astrophysical neutrino prompted a search with the **Zwicky Transient Facility** which discovered a new optical transient. Study of earlier images found a new TDE (candidate) which had begun nearly half a year earlier.

Stein et al. (2021)



TDE 2019sdg

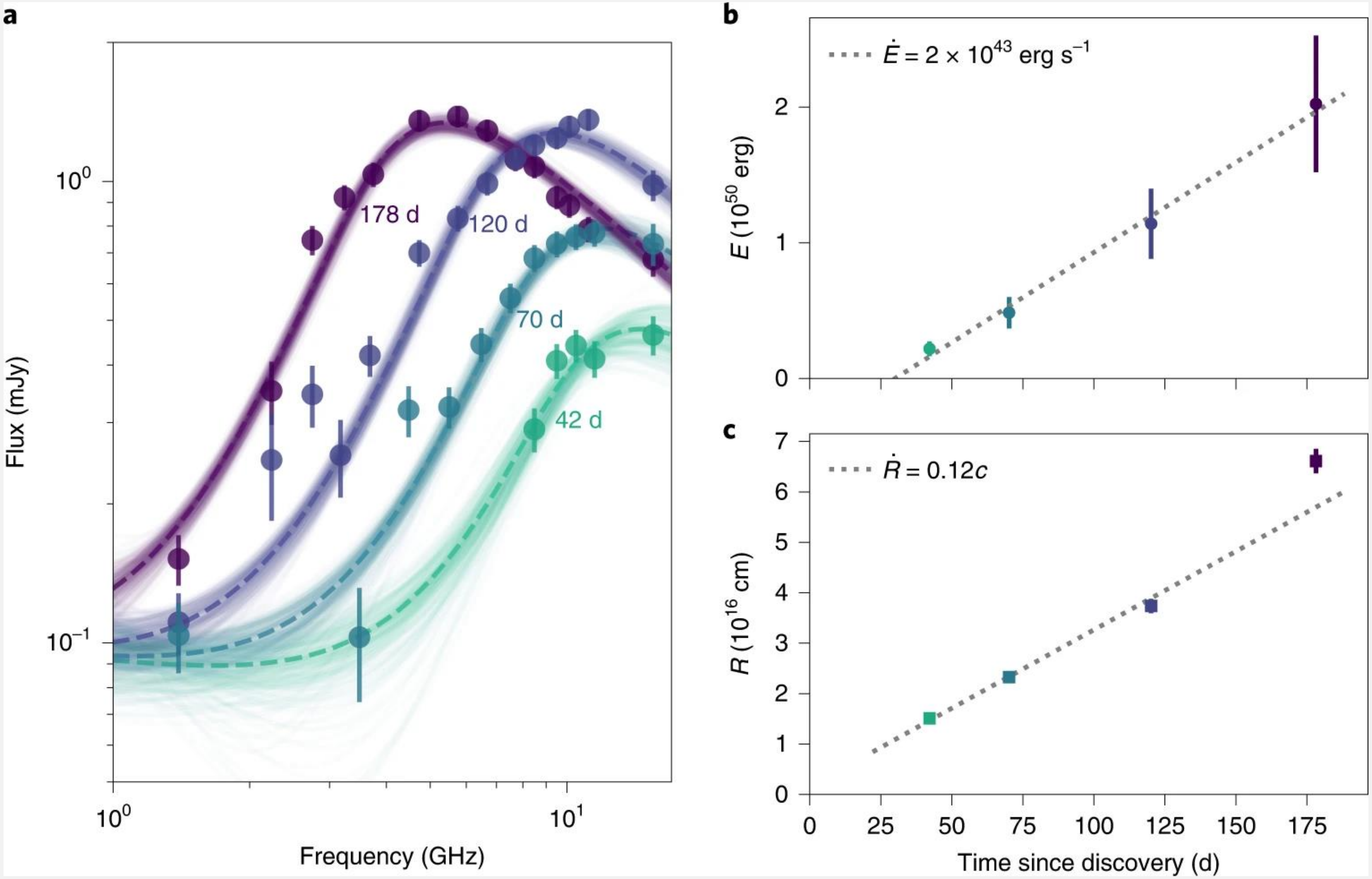
(**T**idal **D**isruption **E**vent)

⋮

Ice Cube neutrino IC191001A

Estimated 59% probability to be astrophysical

Chance of coincident TDE estimated to be 0.2%. Occurred ~half year after event initiation.

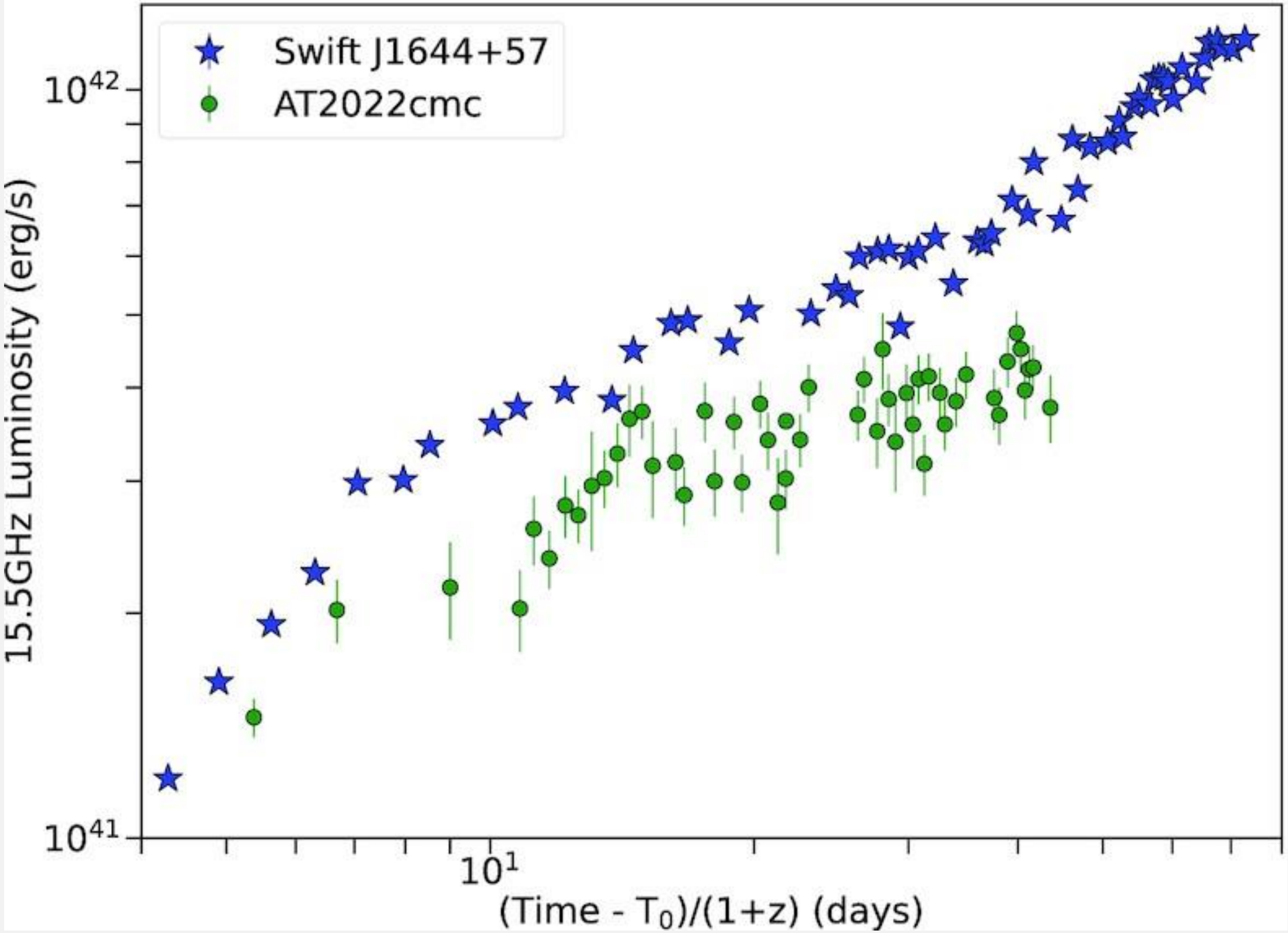


Size from synchrotron self-absorption

Strong and variable radio emission (relativistic outflow / jet)

Radio emission indicates unusual, optically thick (i.e. opaque) ejecta, expanding at ~0.1c and being continuously powered at a high rate (ongoing accretion likely)

Particle acceleration continuing until at least date of neutrino detection



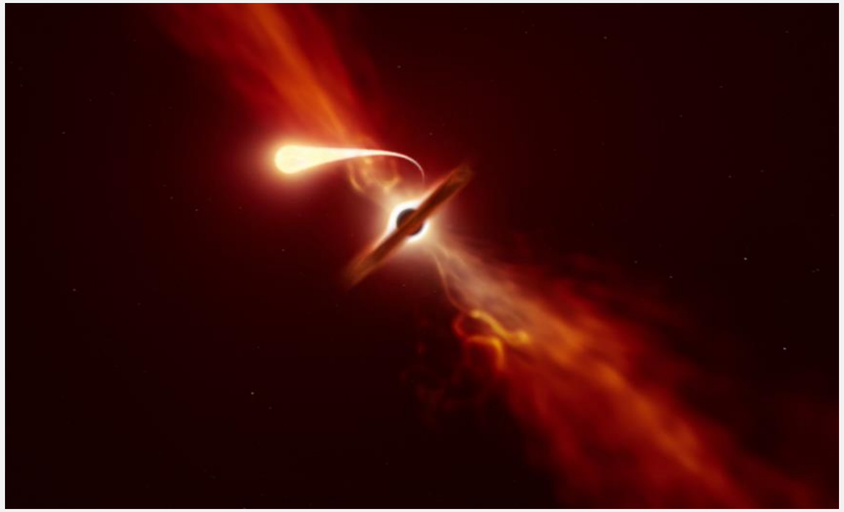
Jetted TDE AT2022CMC

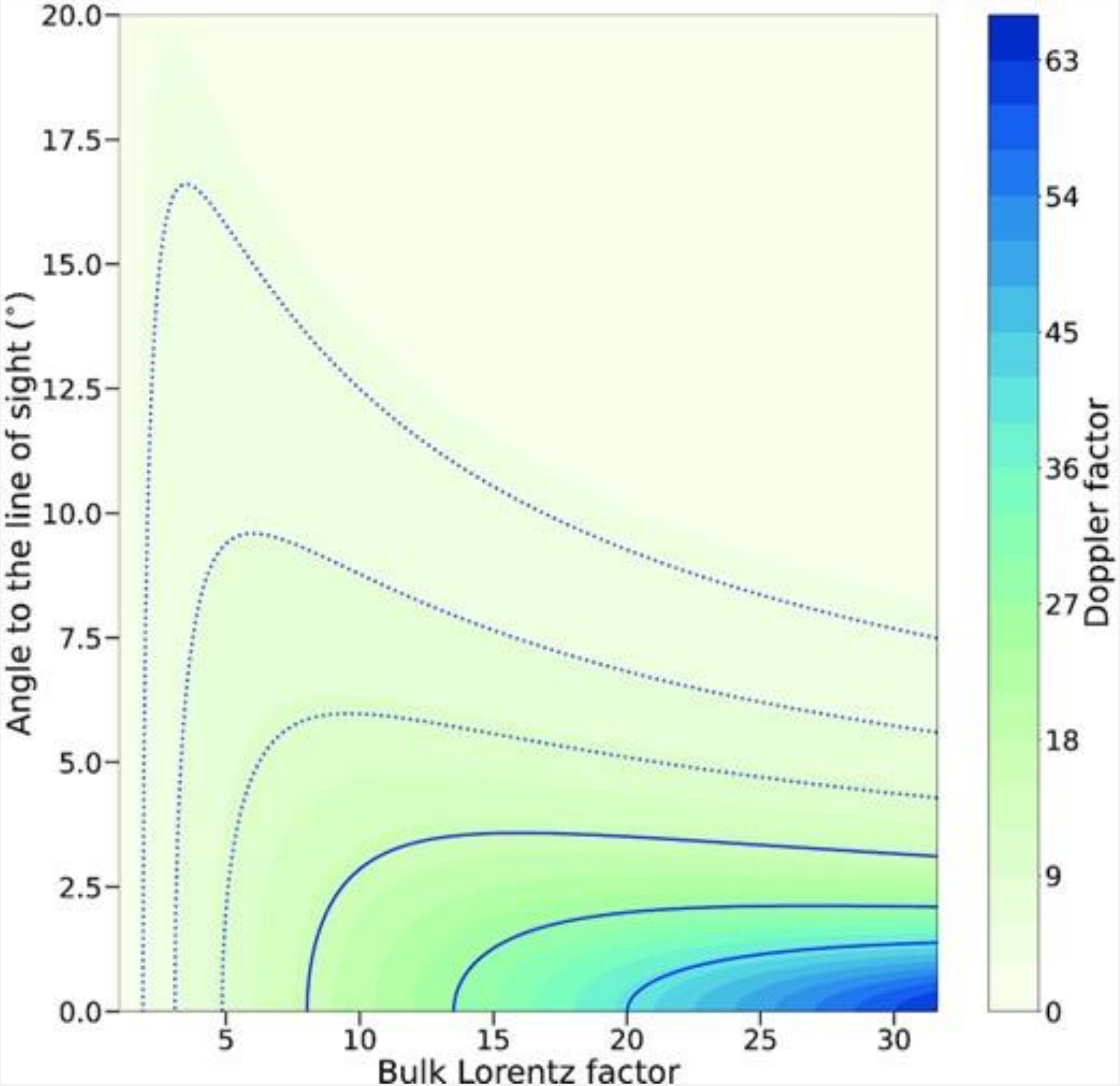
High cadence long observational monitoring of jetted TDE AT2022cmc

Variability implies strong Doppler boosting

(because $T_{B,\ apparent}$ = 2 x 10^{15} K)

Rhodes et al. (2023)



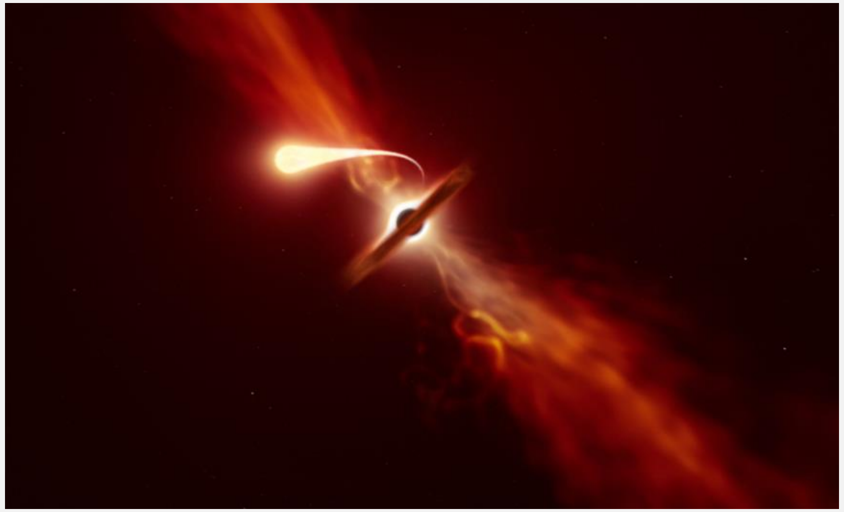


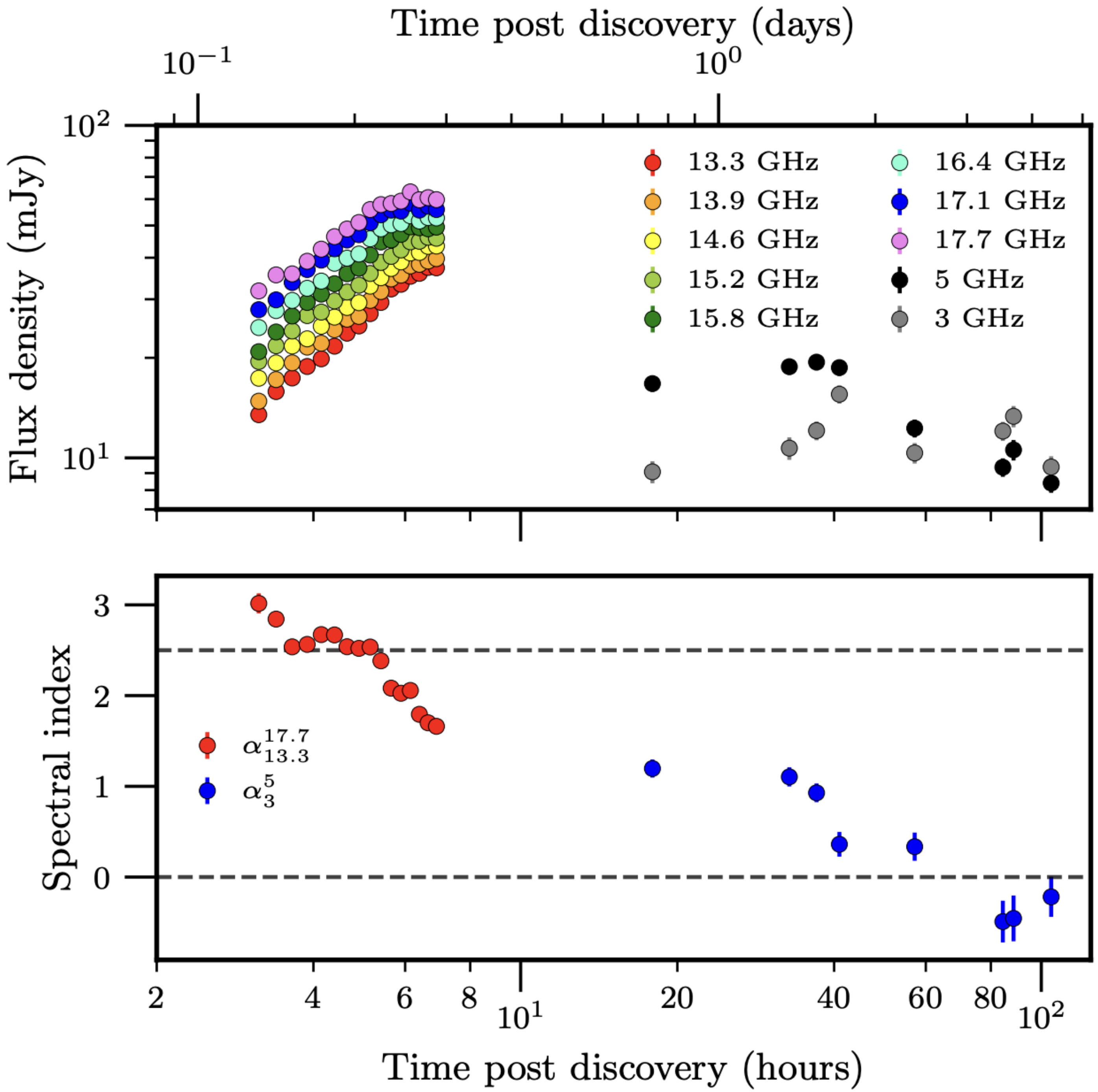
High cadence long observational monitoring of jetted TDE AT2022cmc

Variability implies strong Doppler boosting, likely minimum Lorentz factor 20

(to reduce $T_{B,\,intrinsic}$ → 10^{12} K)

Rhodes et al. (2023)

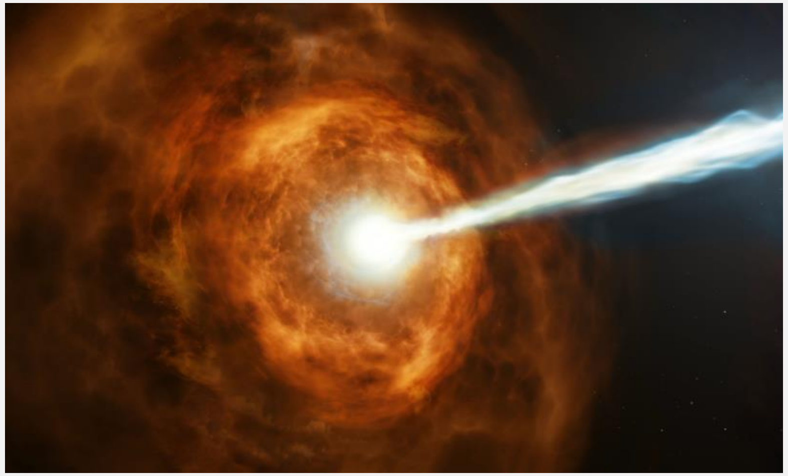


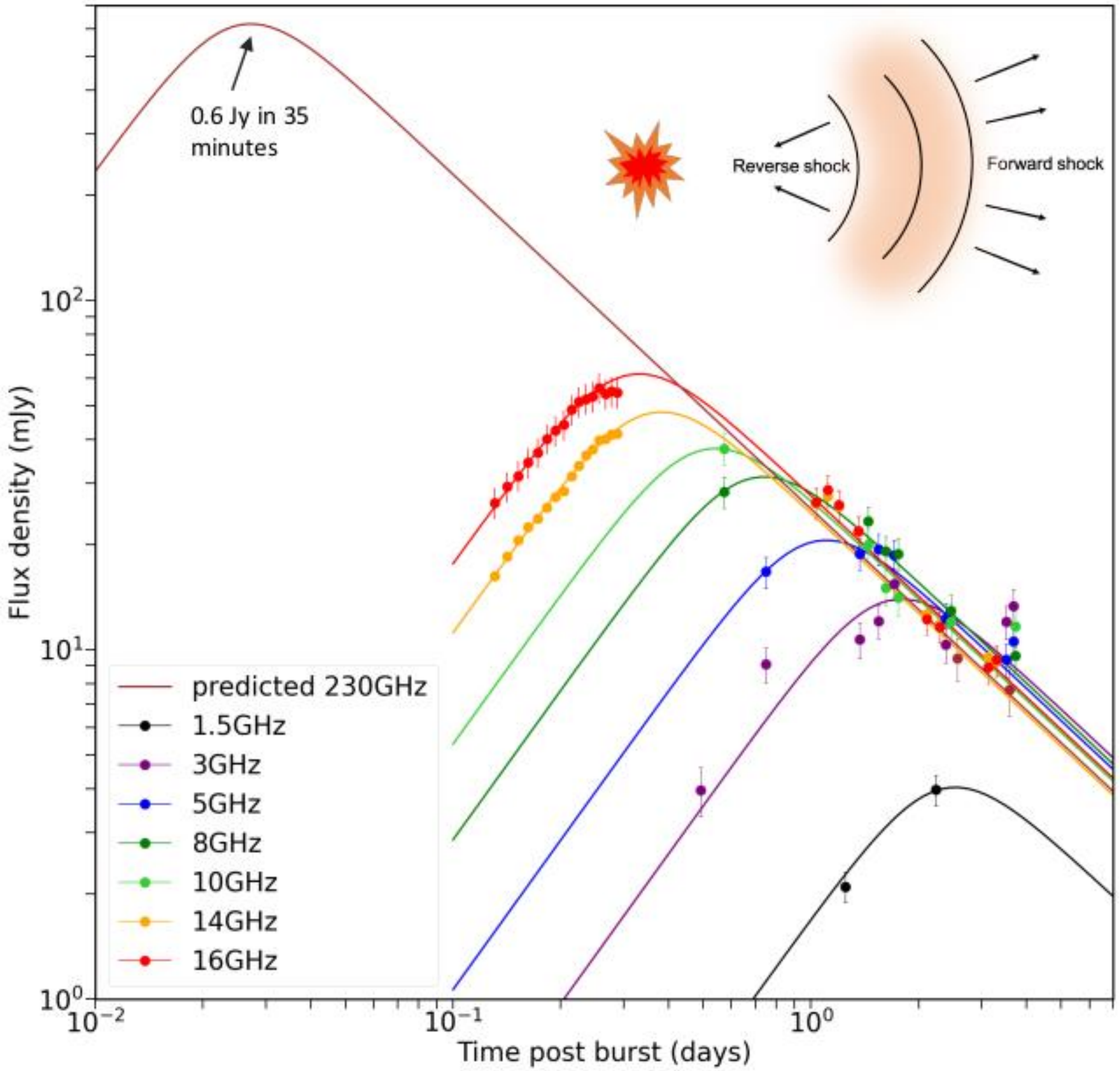


GRB 221009A reverse shock

Rapid response with a small array (AMI-LA, UK) produced the most comprehensive ever study of a reverse shock from a GRB (the 'BOAT')

Bright et al. (2023)

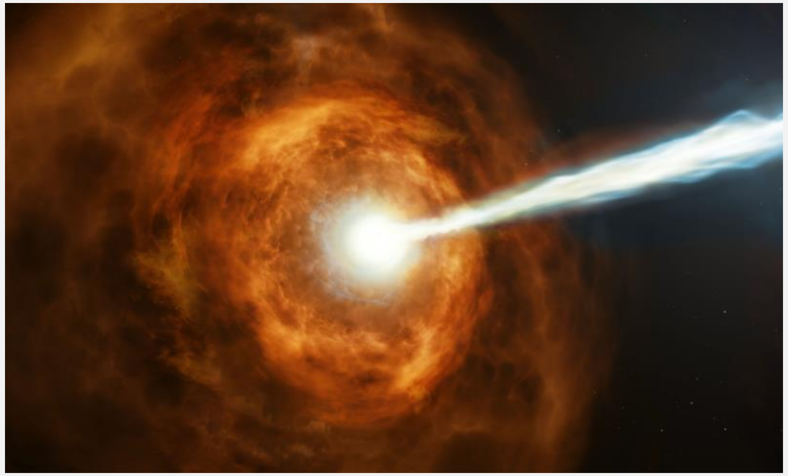


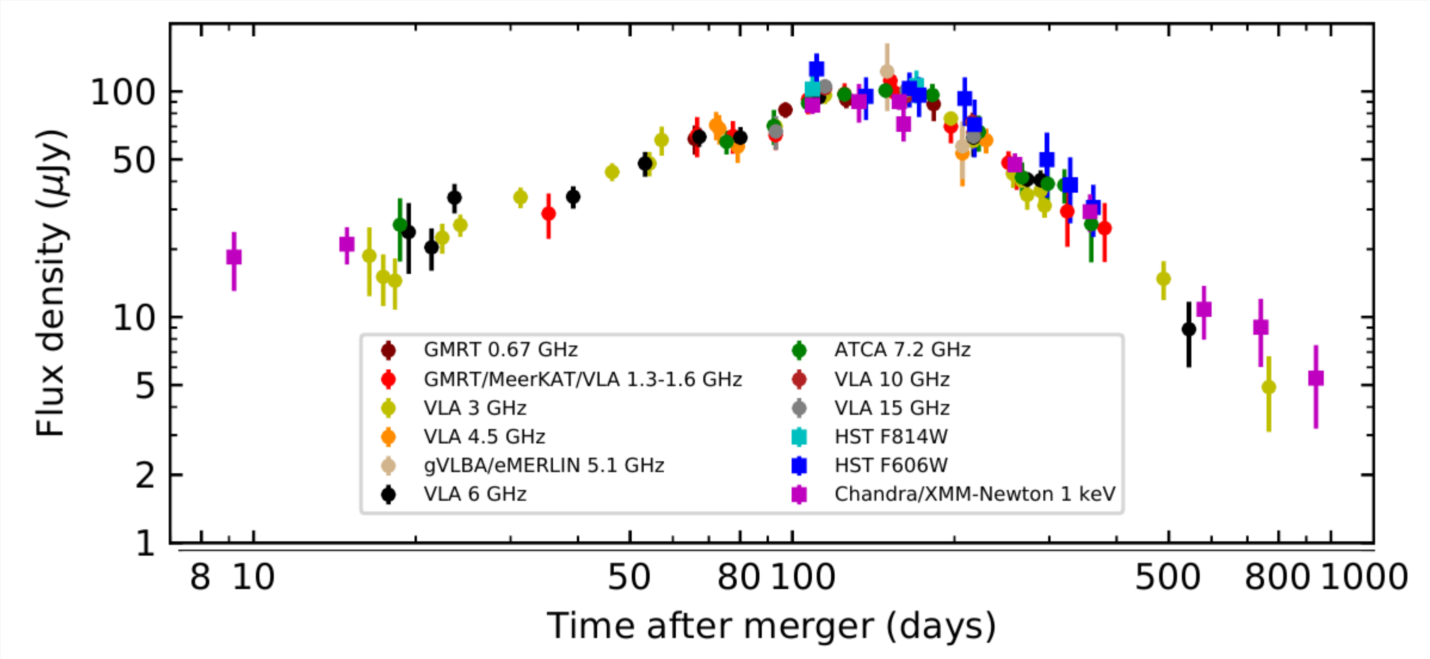


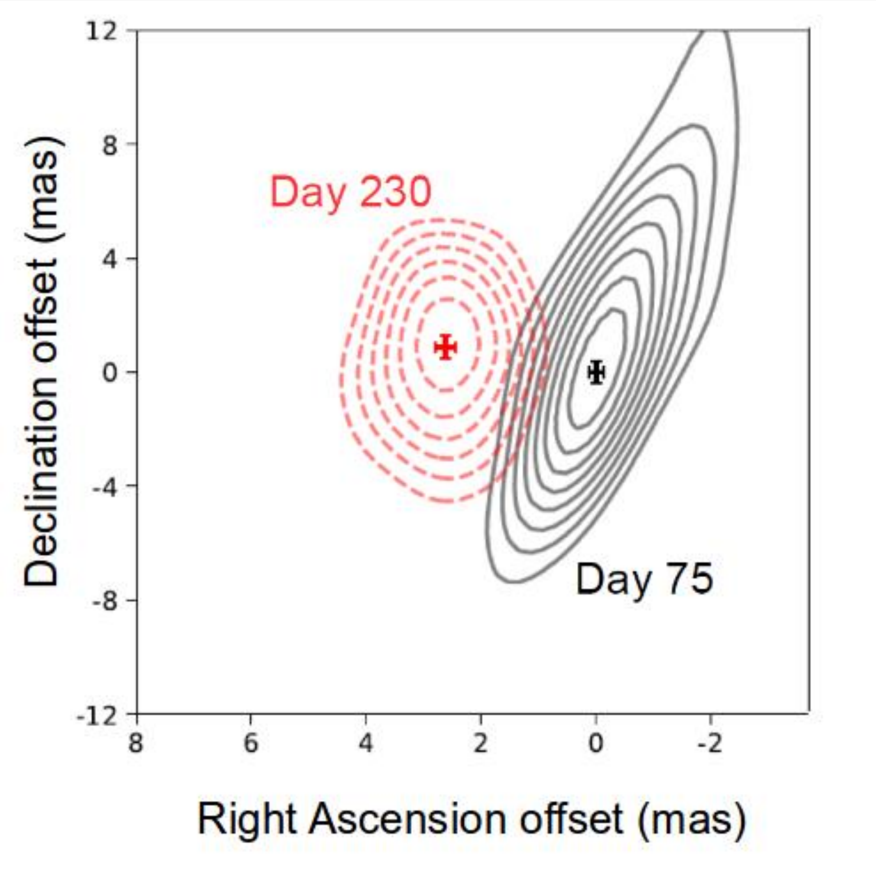
This event would have been 0.6 Jy (that's a lot!) at 35 minutes at 230 GHz (mm band)

Single mm dishes can contribute to transients science if respond rapidly

Bright et al. (2023); figure by Lauren Rhodes





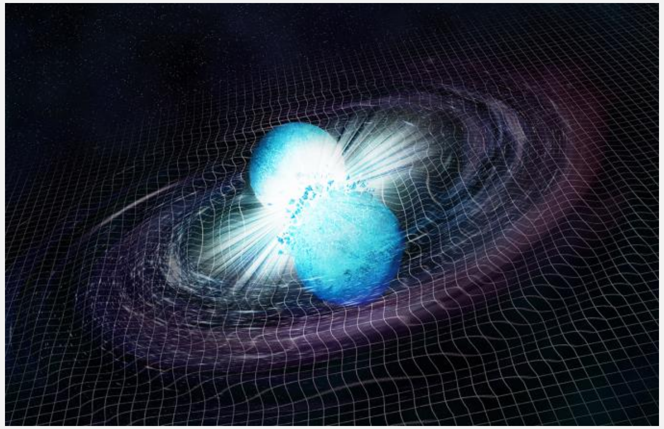


Neutron star merger / gravitational wave / short GRB GW170817

Very long lasting radio afterglow

Most likely interpretation from lightcurve was a jet

Unambiguously established by VLBI observations of superluminal motion



Makhathini et al. 2021, Mooley et al. 2018

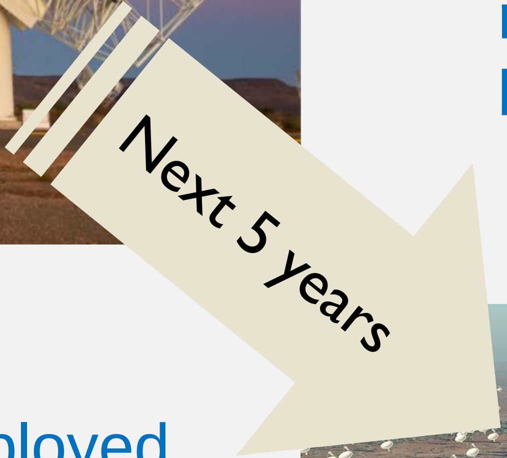
RADIO ASTRONOMY

RADIO TRANSIENT ASTROPHYSICS

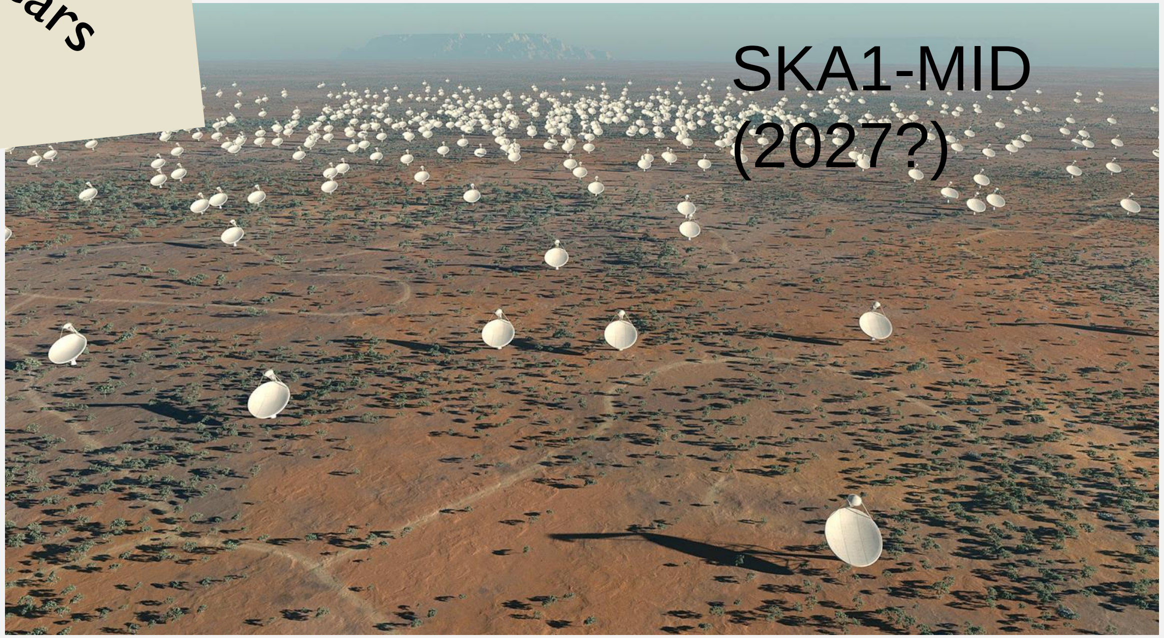
FUTURE FACILITIES AND PROSPECTS

On a timescale of ~5 years **MeerKAT** will become **SKA1-MID**

Increased sensitivity, frequency range and greatly improved baselines



In the meantime, MeerKAT has deployed ‘S-band’ receivers (current are ‘L-band’) → double the frequency, double the angular resolution



In addition MeerKAT → MeerKAT+: longer baselines, again improving angular

MONITORING BRIGHT TRANSIENTS IN THE SKA ERA

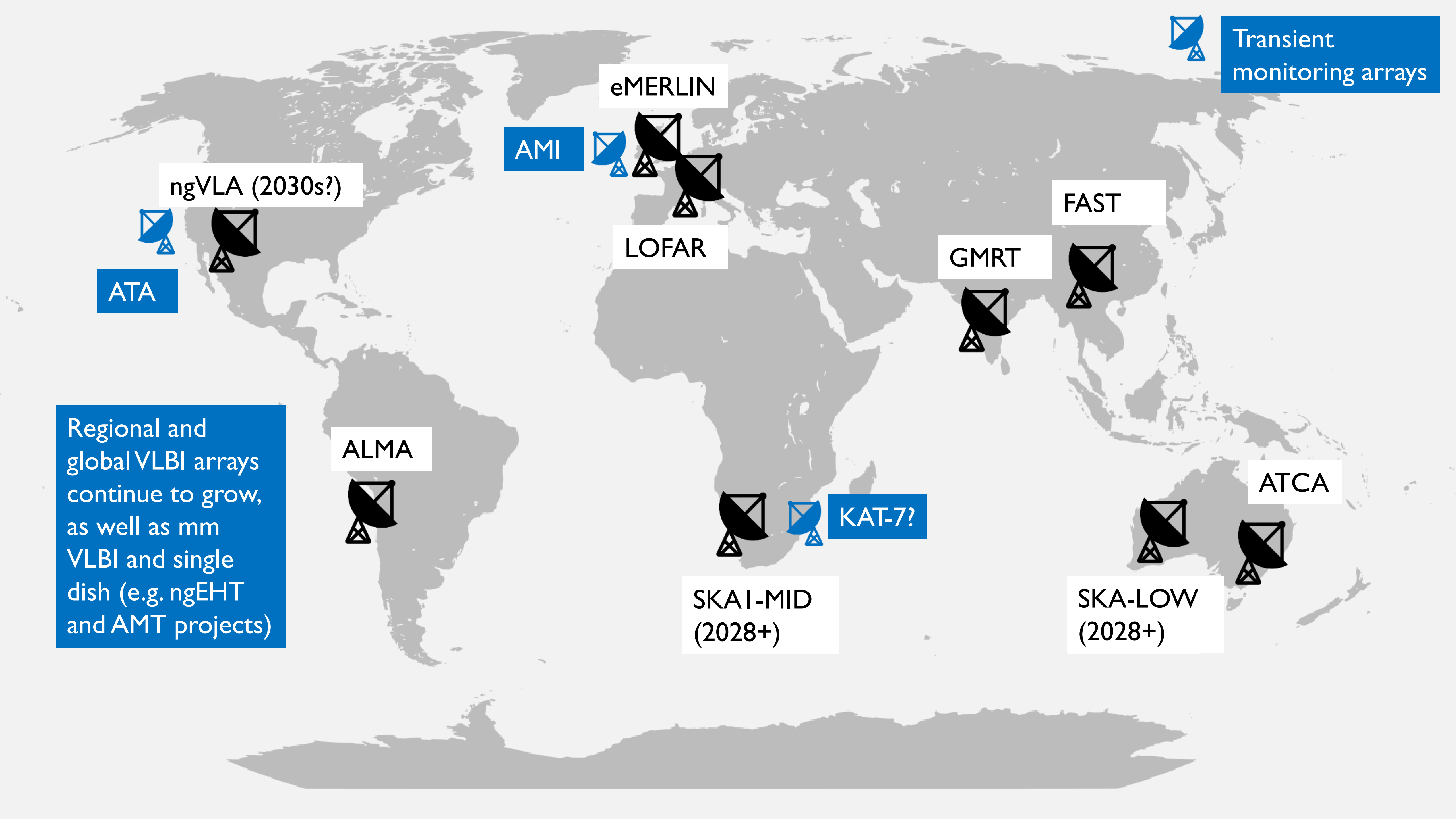
The SKA (+extended VLA or equivalent) will be **the** main facility for radio science in the 2030s

You do not need sub-μJy sensitivity to monitor many of these transients (of course there will be transients at all flux levels)

Optical astronomy faced this issue and responded by building large numbers of smaller telescopes to support the very large front-line (8m+) faciliites

What about for radio transients?

- SKA can do the deep observations **and** the monitoring, but this may require continuous use of a subset of antennas
- A possible alternative is a dedicated array for rapid follow-up and monitoring of radio transients, building around the lessons from AMI


Transient monitoring arrays
eMERLIN
AMI
ngVLA (2030s?)
ATA
LOFAR
FAST
GMRT
ALMA
KAT-7?
ATCA
SKA1-MID (2028+)
SKA-LOW (2028+)
Regional and global VLBI arrays continue to grow, as well as mm VLBI and single dish (e.g. ngEHT and AMT projects)

The **Africa Millimetre Telescope**

A transformational upgrade to the Event Horizon Telescope **and** a mm transients monitor

baseline

Longer baselines: higher resolution
More baslines: more complete image

Radboud University
University of Amsterdam
University of Oxford

THE END