

# RADIO SURVEYS: A CURRENT OVERVIEW

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# OUTLINE

- Why radio?
- Things to bear in mind before you start
- Host finding
- Galactic plane
- Variability
- How to make best use of radio surveys



# WHY RADIO?

- No need to worry about:
  - Daylight, clouds (with some caveats)
  - ICM/IGM absorption
- Different bands can map different physical and time scales
  - Source evolution
  - Different physical mechanisms
  - Polarisation for extra magnetic funtimes!
- SKA will revolutionise astronomy



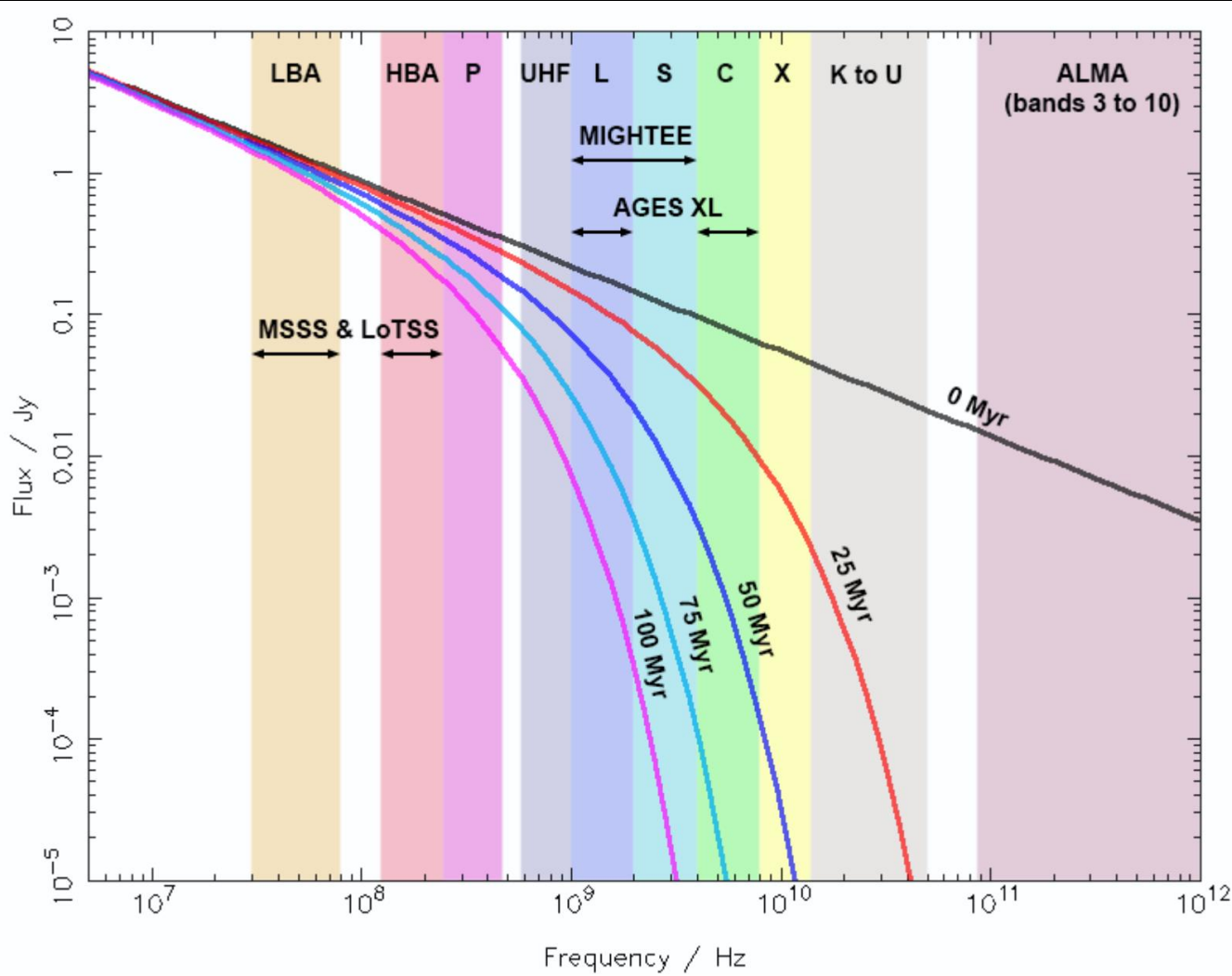
# WHY RADIO?

- Often, radio traces the same physical processes as Gamma-rays and X-rays
- Some of these processes are (mostly) invisible at other wavelengths



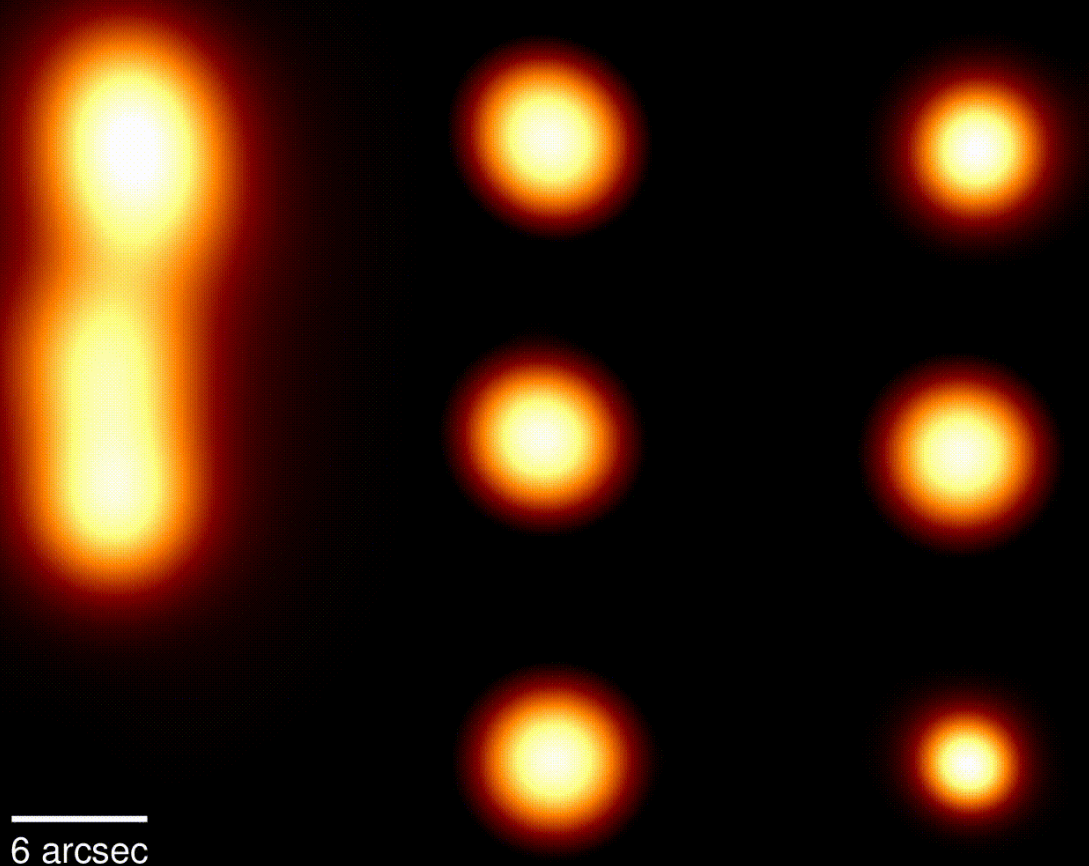
$$P_\gamma = \frac{1}{6\pi\epsilon_0} \frac{q^2 a^2}{c^3} \gamma^4$$

# BEFORE YOU START



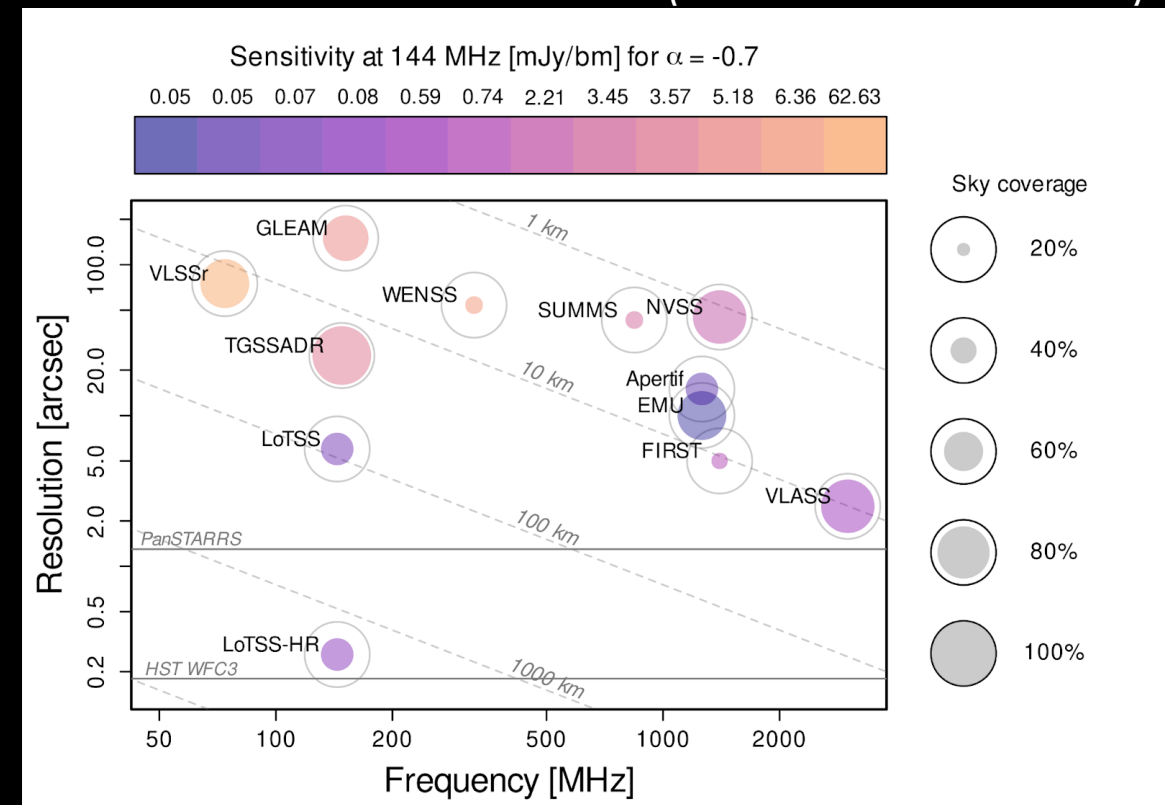
- Do you know the spectral shape of your source?
  - Re-acceleration
  - Self-absorption
  - SSC
  - Cooling break

LOFAR high-resolution (~90  $\mu$ Jy/bm, 0.3" resolution)  
 (A&A spec. ed. Jan 2022; Sweijen+ 2022)

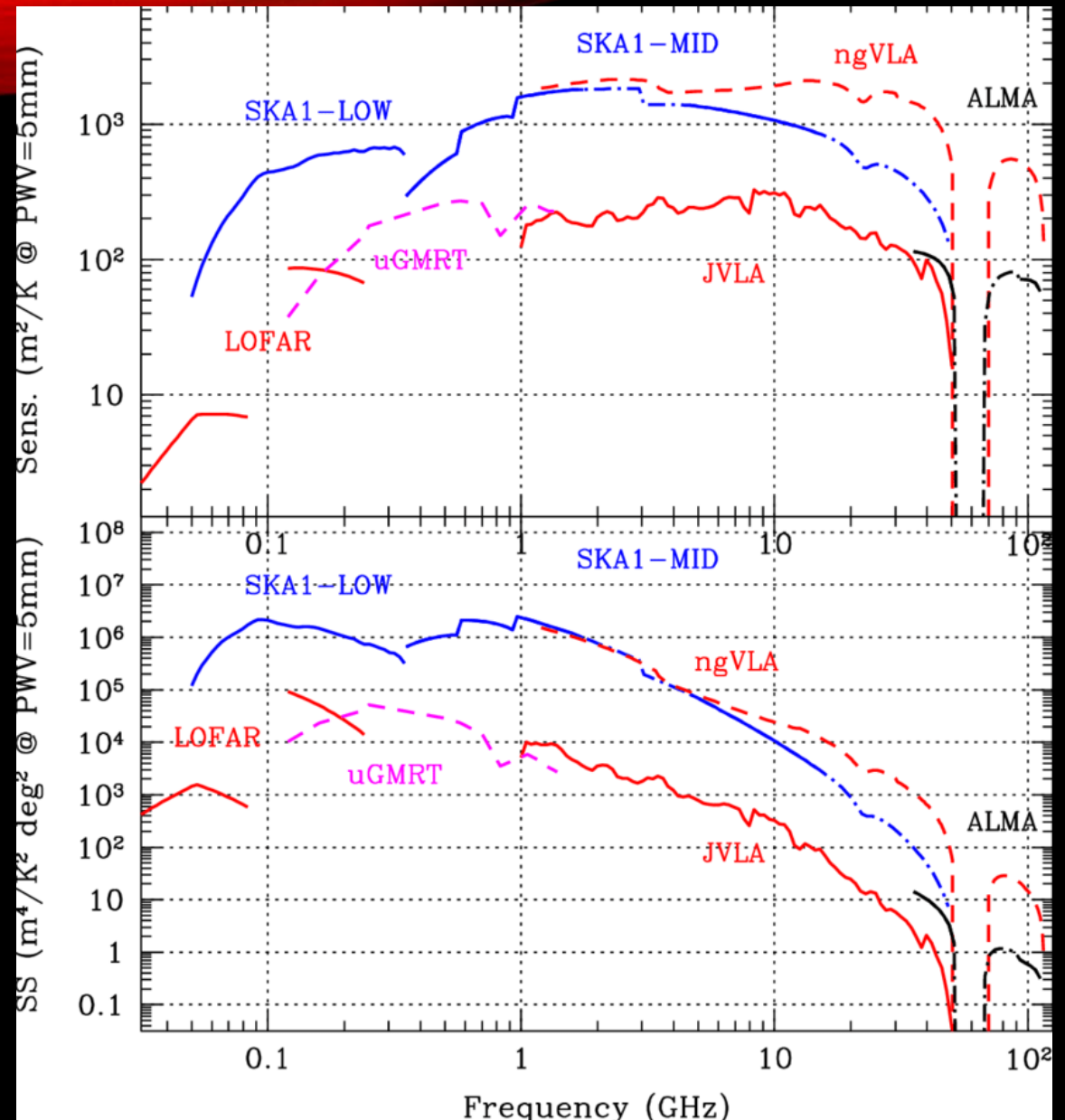


# RESOLUTION

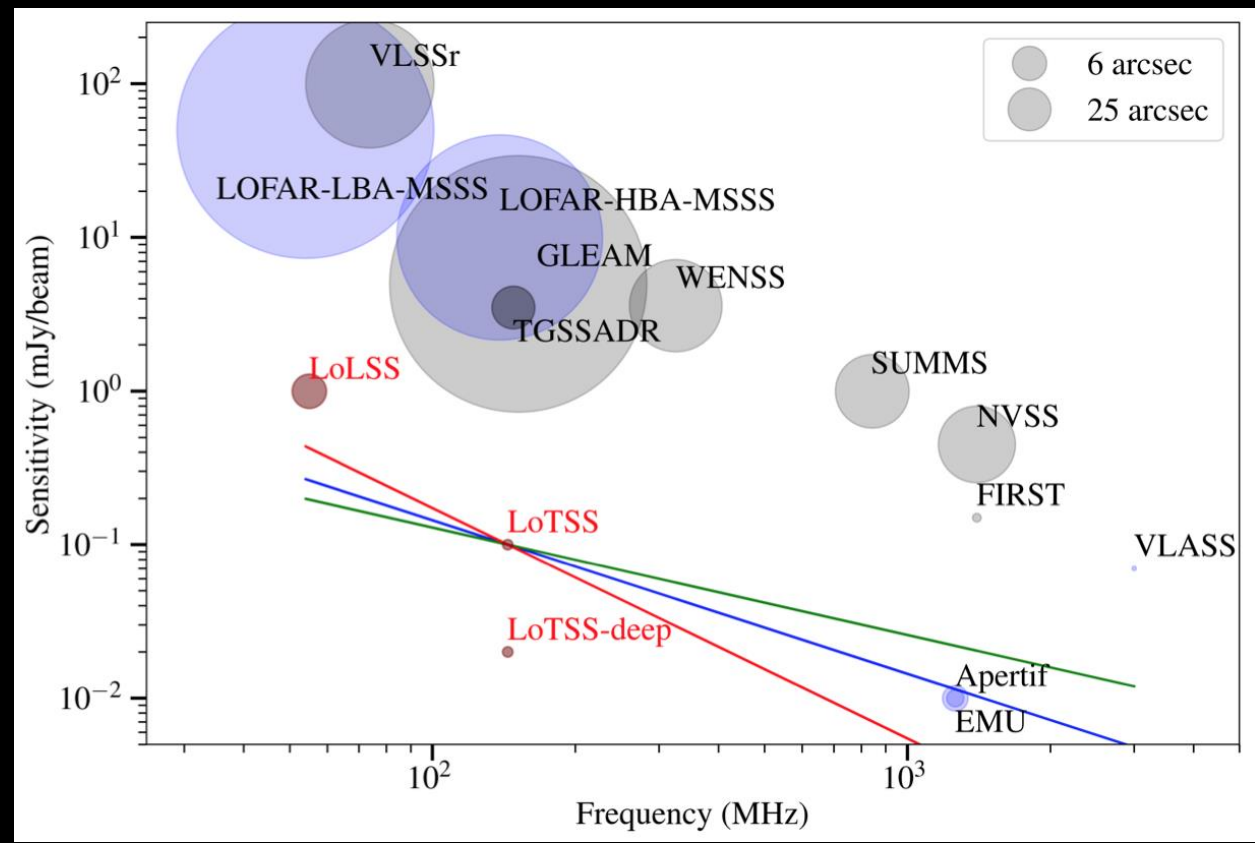
(Credits: L. Morabito)



Resolution  $\sim \lambda/D$



# SENSITIVITY

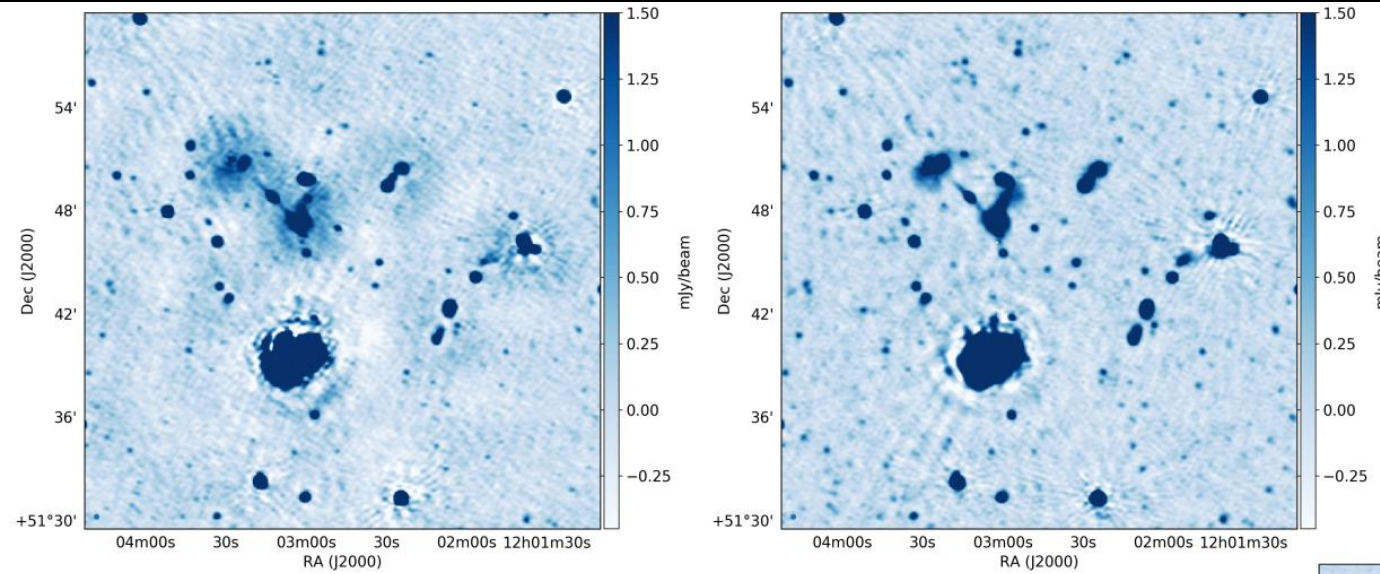


(Why so many non-radio people avoided radio surveys in the past)

# HOST FINDING: IT'S COMPLICATED!

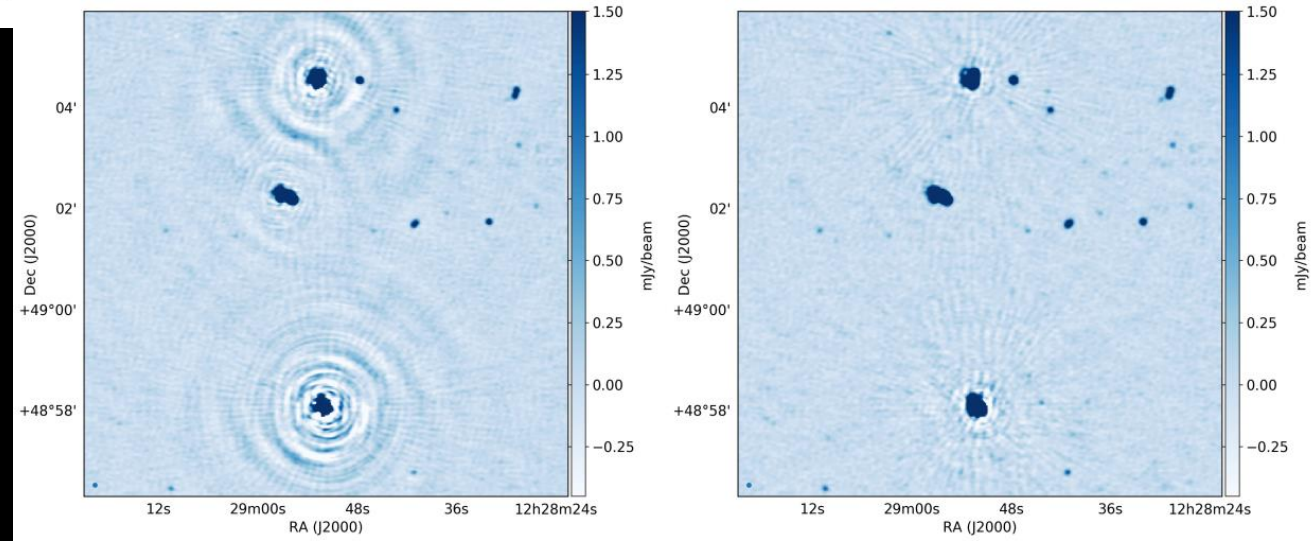
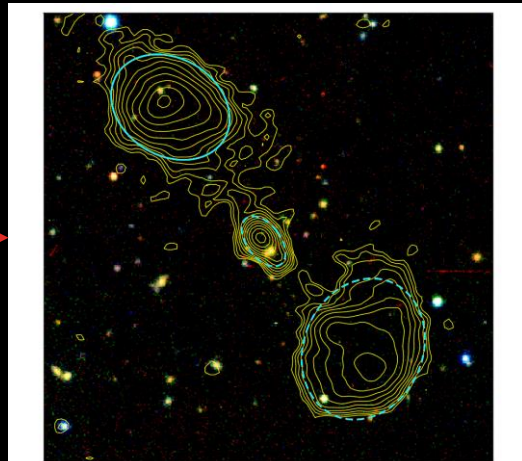
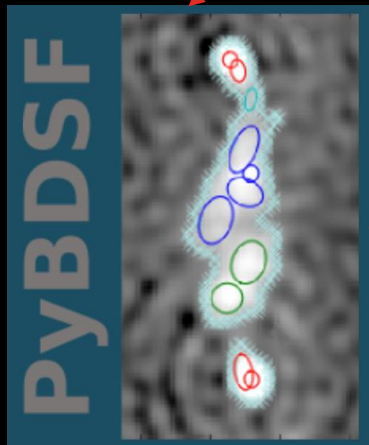
- **Most radio sources are compact**, even at low frequencies
  - Figuring out how compact/unresolved is tricky!
    - Astrometric uncertainties
    - Variations in beam size
    - Noise (especially for bright sources)
    - Need for “one size fits all” pipelines for surveys
- LOFAR: 92% of sources are compact (Shimwell+ 2019, 2022)
- VLASS: 73% of components are unresolved (Gordon+ 2021)

# RADIO NOISE EXAMPLES



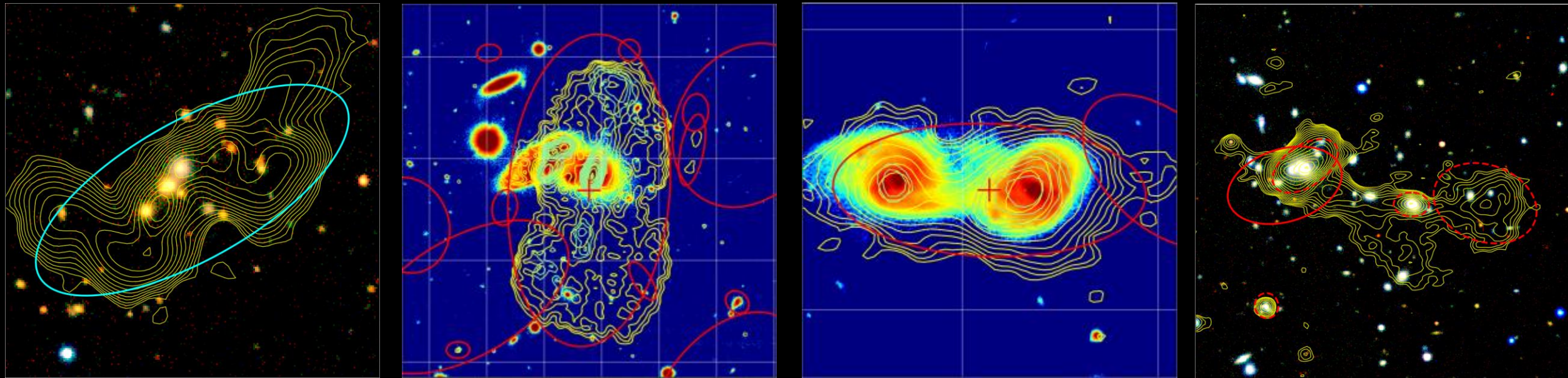
Shimwell+ 2022

LoTSS DR1 vs DR2



# EXTENDED RADIO SOURCES CAN BE MESSY!

Images from LOFAR Galaxy Zoo (LoTSS DR2 has  $\sim 4.3$  M sources,  $\sim 800$ /sq. deg., 27% of N. Sky)



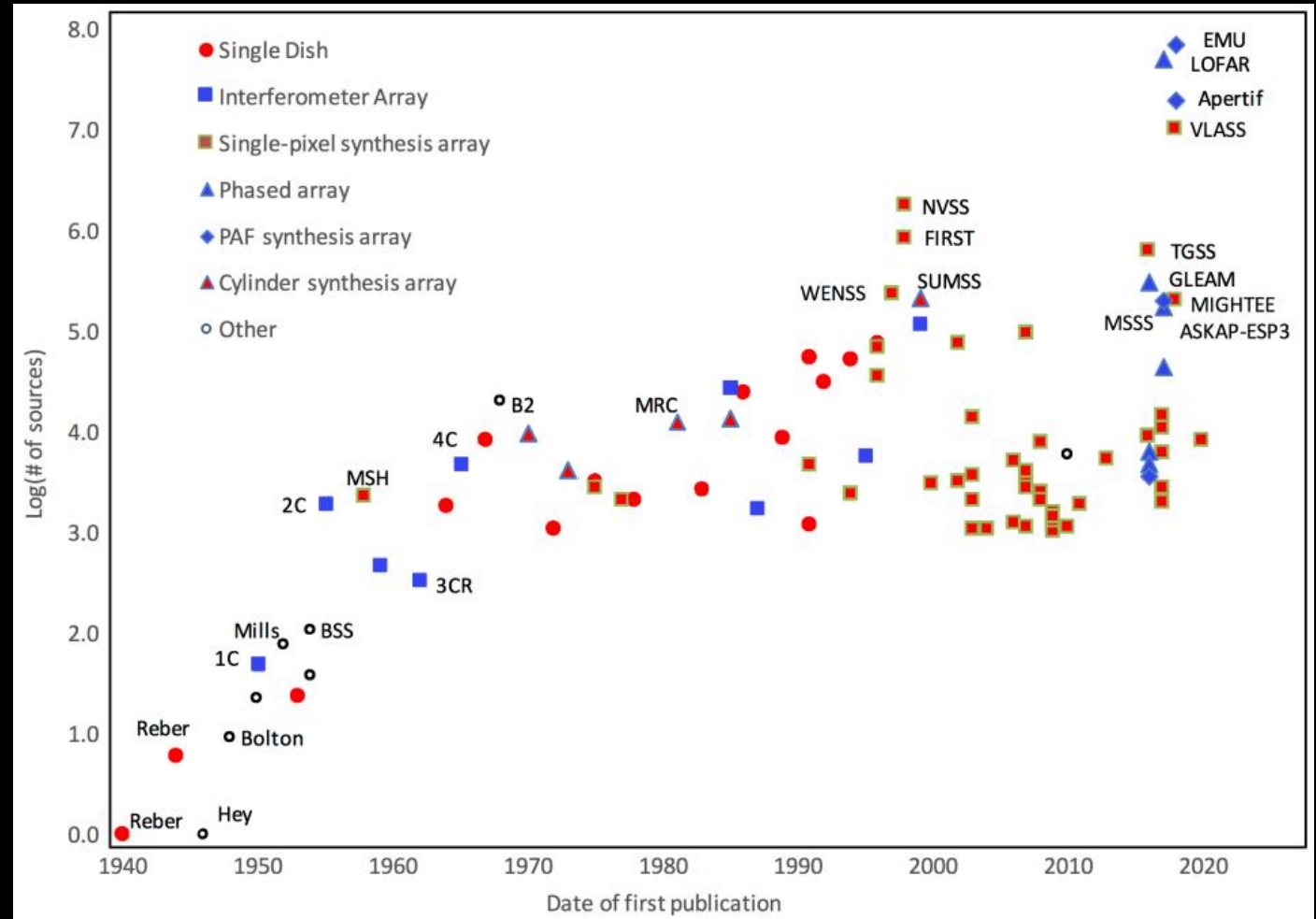
Some visual inspection is still required (but not for much longer?)

Brienza+ 2021



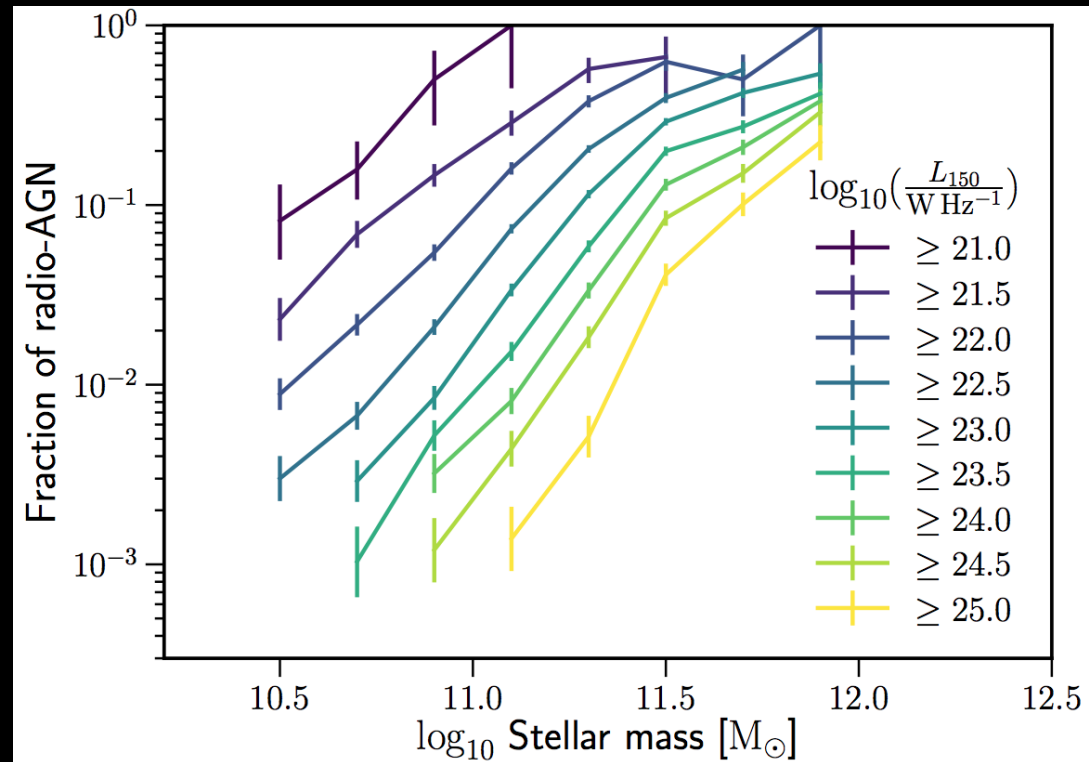
# HOST FINDING IN THE PAST

- Almost exclusively via direct cross-matching or by eye
- Far less of a problem with shallower, lower-res. surveys



# HOST FINDING NOW

Sabater+ 2019



- Not all optical sources are equally likely to host a radio source
- Dependence on:
  - Source type
  - Radio luminosity
  - Survey characteristics
  - Where in the sky



See Williams+ 2019; Barkus+ 2022

# LIKELIHOOD RATIO

Probability distribution function  
for offset  $r$

A priori probability that the radio source  
has a counterpart with given parameters

$$LR = \frac{q(x_1, x_2, \dots) f(r)}{n(x_1, x_2, \dots)}$$

Sky surface density of objects with properties described by given parameters  
Gaussian kernel estimator (KDE) was used for LOFAR (smoother than binning)

Two parameters used for LoTSS – magnitude ( $m$ ), colour ( $c$ ) (Nisbet 2018)

## LIKELIHOOD RATIO

$f(r)$  must consider positional uncertainties for radio and IR/optical, and uncertainty on the relative astrometry

$$f(r) = \frac{1}{2\pi\sigma_{maj}\sigma_{min}} \exp\left(\frac{-r^2}{2\sigma_{dir}^2}\right)$$

Combined radio positional uncertainty

Combined positional uncertainty along direction to possible counterpart

$$\sigma_{maj}^2 = \sigma_{maj,rad}^2 + \sigma_{maj,opt}^2 + \sigma_{ast}^2$$

# LIKELIHOOD RATIO

- $q(m)$  is relatively straightforward, even when avoiding clustering (Ciliegi+ 2003, Fleuren+ 2012, McAlpine+ 2012)
  - Pick search radius (based on resolution), find mag distribution of sources within it, correct for clustering/overdensities

$$q(m) = Q_0 \frac{real(m)}{\sum_i real(m_i)}$$

- $q(m,c)$  is far more complicated: clustering biases cannot easily be corrected
  - An iterative approach can help!

# LIKELIHOOD RATIO

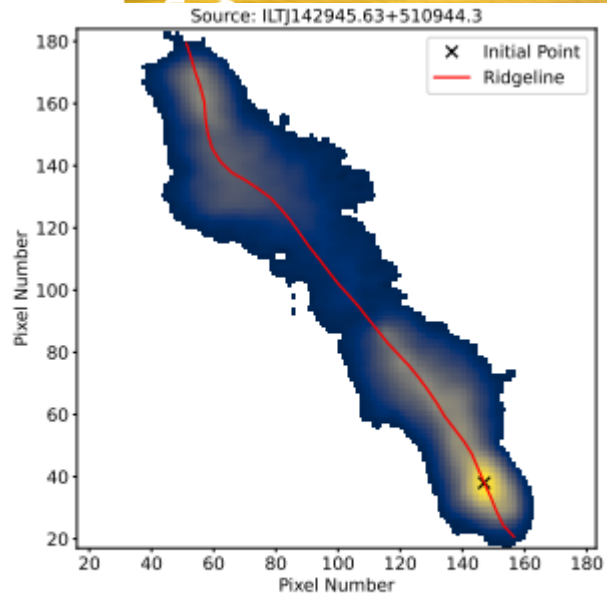
1. Rough starting estimate (magnitude-based, pre-combining PS  $i$  and WISE  $W1$  bands)  $\rightarrow$  pass list
2. Split list by colour ( $i-W1$ ) to obtain  $Q_0(c)$  (fraction of radio sources which have counterparts in each colour bin), then divide by mag for first estimate of  $q(m,c)$
3. LR are obtained for all galaxies around each radio source, to a given  $r$  ( $15''$  for LoTSS)
4. Use LR to reduce list in 1)
5. Iterate until convergence

# COMPLETENESS, RELIABILITY

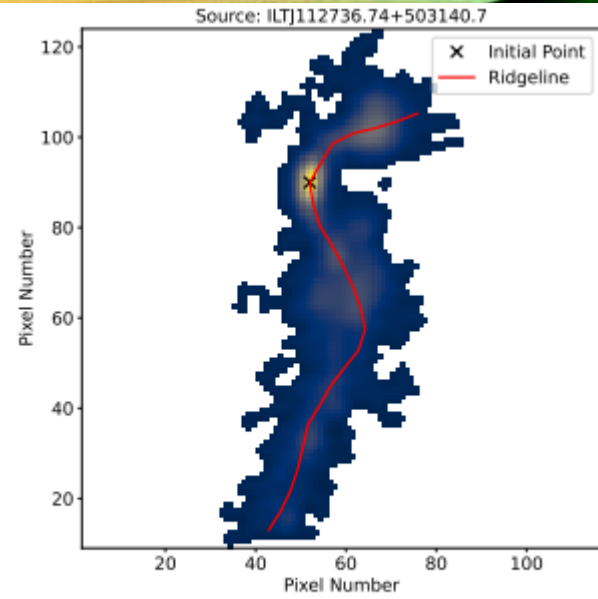
For a given LR threshold ( $L_{thr}$ ):

$$C(L_{thr}) = \frac{1}{N_{radio} Q_0} \sum_{LR_i < L_{thr}} \frac{Q_0 LR_i}{Q_0 LR_i + (1 - Q_0)}$$

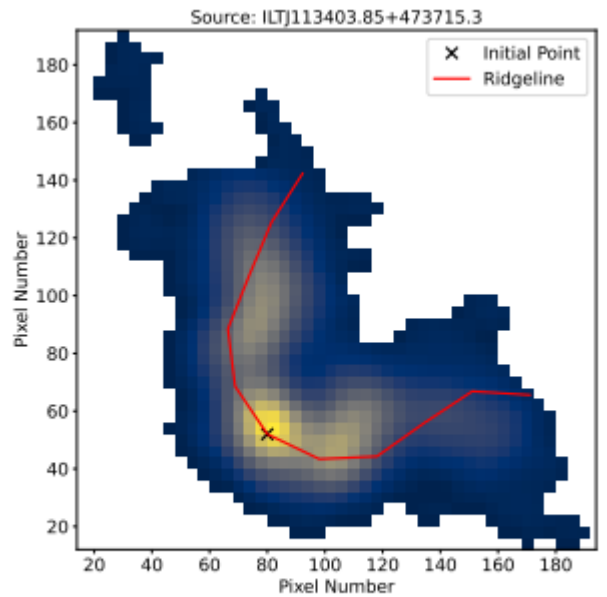
$$R(L_{thr}) = 1 - \frac{1}{N_{radio} Q_0} \sum_{LR_i \geq L_{thr}} \frac{1 - Q_0}{Q_0 LR_i + (1 - Q_0)}$$



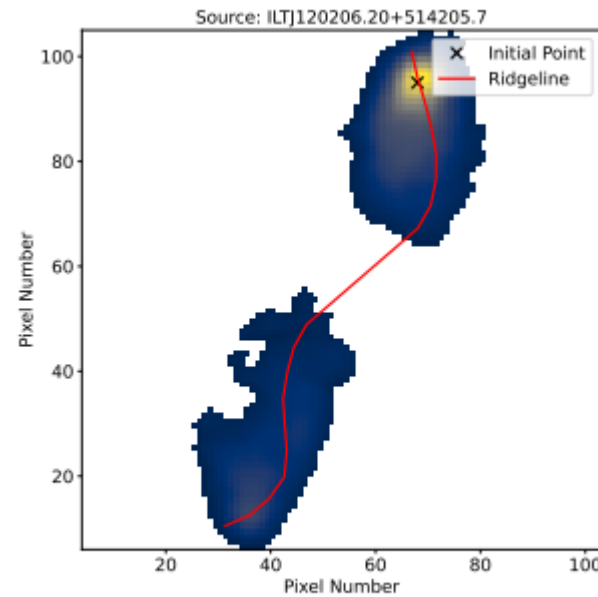
(a)



(b)



(c)



(d)

# EXTENDED SOURCES

Barkus+ 2022

Trace the path of maximum brightness, then use LR along the Ridgeline to find host

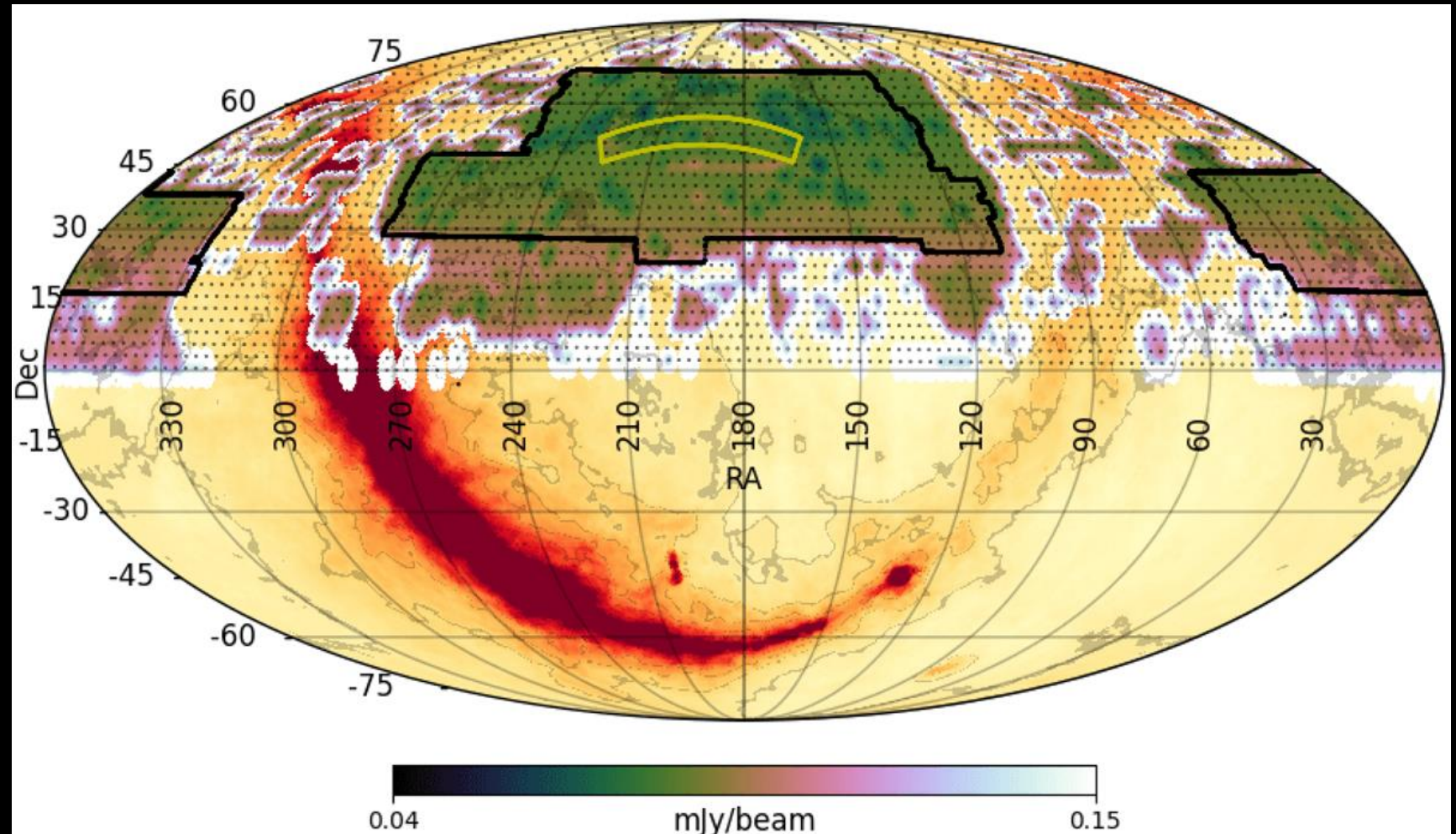
# WHAT ARE THE LIMITATIONS?

- LOFAR – hosts found for 73% of sources in LoTSS DR1 (Shimwell+ 2019, Williams+ 2019).
  - Limited by optical surveys! Pan-STARRS only reasonably complete up to  $z \sim 0.8$
  - DR2 uses DESI Legacy Survey + WISE
- VLASS – hosts found for  $\sim 50\%$  of point sources,  $\sim 30\%$  of resolved sources (so far!), using WISE
  - Component association is not complete, improvements still in progress

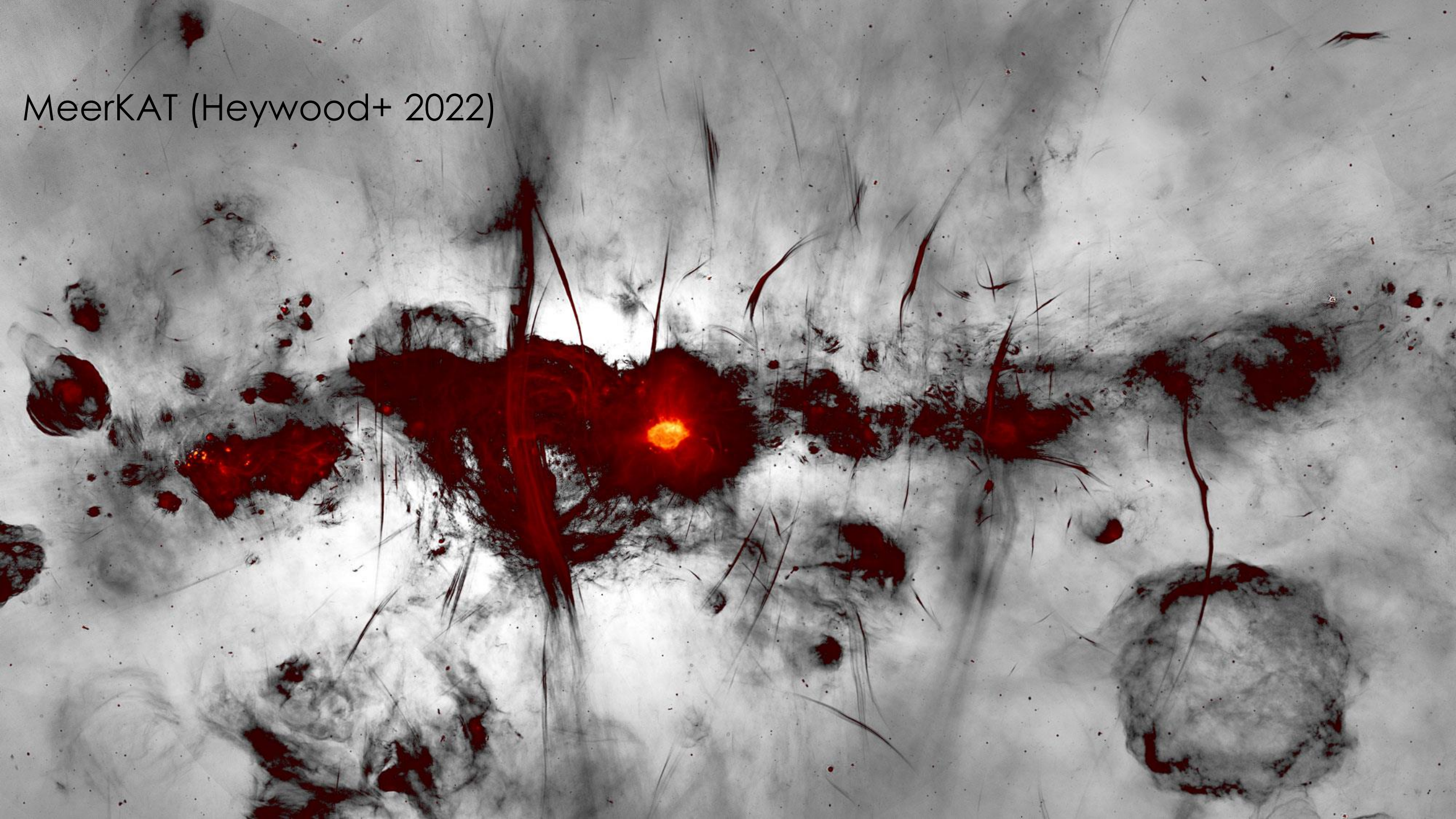
# WHAT ABOUT THE GALACTIC PLANE?

Shimwell+ 2022

If you want LOFAR data, you might need some patience...



MeerKAT (Heywood+ 2022)



# WHAT ABOUT VARIABILITY?

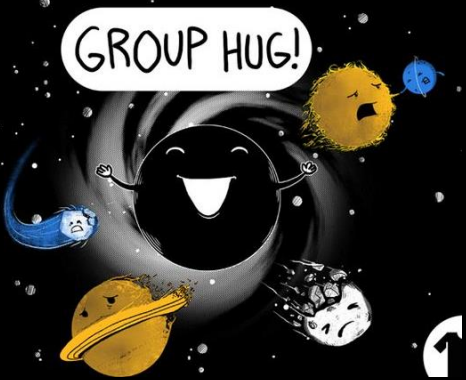
- Real-time data analysis is nigh on impossible for modern radio surveys ☹
  - Huge data volumes (up to 100s of TB)
  - Very complex, computationally-intensive data reduction
- Serendipitous finding of variable sources within radio surveys is challenging!
  - Many surveys are single-epoch
  - There is hope!
    - Multi-epoch and/or multi-survey searches
    - Dedicated teams looking for intra-observation variability

# SUMMARY – HOW TO USE

- Do you know **what type of source** you are looking for?
  - Yes: consider physical properties (and sky location!), then find the best survey for your needs.
  - No: search anyway! 😊
- Use **multiple surveys**, if you can
  - Radio surveys work best together!
  - But be mindful of the individual biases, limits, etc.
- **Most modern surveys have associated catalogues!** 😊
  - Explore, use other tools, but **don't x-match blindly!**

# THIS STILL DOESN'T HELP ME...

- The radio party is only just starting!
  - Most modern surveys haven't released the bulk of their data!
- There are always targeted observations!
  - Find your nearest radio astronomer (we are a friendly bunch!)
  - Consider best instrument, co-write a proposal, let them have their adventures in Fourier-transform land, get beautiful data.



Stay tuned!