Radio Sky surveys

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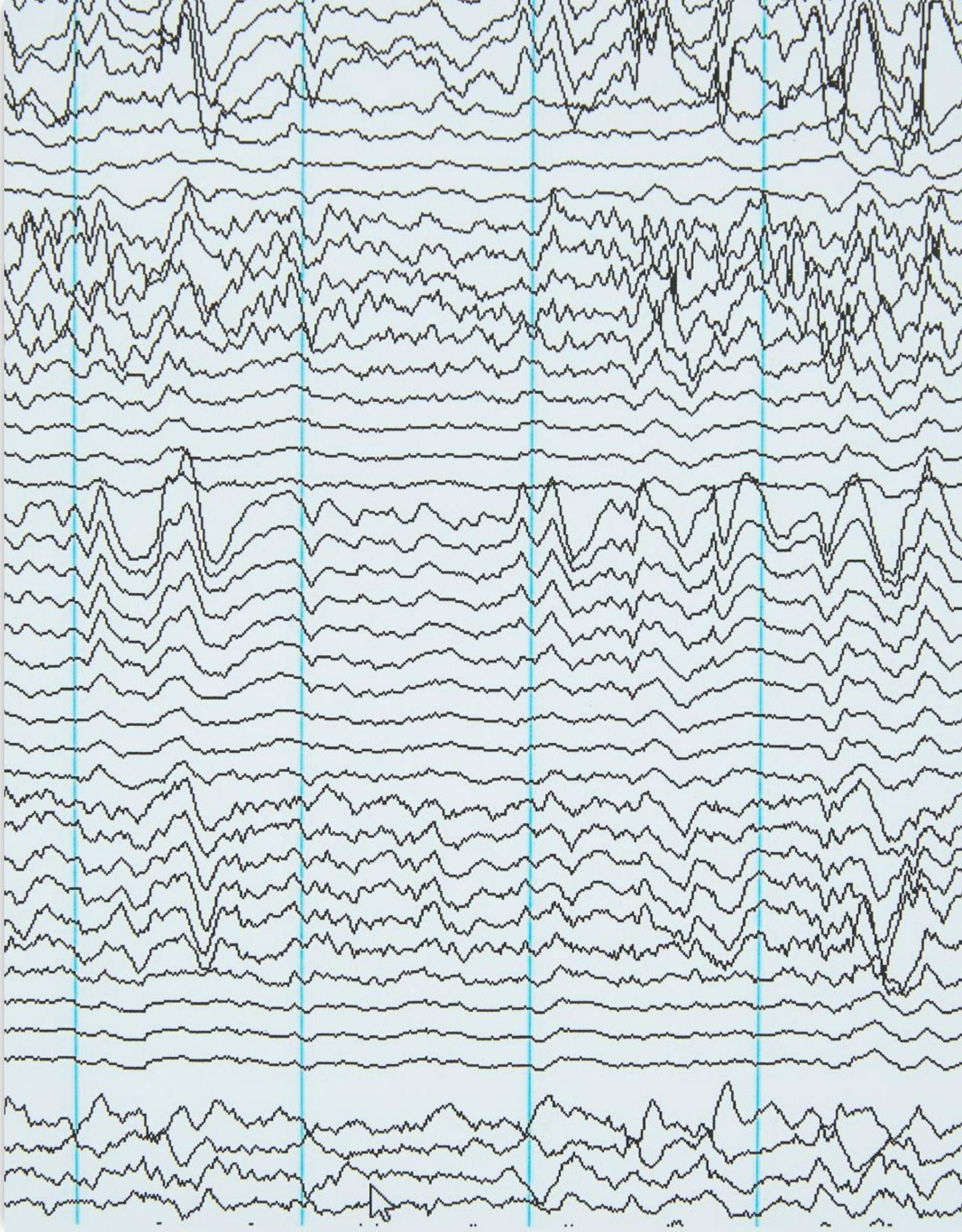
Outline

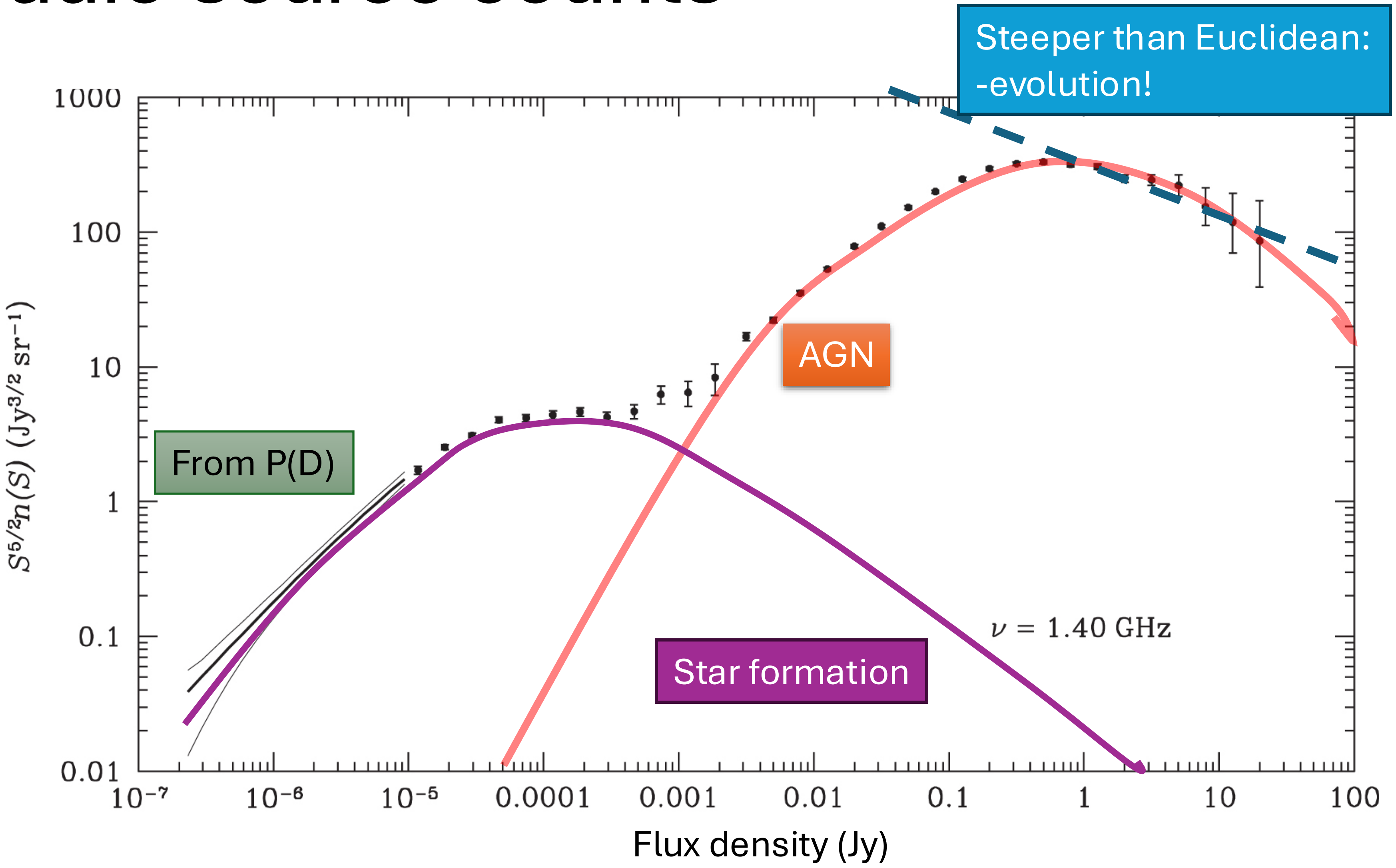
- A brief history of radio surveys
  - Radio source counts and the source population
  - The radio background
- Survey technologies and methods
- Source classification and identification
- Polarimetry
- Time domain
- HI line surveys
- Current and future radio surveys
- Using large radio survey datasets

Early radio surveys

- The first radio surveys were limited by sensitivity and source confusion.
- Improved telescopes and a better understanding of the effects of source confusion gave the first reliable surveys (e.g. 3C, Parkes).
- The P(D) method (Scheuer 1957) for constraining the source population below the confusion limit using fluctuations in the confusion noise remains important for deep interferometric surveys to this day.



The radio source counts

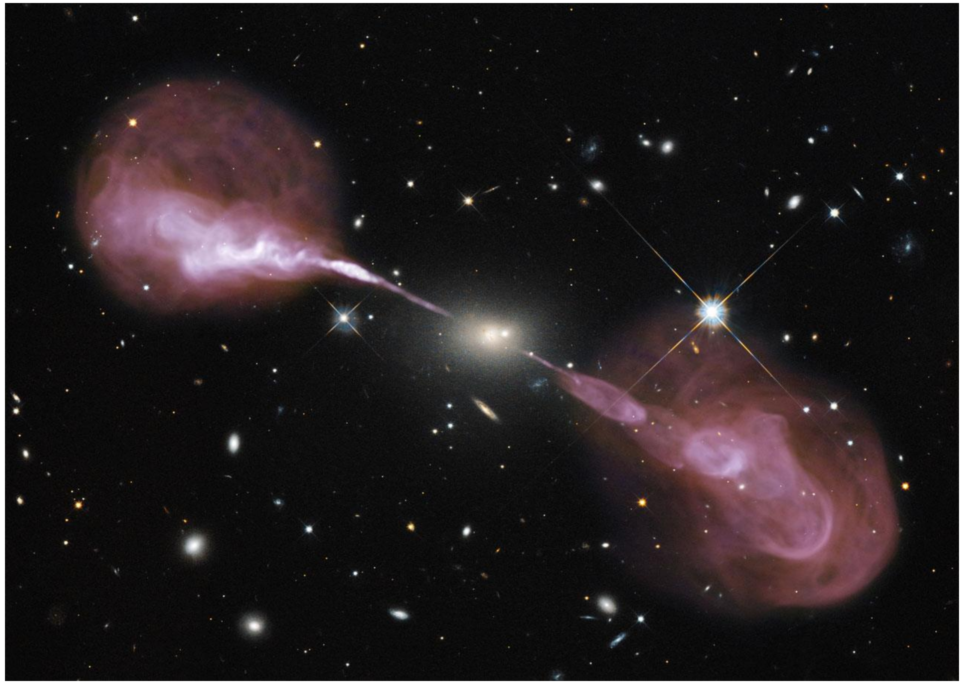


Matthews et al. 2021

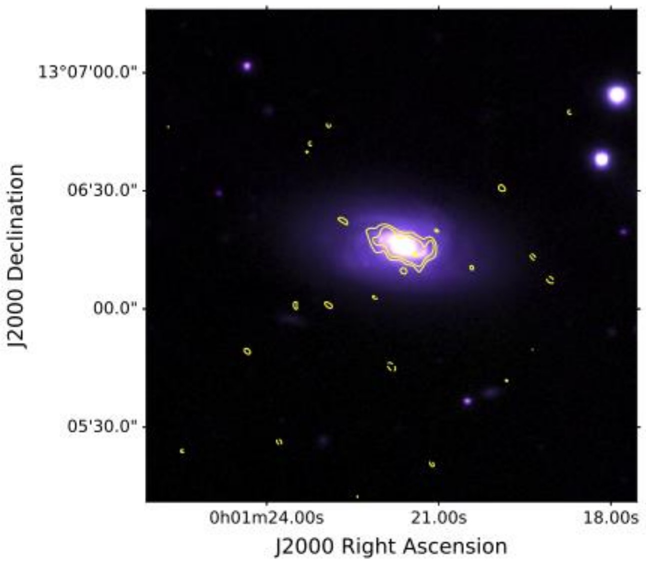
Traditionally plotted normalized to a Euclidean distribution

The radio sky

- AGN sources divided between "radio quiet" and "radio loud" (though in fact there is a continuum of radio-loudness).
- Typical radio-loud AGN (and at least some radio-quiet) have radio emission powered by relativistic jets on scales ranging from nuclear to several Mpc.
- Radio-quiet AGN may alternatively (or additionally) have some fraction of their radio emission powered by shocks from thermal winds or star formation.
- Sources having radio emission from star formation dominate below ~1mJy at 1.5 GHz.



AGN- Hercules A



Star-forming galaxy NGC 7803

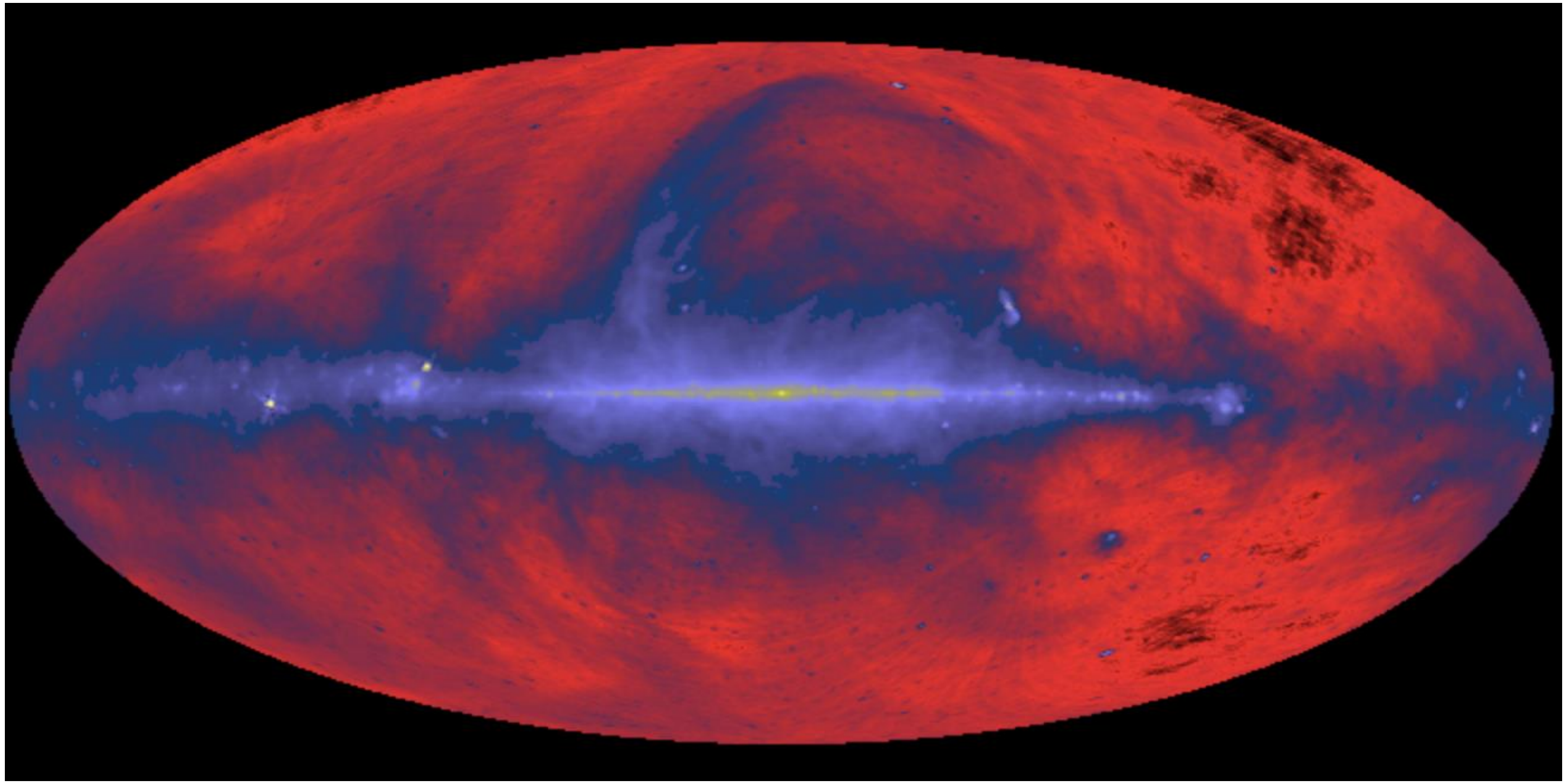
ARCADE 2 and the GHz background

- Source counts are not the whole story however....
- Background measurements, both ground-based (e.g. Haslam et al. 1981; Roger et al. 1999; Maeda et al. 1999; Reich & Reich 1986) and balloon-based (ARCADE-2; Fixsen+2011) detect an excess of emission relative to that obtained by summing up the source counts.
  - Ground-based measurements have uncertain (though improving) calibration, but ARCADE-2 was well-calibrated against an absolute standard.
  - Spectrum consistent with optically-thin synchrotron ($\alpha \sim -0.6$)
- The radio background is only about 20% accounted for by the known discrete sources (Matthews+21; Thompkins+23).

The cm-wave background's origin

- Summary of a recent workshop on the problem: Singal+23, PASP, 135:036001
- The local bubble?
- Galactic?
- Very faint (nJy) sources?
- Diffuse extragalactic (dark matter decay??)

Constraints may be possible from cross-correlation with other wavelengths, polarization and even Radio SZE measurements (where the radio background takes the place of the CMB).



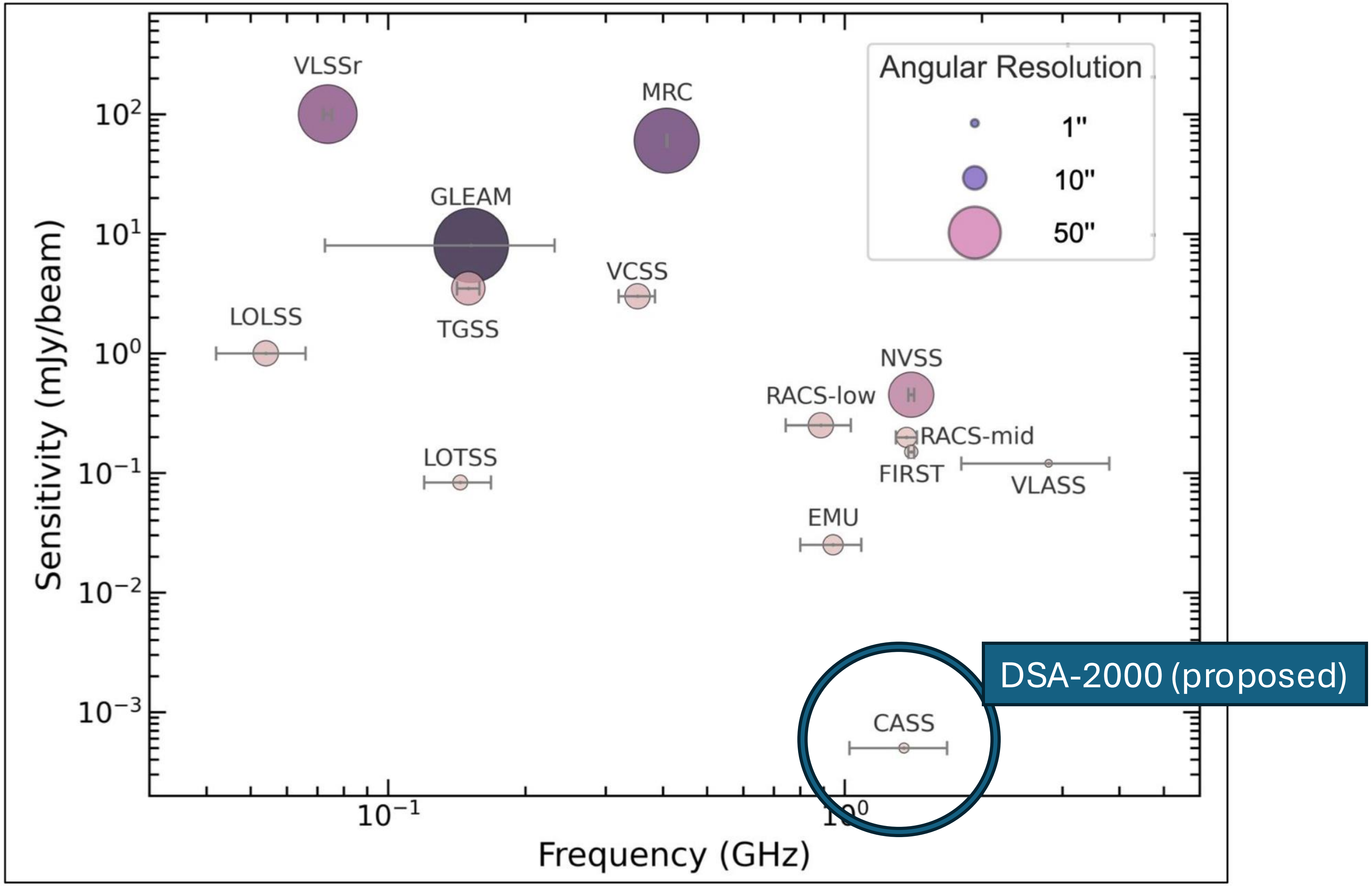
Haslam+81; Jodrell Bank Mk1A/Effelsberg/Parkes 408MHz

Interferometric radio surveys

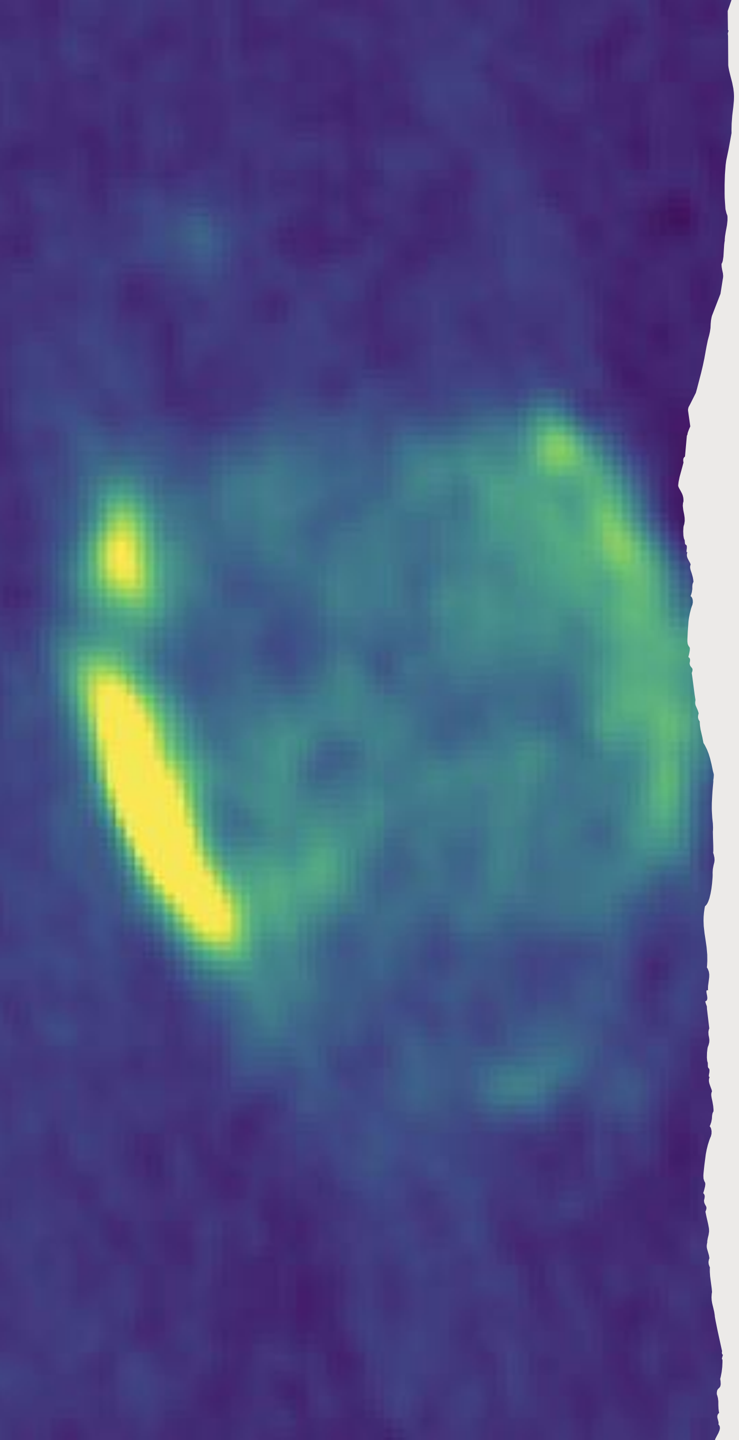
Survey technologies and methods

- Beam-forming (CHIME, MWA, LoFAR)
  - Typically ~< 300 MHz, dipole or 2D parabolic antennas with many sr of response.
  - Complicates calibration: "everything at once".
- Point and shoot single element (VLA: NVSS, FIRST; GMRT: TGSS)
  - Straightforward to calibrate and image, but slow and inefficient observing.
- Phased-array feeds (ASKAP: RACS, EMU, POSSUM; Westerbork: APERTIF)
  - Multi-beam, very efficient for surveys, though typically noisier than single element and again, high data rate.
- On-the-fly (VLASS, MeerKLASS)
  - Fast observing, high data rates, imaging can be computationally intensive.

A golden age of radio surveys



Pallavi Patil, JHU



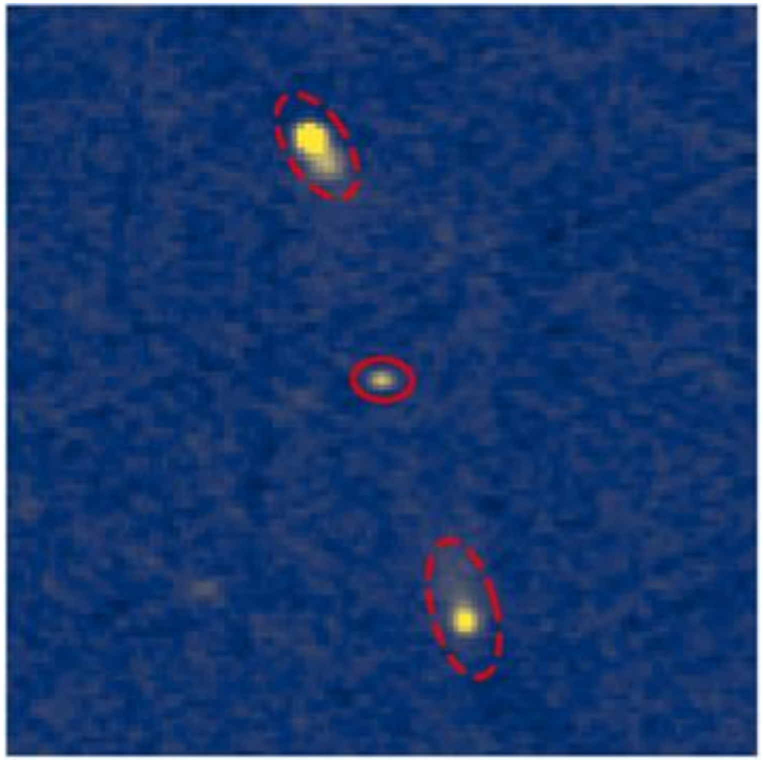
Radio surveys can now match optical telescope resolution

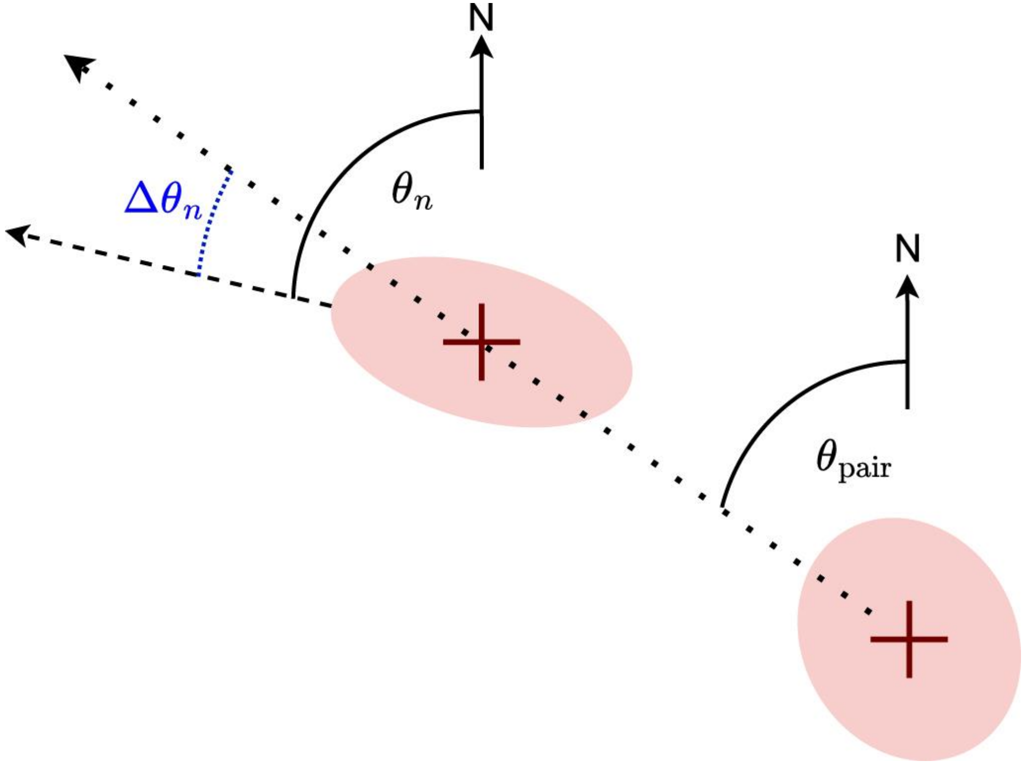
- Modern radio surveys like VLASS can match optical resolution.
- The Bow-tie nebula(VLASS left; optical right) - about 1 arcmin in size.
- Allows secure identifications with multiwavelength counterparts.

Source classification and identification in modern surveys

- Compact/unresolved sources are usually simple to identify (unless confused). Standard likelihood ratio techniques can be used to make multiwavelength identifications (Sutherland & Sanders 1992, McAlpine 2012).
- Extended/multicomponent sources much more complicated
  - Radio galaxy zoo (Banfield+15)
    - Use citizen science to crowd source source associations and identifications. Can also be used to train machine learning techniques.
  - DRAGN hunter (Gordon+23)
    - Algorithmic, including likelihood ratio.
  - Machine learning (SOMs, CNNs, Transformers..)

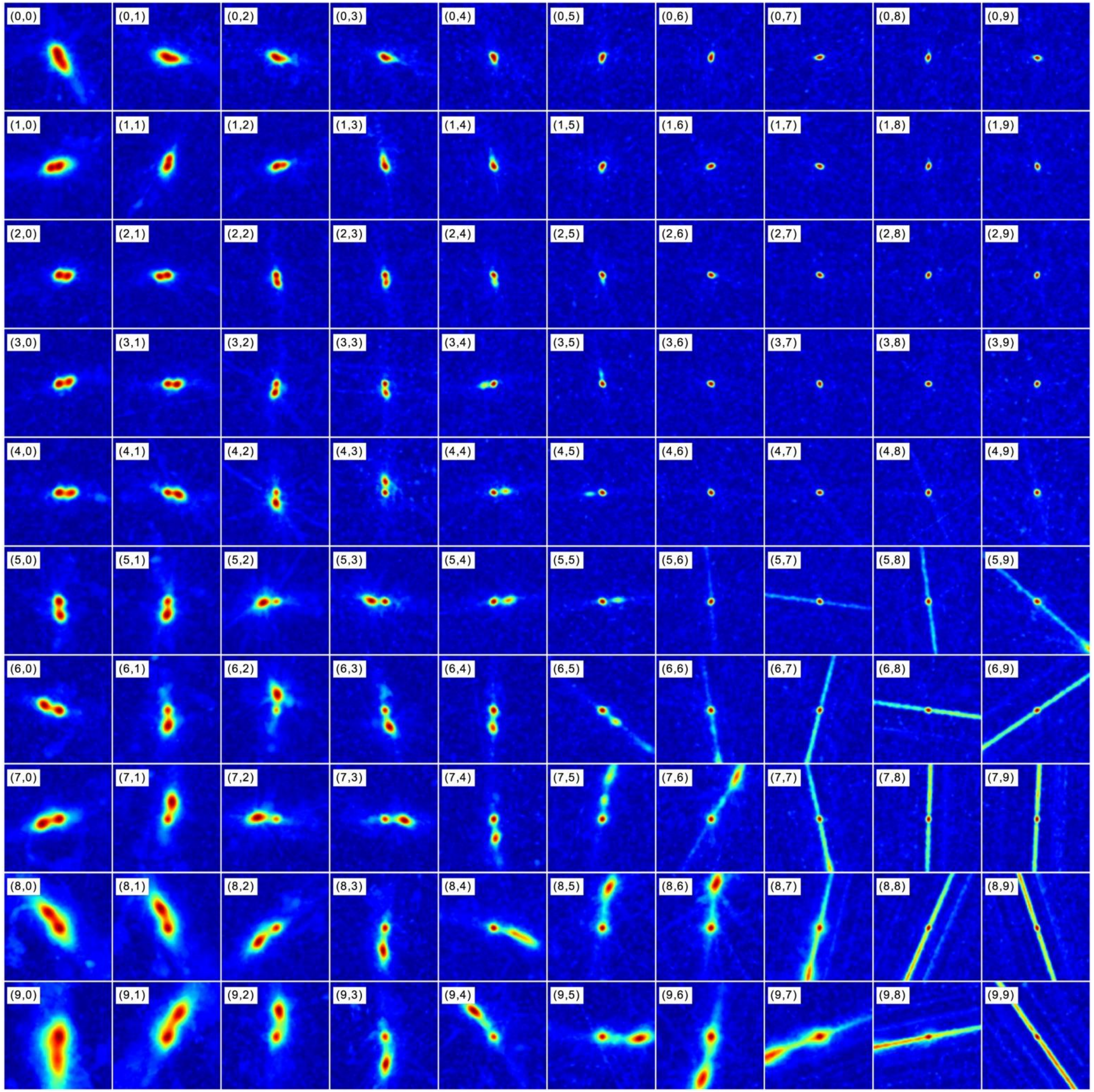
DRAGNhunter (Gordon et al. 2023)





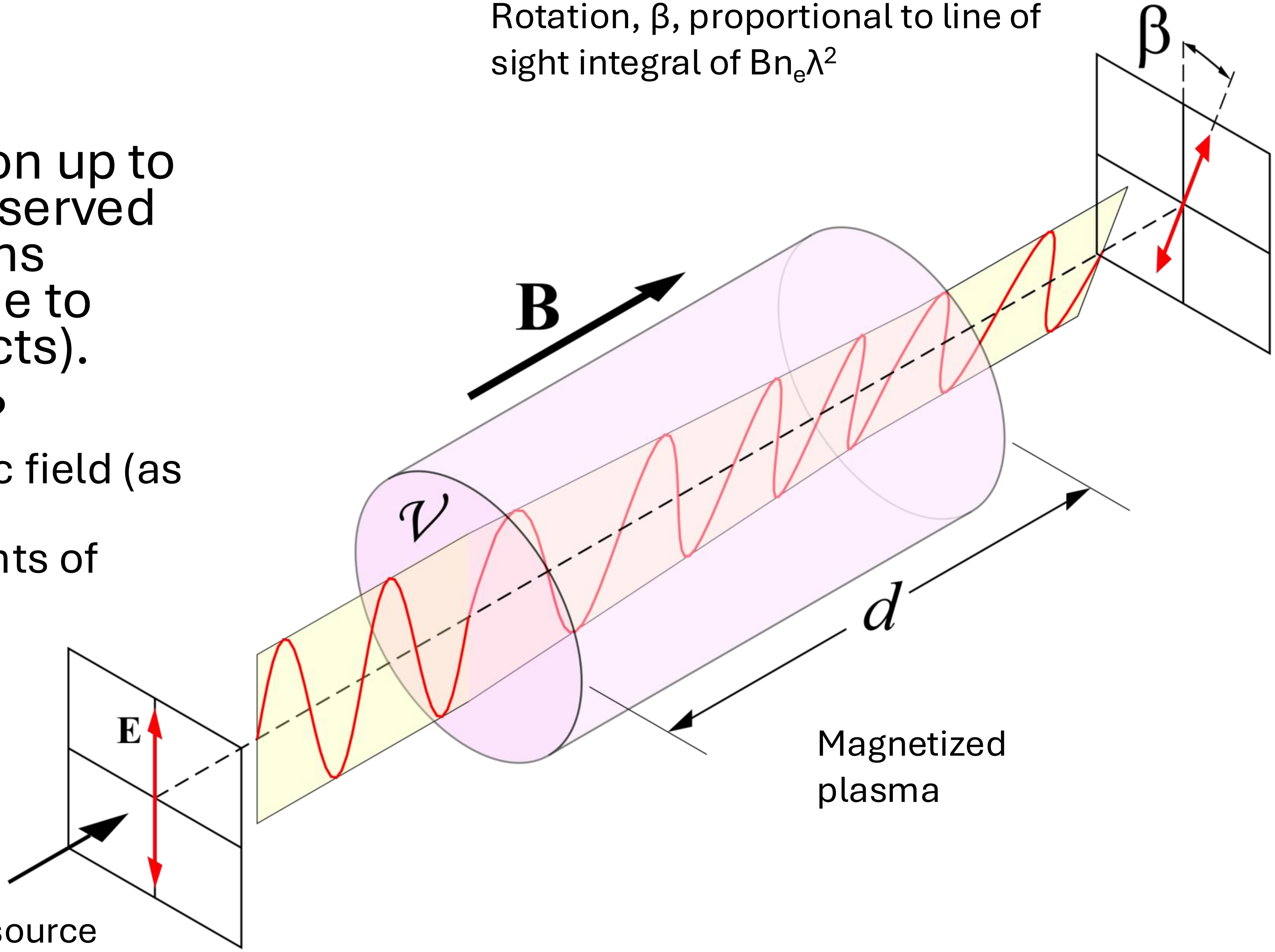
Self-organizing map (PINK) Vantyghem+24

Each neuron corresponds to a specific morphology (including artifacts, bottom right).

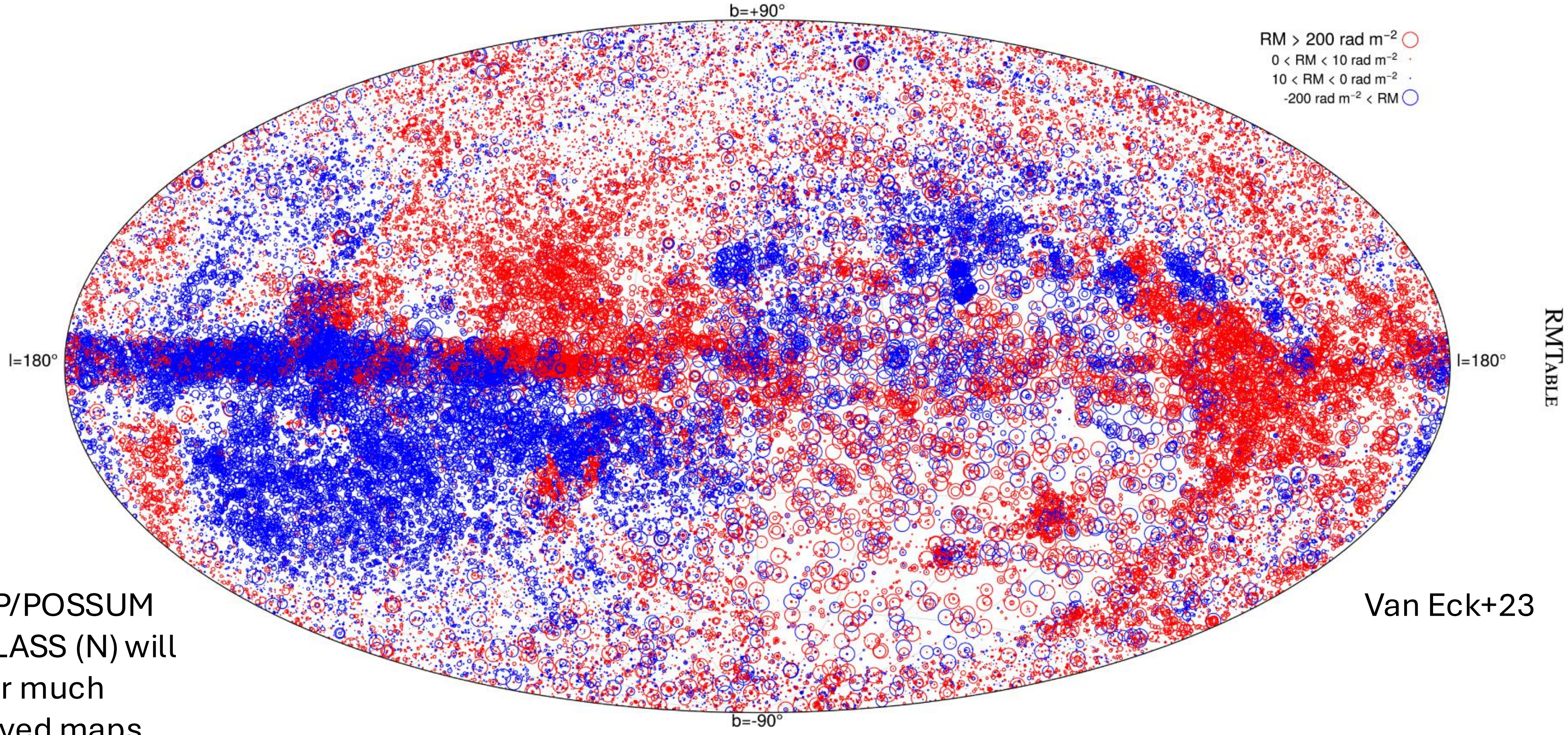


Polarimetry

- Synchroton emission up to ~75% polarized (observed polarization fractions typically smaller due to depolarization effects).
- What can we learn?
  - Milky Way magnetic field (as a foreground)
  - Nearby environments of radio sources



Milky Way RM structure (galactic coords)

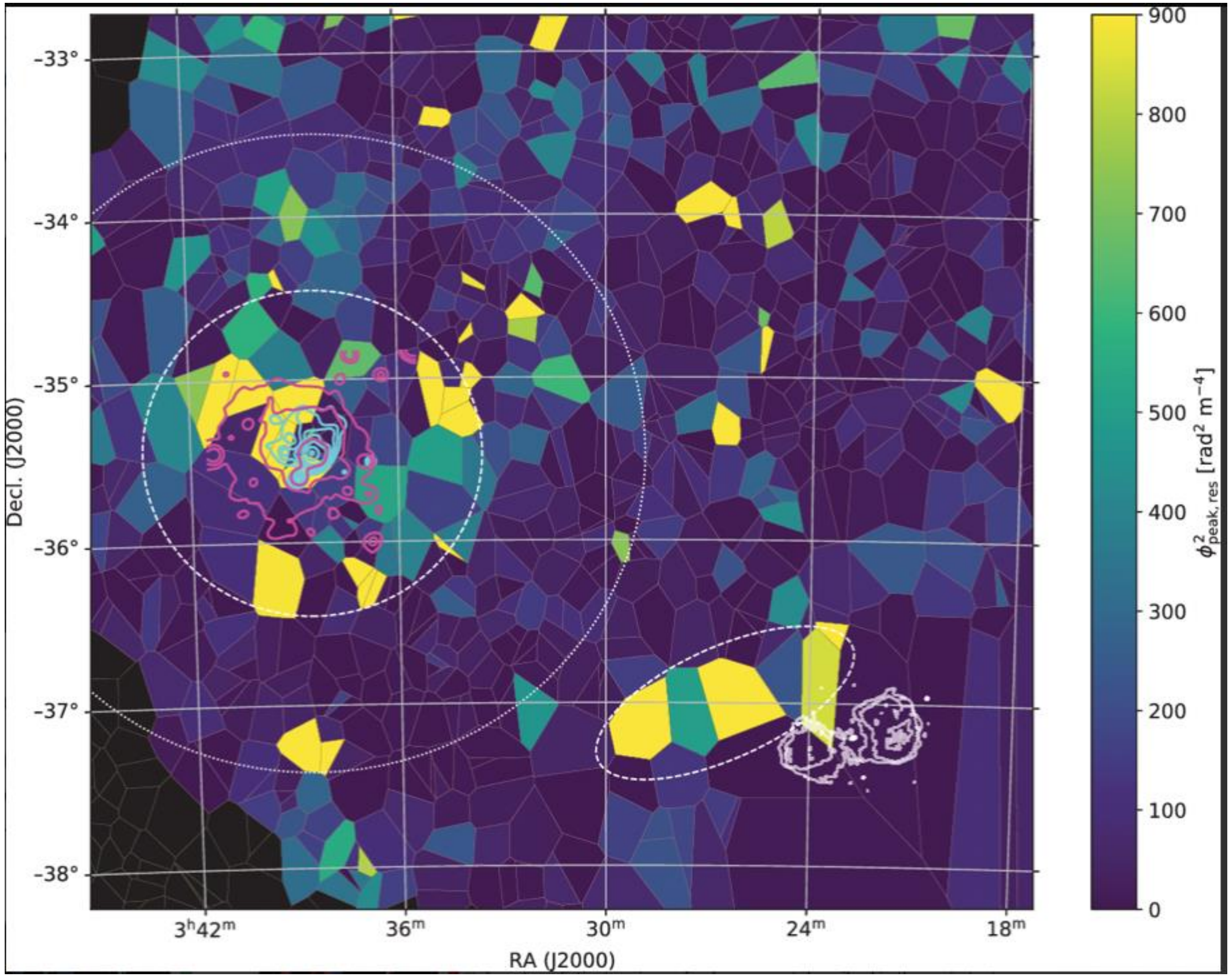


ASKAP/POSSUM (S)+VLASS (N) will deliver much improved maps

Van Eck+23

Polarimetric surveys

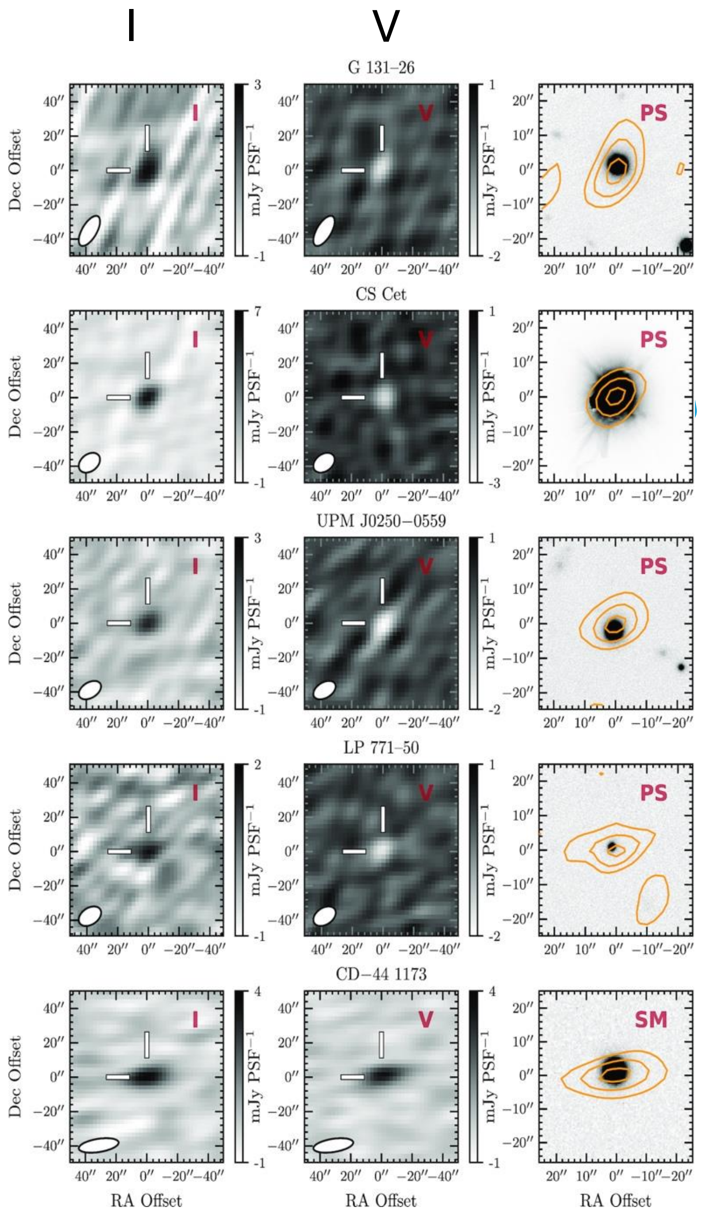
- Depolarization and Faraday complex emission.
- Maps of RM in clusters.
- Potential for detecting filaments in the cosmic web (Vernstrom+21)



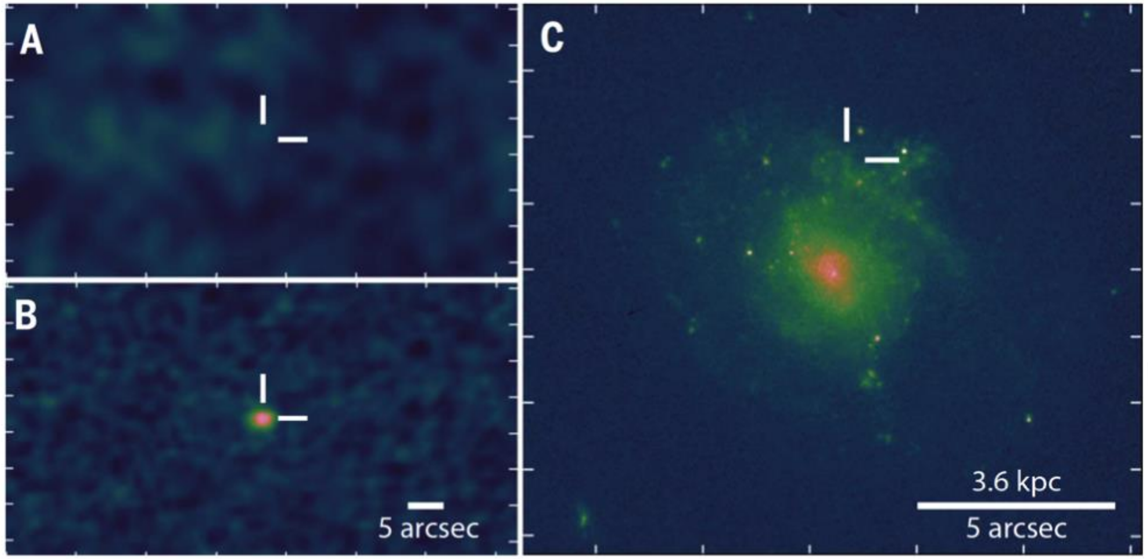
Fornax cluster with ASKAP/POSSUM; Anderson+22

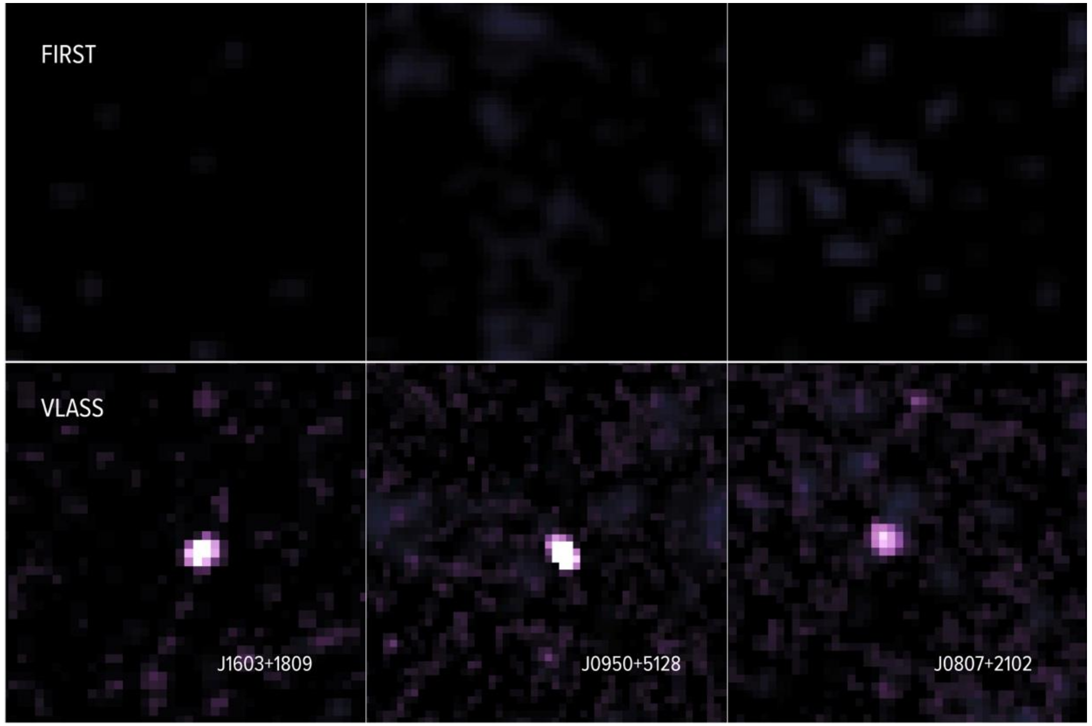
Circular polarization

- Synchrotron radiation ~ zero circular polarization
- Other forms of emission, e.g. cyclotron, can have very high circular polarization.
  - Stellar flares, for example.



Pritchard+23 (ASKAP/RACS)





Time domain

- Radio surveys have now entered the time domain:
  - "Slow" transients (days to years)
    - VLASS (VLA, 3 GHz, 32+ month cadence, 34,000 deg^2)
    - VAST (ASKAP, 1 GHz, 2 - 5 week cadence, 10,000 deg^2)
  - Rapid transients (milliseconds to seconds)
    - Commensal surveys on many telescopes
      - VLA: realfast, COSMIC-SETI, VLITE
      - MeerKAT: MeerTRAP
      - ASKAP: CRAFT
      - CHIME

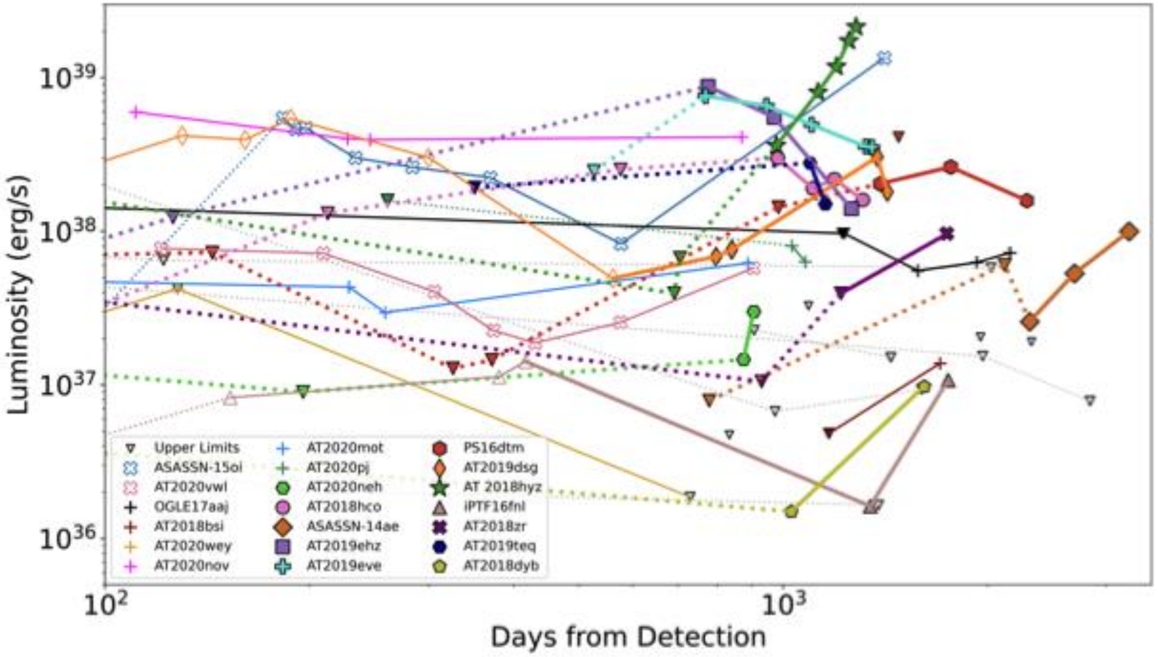
Time domain survey science highlights

“Slow” transients:

- Radio supernovae (Dong+ 20)
- Radio-quiet to radio-loud AGN transitions (e.g. Nyland+20)
- Late-time radio emission from Tidal disruption events (e.g. Cendes+24)

“Fast” transients:

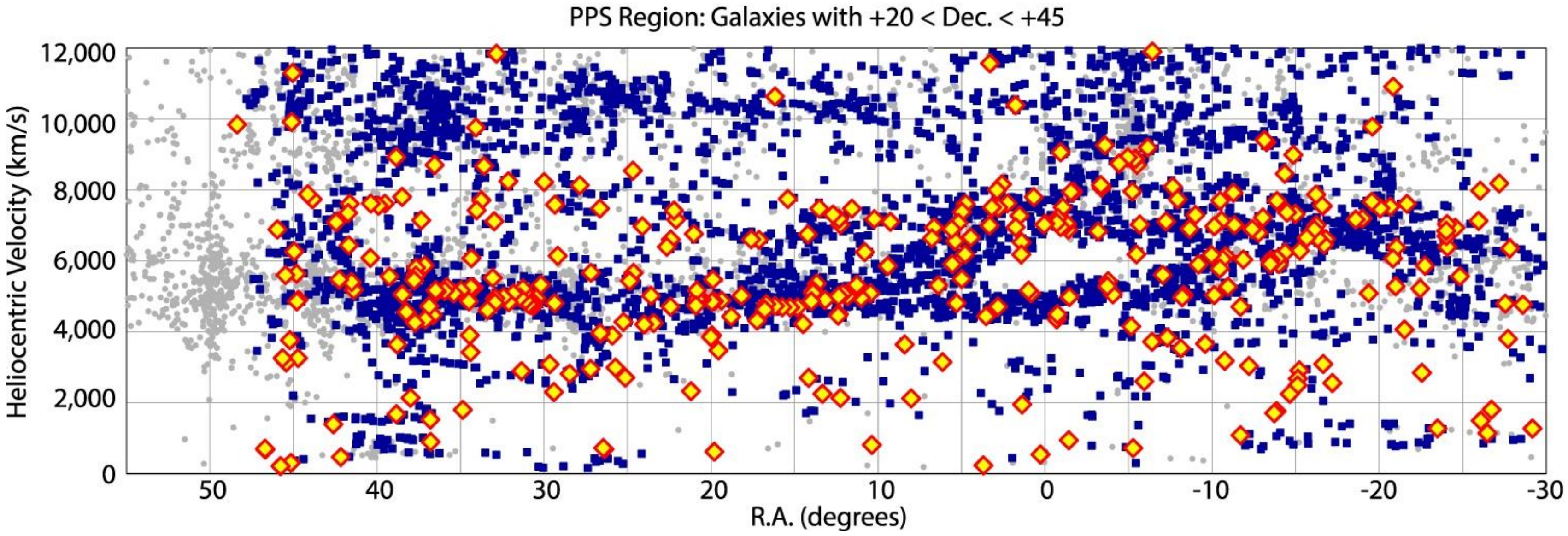
- (Localization of) fast radio bursts (e.g. CHIME/FRB collab 2020).
- Long (21 min) period radio transients (Hurley-Walker+23)



Cendes+24

HI (21cm line) surveys

- HI surveys can measure the redshift of emitting (or absorbing) systems directly.
- The HI line is weak, however, and low brightness, making direct detection of emission at z>~0.1 difficult. Nevertheless, a lot of potential for cosmology as Milky Way obscuration is not an issue.
- Surveys: ALFALFA (Arecibo), LADUMA (MeerKAT), WALLABY (ASKAP)
- HI intensity mapping – low-z MeerKLASS, high-z CHIME, HERA
- Absorption line (MALS: https://arxiv.org/abs/2408.16619)



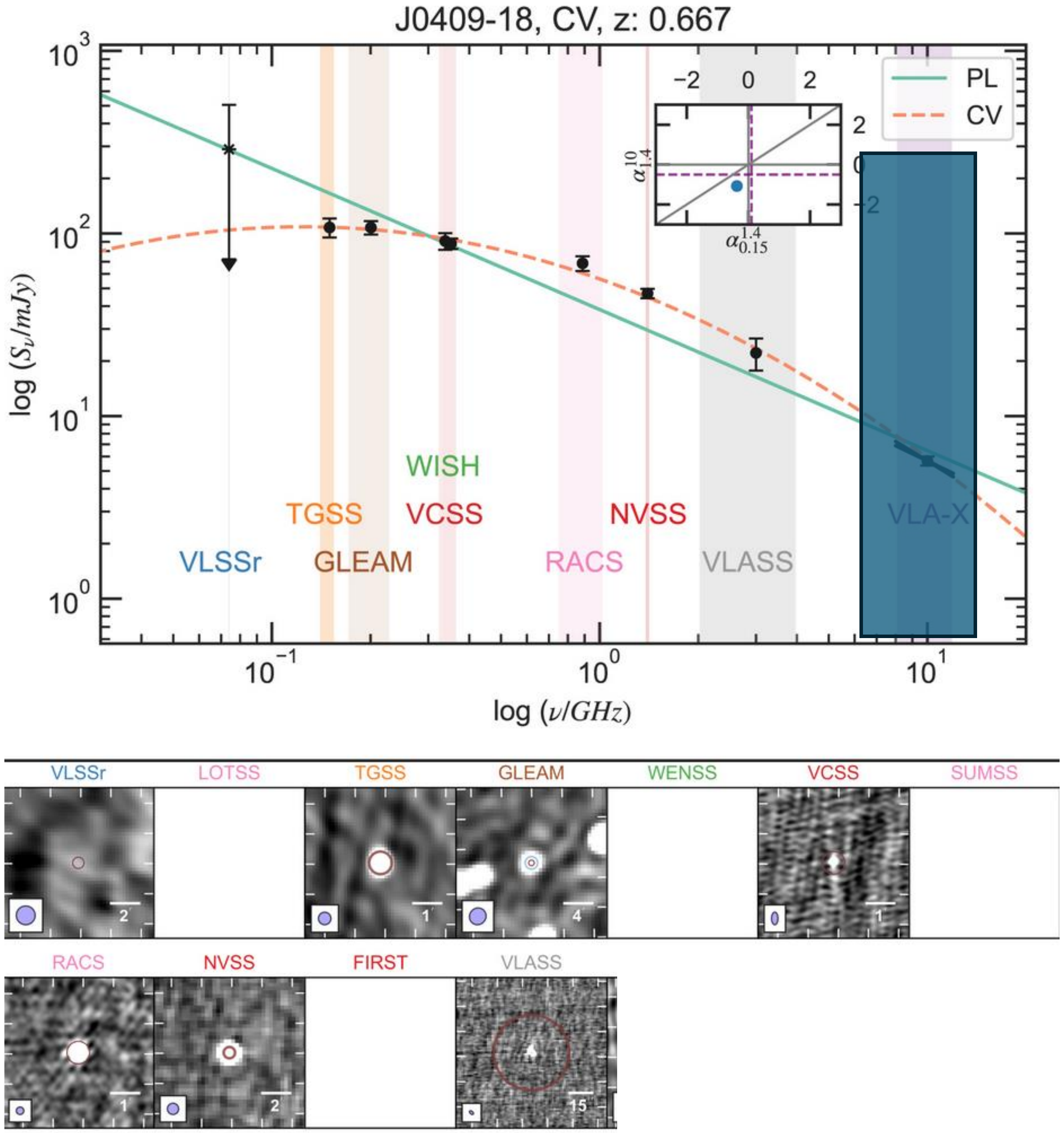
Pisces-Perseus Supercluster with ALFALFA; O'Donoghue et al. 2019

How to use radio surveys

- Modern radio surveys are typically released with processed images and catalogs. Some caveats:
  - Interferometric surveys miss flux on scales larger than the smallest spacing in the array (~20 arcsec for VLASS, for example). Conversely, low resolution surveys can blend sources together, resulting in incorrect fluxes.
  - Positional accuracy is determined by the accuracy of the calibrator positions (usually from VLBI so typically <0.1" error) and the imaging algorithm (can be larger) and the SNR (error ~ 0.6 θ/SNR, where θ is the beam FWHM; Condon 1997) . Check the survey documentation, especially if you need accuracy much less than the beam size!

0.03-3 GHz SEDs

- Surveys now cover enough frequency range to define SEDs etc. from the ionospheric cutoff to ~4 GHz.
- Can readily identify MHz and GHz peaked spectrum objects (Ballieux+24)
- Some surveys at higher frequencies, but typically not comparably sensitive to steep-spectrum objects (87GB, AT20G).
- Beware source blending in low resolution surveys.



Patil et al. 2022

Dealing with large survey data

- Modern radio surveys have high computing needs both in terms of processing FLOPS and memory/disk storage.
  - Currently limiting the output from many survey projects.
  - New techniques (use of GPUs, careful software design to optimize performance) being developed.

- On the user side, cutout servers, server-side visualization (CARTA), automated source detection and classification etc are needed to make these surveys useful for science.
  - The Virtual Observatory standards are being adopted across the field to help with this.

Current status of the radio sky

"Go to" wide area surveys now:

- Dec > -40 deg VLASS (Quick Look products) 3GHz, 2.5" resolution, 150 μJy/beam.
- Dec < +40 deg RACS ~1GHz (3 bands), 15" resolution, 250 μJy/beam .

Coming soon (~5 years):

- VLASS (Single Epoch/Combined) – no deeper, but higher dynamic range and spectra.
- EMU (21% observed to date, much deeper than RACS/VLASS, RMS ~25μJy/beam).

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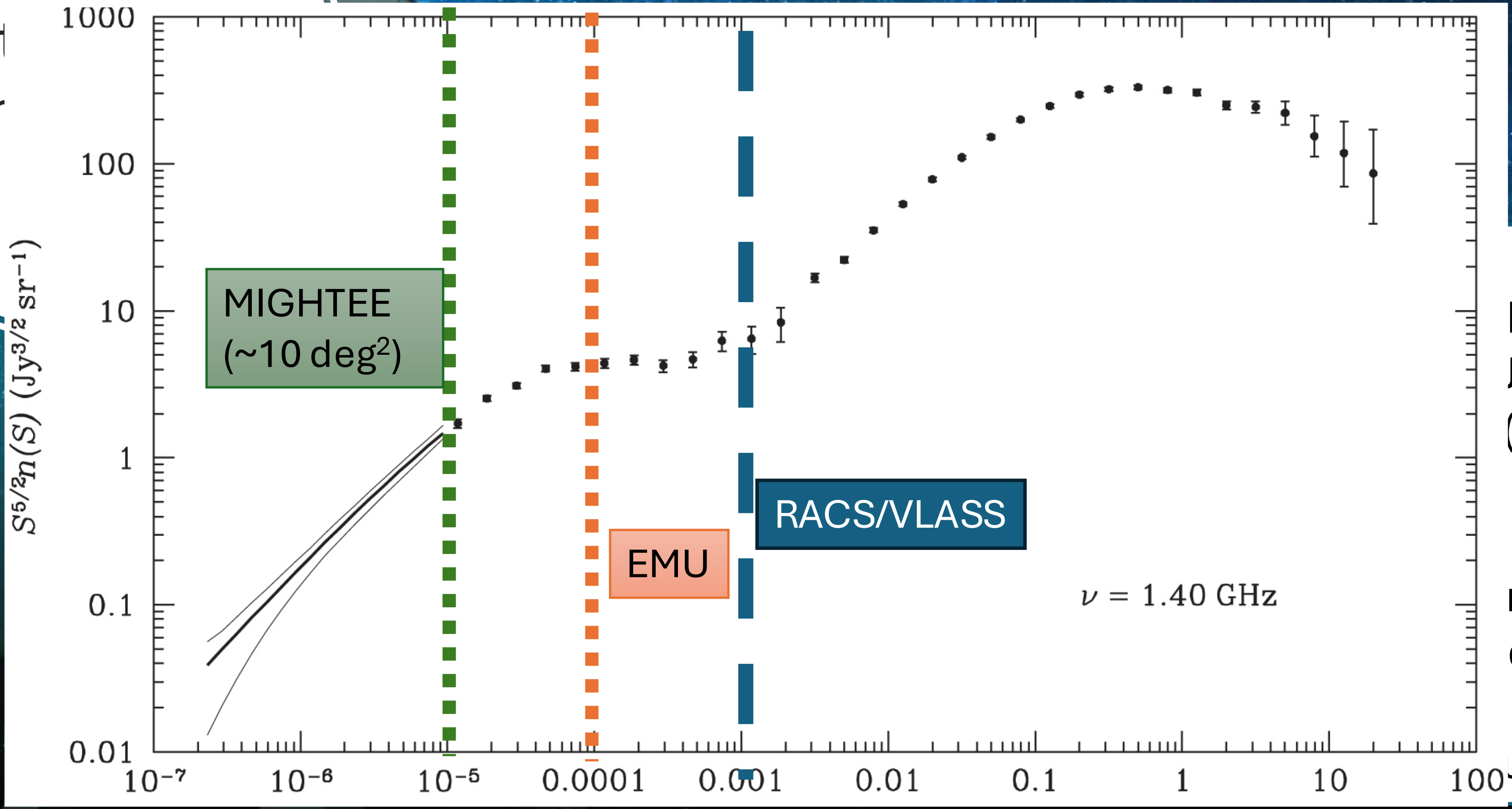

Look products)
Jy/beam.
(3 bands), 15”

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The future

- SKA-mid – weak lensing, deep HI surveys.
- ngVLA – high resolution, reference frame, “real time” cosmology.
- Background experiments/cross-correlations: HERA, SKA-low, GBT 310MHz, lunar telescopes?
- DSA-2000 – time domain, HI and continuum cosmology on wide fields.
- Radio stars and exoplanet environments (SKA-low)

Useful links

- VLASS: science.nrao.edu/vlass : 3GHz, 2.5 arcsec resolution, all sky Dec > -40°.
- RACS & EMU: research.csiro.au/racs/, http://emu-survey.org : 1GHz, 15 arcsec resolution, all sky Dec < +40 °.
- LOTSS: www.lofar-surveys.org/surveys.html 150MHz, 6 arcsec resolution, northern sky.
- TGSS: https://tgssadr.strw.leidenuniv.nl/doku.php?id=start : 150 MHz, all sky Dec > -53 °, 25 arcsec resolution.
- GLEAM: www.mwatelescope.org/science/galactic-science/gleam/ : southern sky, ~150 MHz, 100 arcsec resolution
- **Cutout server: cutouts.cirada.ca**

MeerKAT