Radio sky surveys – why, how, where?

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NRAO/Socorro

NRAO/GBO Summer Lecture Series – 15 June 2022

Background: GASS Survey (Parkes/ATNF; S. Janowiecki)

Talk overview

PART I – more technical

Some definitions, survey purpose, survey definition/properties, survey design, a few important concepts and equations

PART II – definitely more practical (for the users)

– online resources

– some radio surveys to know about

– a brief word on data mining

PART I starts now

Some definitions and the lecture focus

1. "All-sky" → for ground based telescopes this often means "all *visible* sky"

   so 3π sr (not 4π)

   "wide field"

   All-sky surveys provide information on all sources detected within observing parameters (sky area, flux density limit, etc.)

2. Frequency/wavelength:

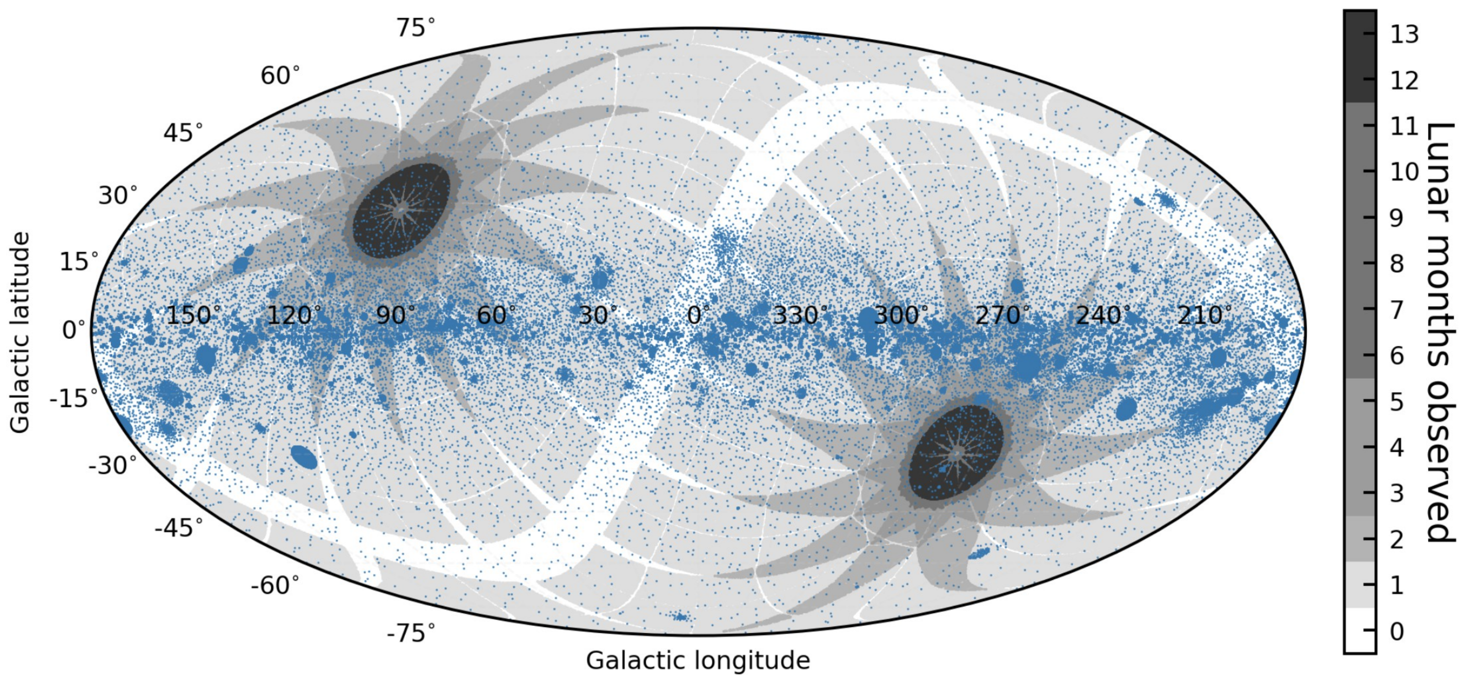
   – in this lecture we are focusing only on radio (though all telescopes, not only NRAO based);

   – the resources I will provide can be used for any survey you may wish to explore or utilise

Survey footprint

A quick note on the coordinate projection format, for reference.

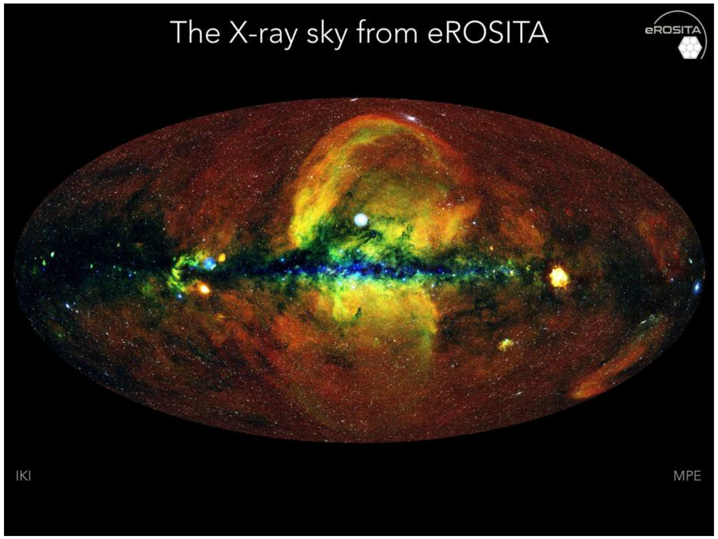
Survey footprint (i.e. coverage area) is often shown as a all-sky Aitoff/Mollweide/HEALPix/... projection in Galactic coordinates, e.g.:



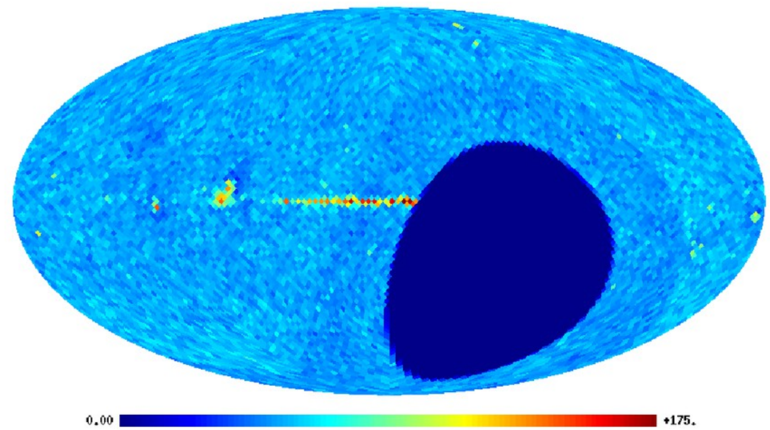
CDIPS target star positions (blue) and nominal TESS observing footprint (gray). Target stars are either candidate members of clusters, or else have other youth indicators. Most will be observed for one or two lunar months during the TESS Prime Mission.

Survey footprint – examples

1. Truly all sky (space based)

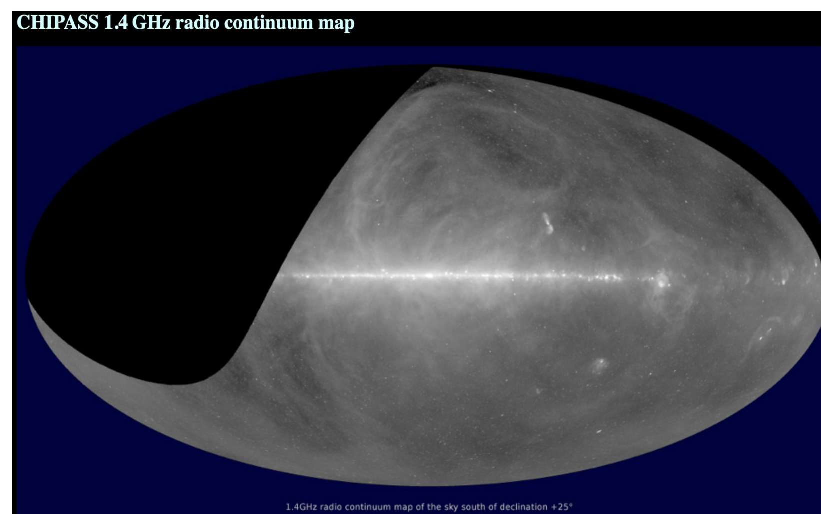


2. Ground based, northern hemisphere



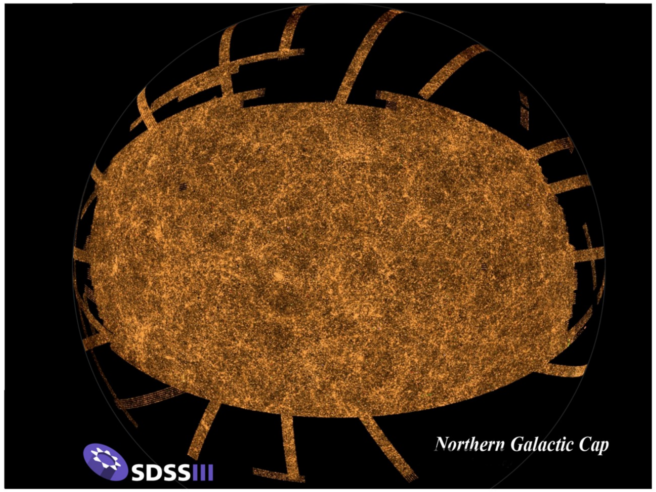
Surface density of NVSS catalogues radio sources

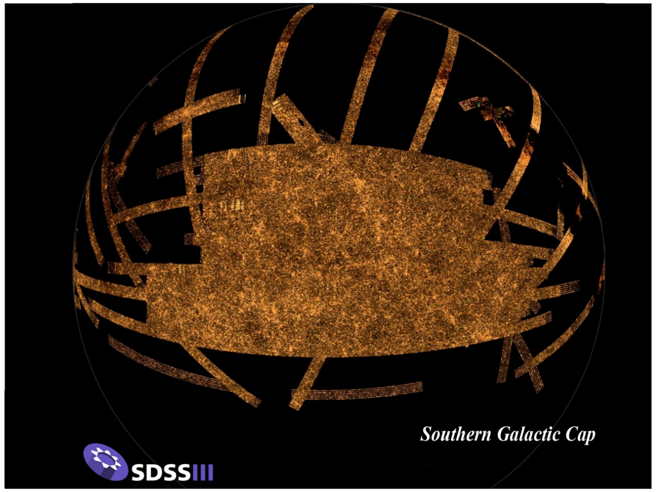
3. Ground based, southern hemisphere



Survey footprint – examples

4. An orange spider coverage...





Survey footprint – examples

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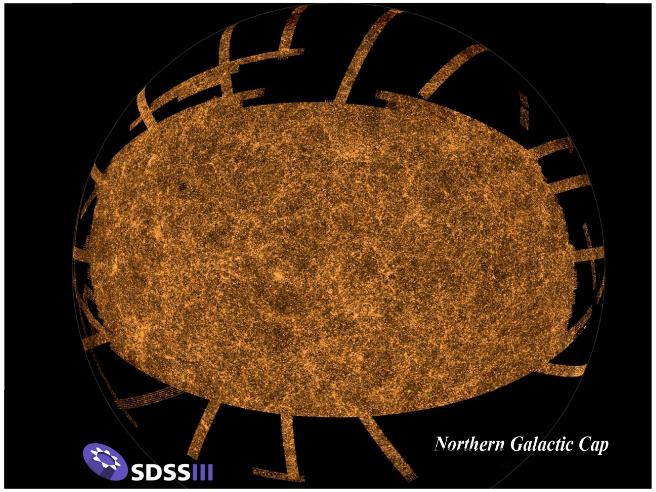
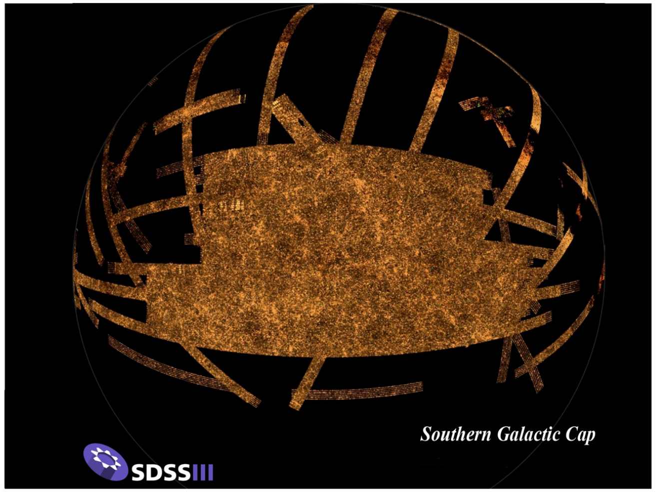
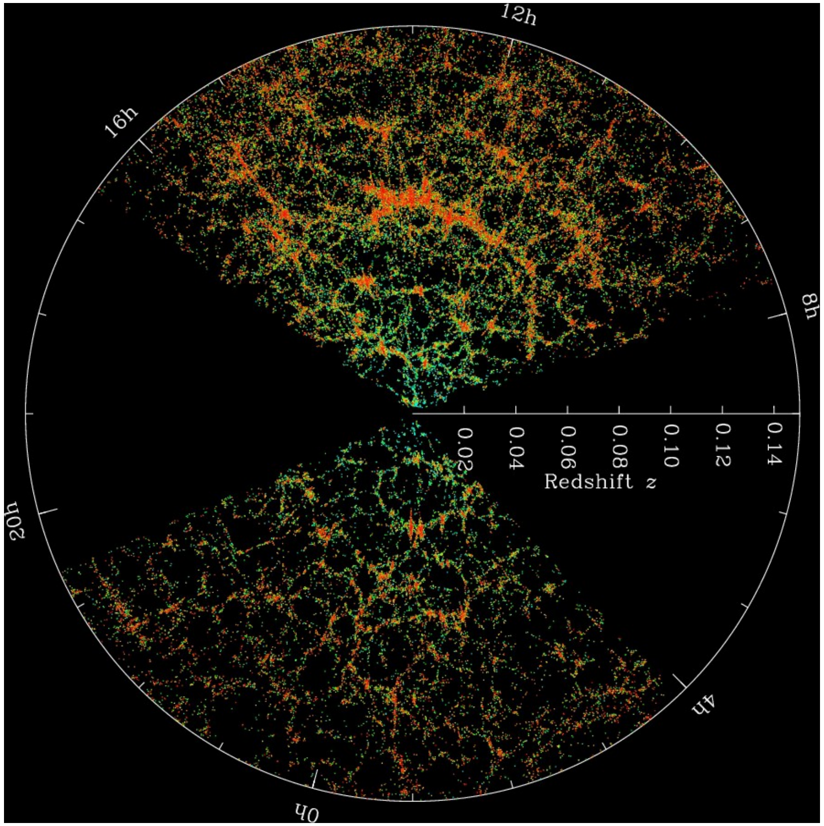


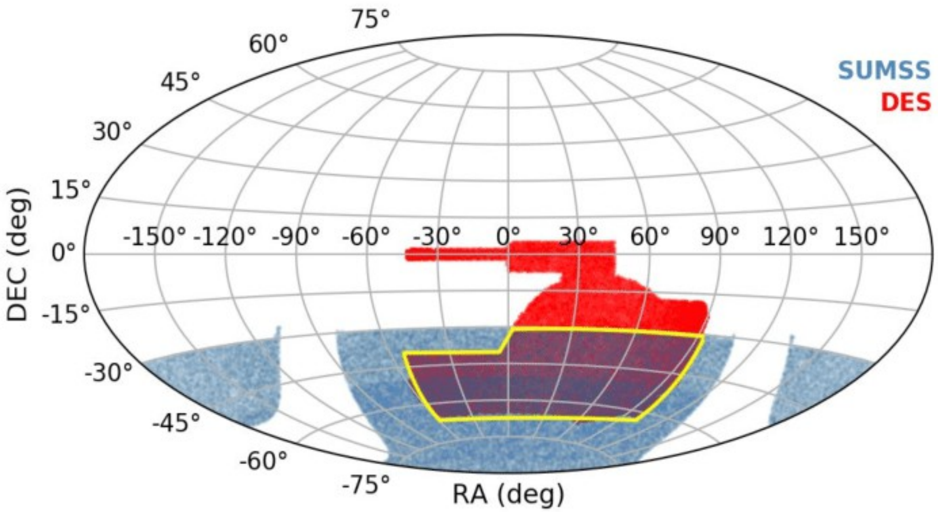


… and an orange pie view

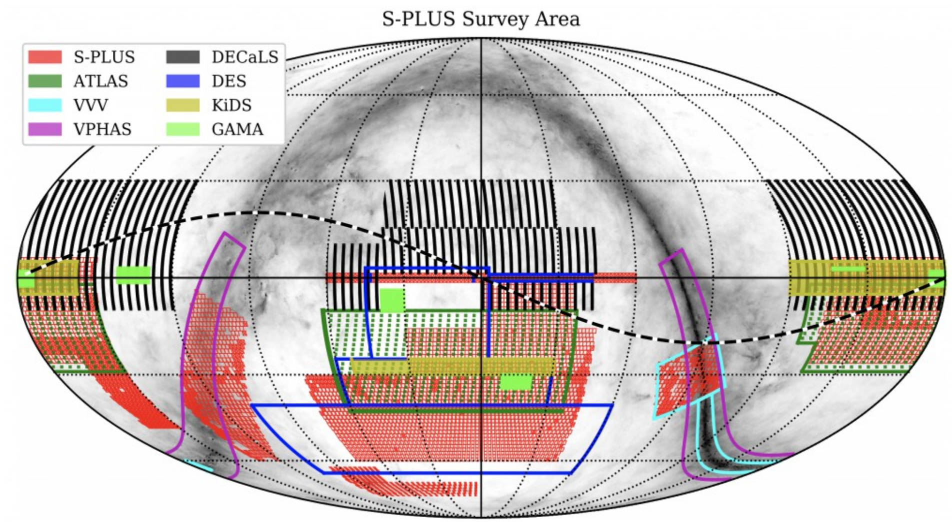


Survey footprint – examples

5. Smaller area footprints (and in equatorial coordinate system)



Credit: Belladitta+ 2019



Credit: S-PLUS surveys team

Building a sky survey: Why & how?

1. Why do you want to create a sky survey?

→ sky surveys are expensive:
  · need years of telescope time, computing power, and manpower
  · not uncommon for a survey to take 1–2 *decades* from the design stage to the final product

→ **LEGACY**: really made for greater good, surveys are rich databases created for the overall astronomical community, enabling science to be done and allowing for unexpected discoveries

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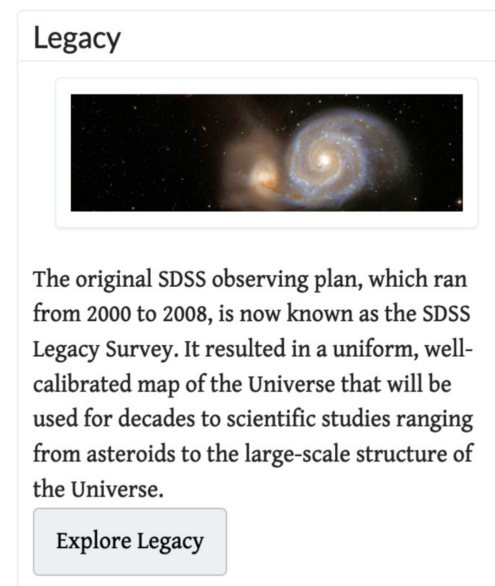
- Usefulness? Let's look at the citation metric. If your publication gets 20 citations, you are doing great (peer attention secured). If your publication gets 100 citations, that's a seminal paper. And surveys? NVSS (1998): 4,595 citations; 87GB (1991): 551 cit. FIRST (1995): 2,288 cit.; WISE (2010): 5,102 cit.

→



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→ sometimes may be driven by a team's specific scientific interest/s (these are usually smaller area or targeted surveys, with all-sky *blind* surveys often being led nowadays an observatory or telescope team, but not always)

Building a sky survey: Why & how?

1. Why do you want to create a sky survey?

→ usefulness of sky surveys from the user point of view

i) can do science more efficiently and faster (not being stalled by years of proposing and observing!)

- Say you have 20 galaxies observed with GBT or VLA and want to know their redshifts or see other radio observations → cross-checking legacy surveys will take you 15 minutes and you potentially may have all the information for you to get on with your project!

- Targeted source population studies can be based on the existing legacy surveys instead of spending years of making your own one (e.g. you don't need to observe said 20 galaxies, or even 200, or 2000, you may target the databases instead)

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ii) you do not need to be expert in every single wavelength to make use of the multi-wavelength data (but yes you need to be able to Interpret it correctly and know biases and limitations!)

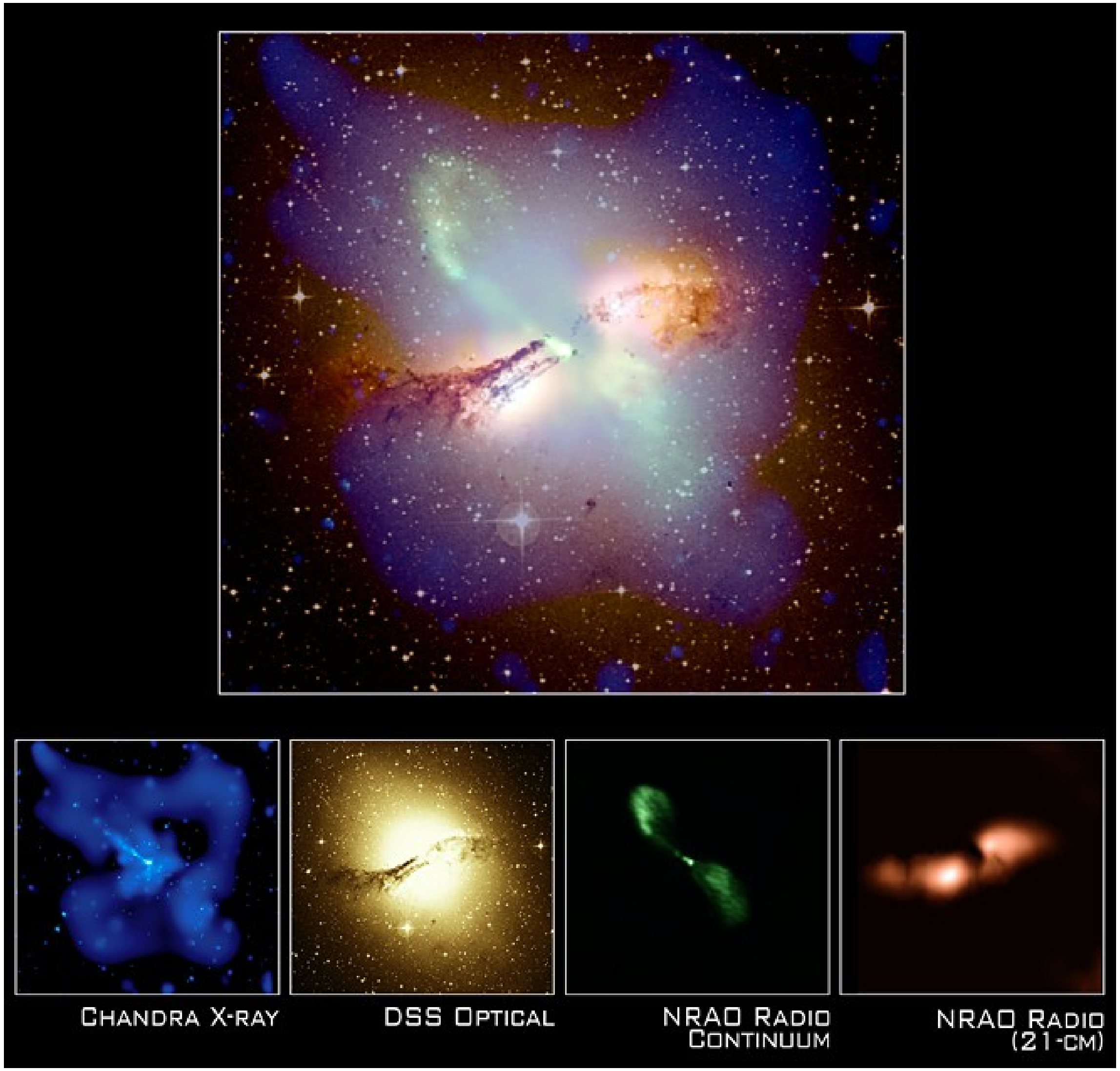
→ Centaurus A multi-wavelength imaging (next slide)

Building a sky survey: Why & how?

1. Why do you want to create a sky survey?

→ usefulness of sky surveys
from the user point of view

EXAMPLE: Centaurus A
multi-wavelength imaging



Building a sky survey: Why & how?

Not everything that shines and sparkles is gold; things good to know

2. Survey definition

- Frequency & telescope
- Radio continuum/polarisation/HI/spectral lines?
- Sky area
- Resolution (angular/temporal/spectral)
- Sensitivity (point source sensitivity, surface brightness sensitivity)

Building a sky survey: Why & how?

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Large radio surveys

Survey	Frequency, MHz	Sky coverage	Area, deg^2	Resolution, arcsec	Sensitivity, (5σ)		Sources per deg^2
					K	mJy beam^{-1}	
WENSS	325	$\delta > +30°$	10,300	54×54 cosec $\lvert\delta\rvert$	60	15	21
SUMSS	843	$\delta < -30°$	10,300	43×43 cosec $\lvert\delta\rvert$	4.7	5	37
FIRST	1,400	NGP	>5,000	5	25	1	90
NVSS	1,400	$\delta > -40°$	33,900	45	0.8	2.5	54

Open in a separate window

NGP, north galactic pole.

From: Condon 1999

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Table 1. Summary of RACS parameters with those of other comparable surveys. The tabulated data allow comparison with RACS; for detailed information consult the reference papers mentioned in Section 1.

Survey	Frequency (MHz)	Bandwidth (MHz)	Resolution (arcsec)	Sky coverage (deg^2)	Sensitivity (mJy $beam^{-1}$)	Polarization	$N_{sources}$ ($\times10^6$)
VLSSr	73.8	3.12	75	30 793	100	*I*	0.93
GLEAM	87, 118, 154, 185, 215	30.72	120	27 691	6–10	*I, Q, U, V*	0.33
TGSS	150	16.7	25	36 900	2–5	*I*	0.62
RACS [a]	887.5 1 295.5 1 655.5	288	15	36 656	∼0.25	*I, Q, U, V*	4
RACS [b]	887.5	288	15–25	34 240	0.2–0.4	*I*	2.8
SUMSS +MGPS-2	843	3	45	10 300	1.5	RC	0.2
NVSS	1 346, 1 435	42	45	33 800	0.45	*I, Q, U*	2
VLASS	3 000	2 000	2.5	33 885	0.07	*I, Q, U*	5.3

[a] RACS full survey capability.
[b] RACS first data release.

From:
McConnell+ 2020

Building a sky survey: Why & how?

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- Number of sources detected
- Measurement uncertainty
- Reliability
- Completeness

Building a sky survey: Why & how?

2. Survey definition

Table 4. Survey properties and statistics. We divide the survey into four Dec ranges, as shown in Fig. 6, because the noise properties, and astrometric and flux calibration, differ slightly for each range. Values are given as the mean±the standard deviation. The statistics shown are derived from the wide-band (200 MHz) image. The flux scale error applies to all frequencies, and shows the degree to which GLEAM agrees with other published surveys. The internal flux scale error also applies to all frequencies, and shows the internal consistency of the flux scale within GLEAM.

Property	Dec $< -83\overset{\circ}{.}5$	$-83\overset{\circ}{.}5 \leq$ Dec $< -72°$	$-72° \leq$ Dec $< +18\overset{\circ}{.}5$	Dec $\geq 18\overset{\circ}{.}5$
Number of sources	920	8780	281 931	16 170
RA astrometric offset (arcsec)	-4 ± 16	-4 ± 16	-0.2 ± 3.3	0.5 ± 2.5
Dec astrometric offset (arcsec)	0.1 ± 3.6	-0.1 ± 3.6	-1.6 ± 3.3	1.7 ± 2.7
External flux scale error (per cent)	80	13	8	13
Internal flux scale error (per cent)	3	3	2	3
Completeness at 50 mJy (per cent)	10	22	54	3
Completeness at 100 mJy (per cent)	81	83	87	30
Completeness at 160 mJy (per cent)	96	95	95	56
Completeness at 0.5 Jy (per cent)	99	99	99	94
Completeness at 1 Jy (per cent)	100	100	100	97
rms (mJy beam^{-1})	23 ± 7	15 ± 5	10 ± 5	28 ± 18
PSF major axis (arcsec)	196 ± 8	176 ± 8	140 ± 10	192 ± 14
PSF minor axis (arcsec)	157 ± 9	149 ± 8	131 ± 4	135 ± 2

From: Hurley-Walker+ 2017

Building a sky survey: Why & how?

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- More technical considerations:
    - telescope mode (pointed observations vs drift scan vs OTF)
    - “sky tiling”

Building a sky survey: Why & how?

2. Survey definition

Telescope mode & sky tiling solutions

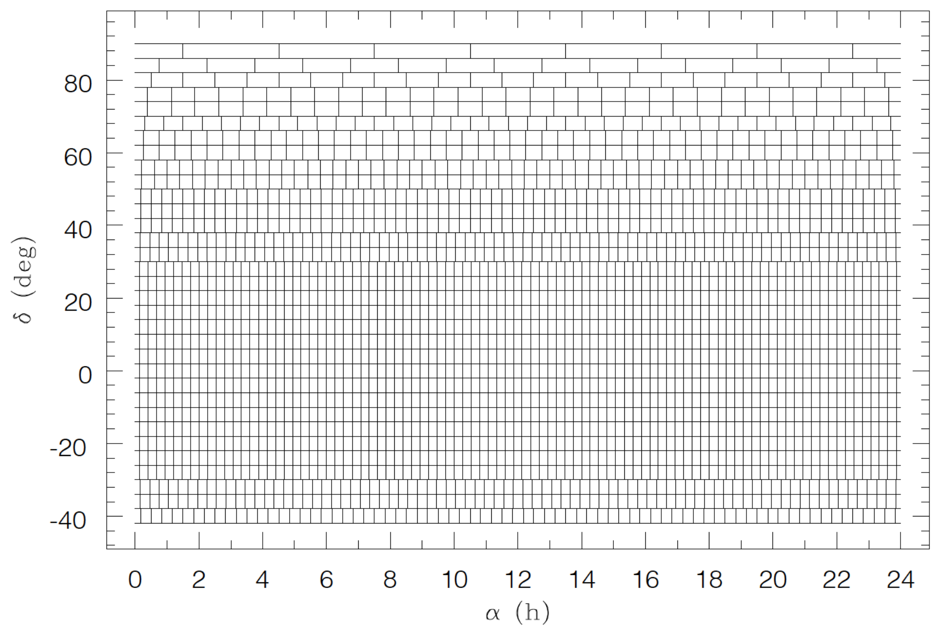


FIG. 25.—Boundaries of the 2326 4° × 4° NVSS sky images. *Abscissa*, J2000.0 right ascension (hours); *ordinate*, J2000.0 declination (degrees).

NVSS: Condon+1998

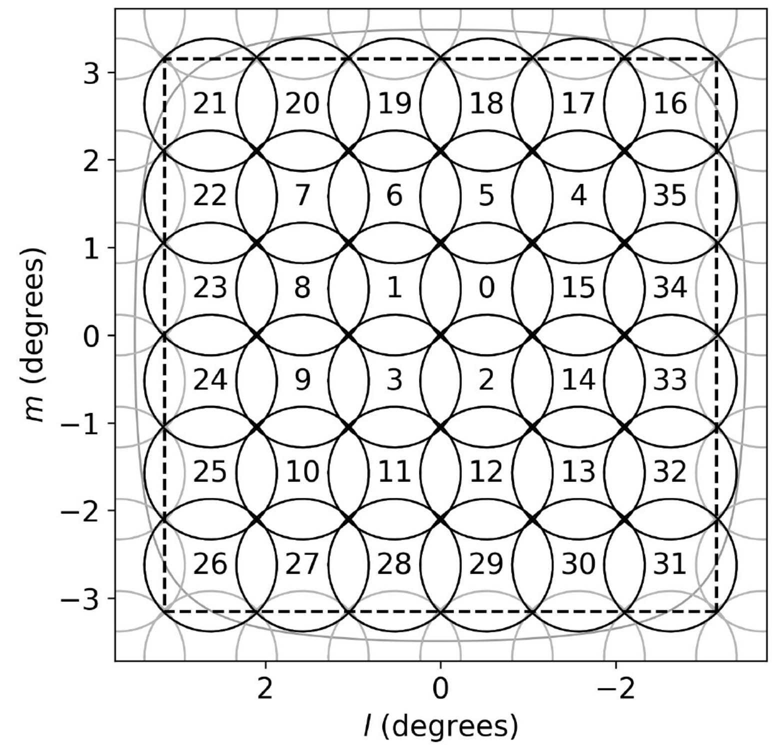


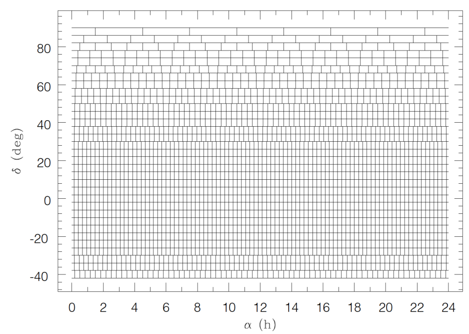
Figure 2. ASKAP field-of-view (l, m) using the `square_6x6` beam footprint. The positions of the 36 beams (numbered 0–35) are shown as idealised circles at their contour of half-power at 1031 MHz.

RACS: McConnell+2020

Building a sky survey: Why & how?

2. Survey definition

Telescope mode & sky tiling solutions



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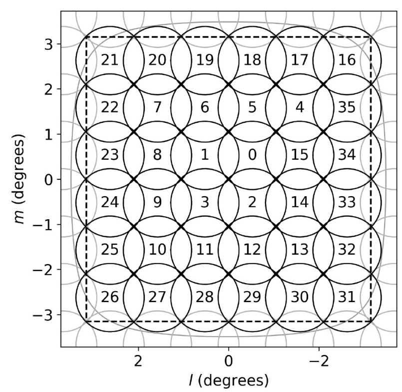
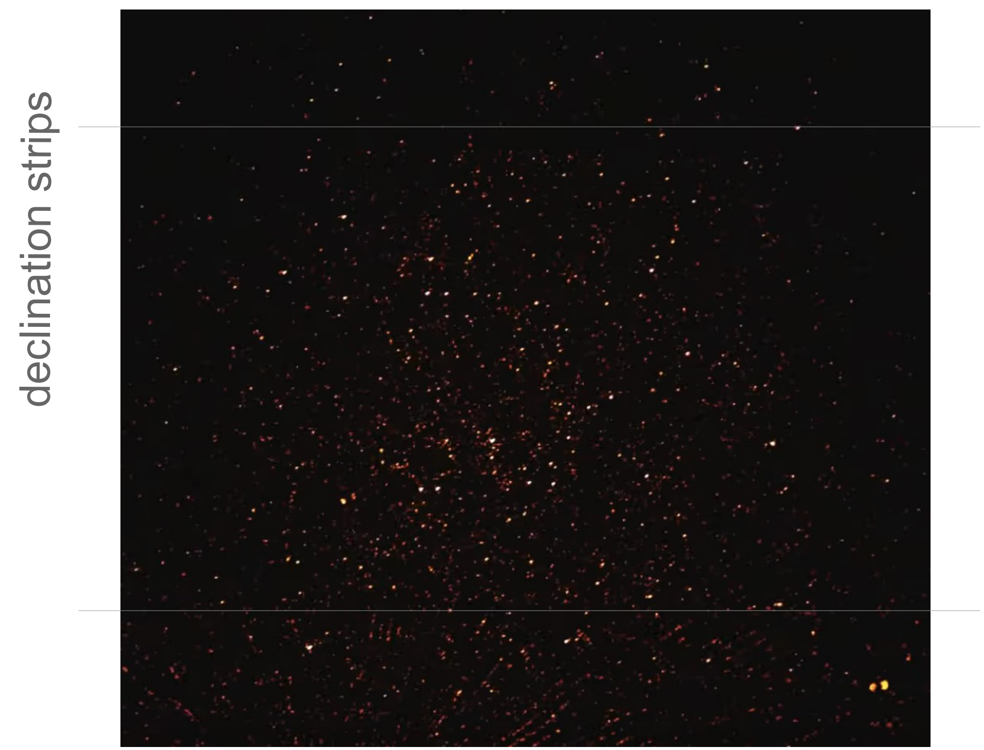


Figure 2. ASKAP field-of-view (l, m) using the `square_6x6` beam footprint. The positions of the 36 beams (numbered 0–35) are shown as idealised circles at their contour of half-power at 1031 MHz. In practice the total-intensity beams are close to

Example: MWA drift scan video



https://www.youtube.com/watch?v=-vwf-zuE-eM

Building a sky survey: Why & how?

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Building a sky survey: Why & how?

Angular resolution

→ single dish = generally low resolution, but with total flux density measurements (think: zero baseline!)

→ radio interferometer = low to high to extremely high resolution, but flux density measurements with * (think: resolving out the flux)

Building a sky survey: Why & how?

Theoretically (actually: measure in the image)

Image sensitivity

→ <u>point source sensitivity</u>

- rms/noise level (Jy/bm)

$$S_{rms} = \frac{SEFD}{n_S \left[N(N-1)\, \Delta\nu\, t_{int} \right]^{0.5}} W_k$$

→ <u>surface brightness sensitivity</u> (brightness temperature)

Building a sky survey: Why & how?

Brightness unit:
Jy/beam
Jy/arcsec^2
Jy/sr
or W/(m^2 Hz sr)

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→ <u>surface brightness sensitivity</u> (brightness temperature)
- sensitivity to the resolved sources/diffuse emission (K)
- defined by Rayleigh-Jeans relation

Minimum brightness temperature

$$T_{b,min} = const \frac{\Delta I}{\nu\, \Theta^2} \qquad const = \frac{2 \ln 2\, c^2}{\pi\, k_b}$$

!! Brightness sensitivity becomes worse as the synthesised beam becomes smaller

NVSS paper, Condon+1998; Chapter 9 in “The White Book”, Taylor+1999; Chapter 6 in Thompson+ 2001

Building a sky survey: Why & how?

Brightness unit:
Jy/beam
Jy/arcsec^2
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or W/(m^2 Hz sr)

Image sensitivity

→ point source sensitivity

- rms/noise level (Jy/bm)

$$S_{rms} = \frac{SEFD}{n_S\,[\,N(N-1)\,\Delta\nu\,t_{int}\,]^{0.5}}\,W_k$$

→ surface brightness sensitivity (brightness temperature)

- sensitivity to the resolved sources/diffuse emission (K)
- defined by Rayleigh-Jeans relation

Surface brightness sensitivity

$$\sigma_{b,min} = \frac{\Delta I}{\Theta} = \frac{T_{sys}}{n_S\,(\,\Delta\nu\,t_{int}\,)^{0.5}}$$

!! Brightness sensitivity becomes worse as the synthesised beam becomes smaller

NVSS paper, Condon+1998; Chapter 9 in “The White Book”, Taylor+1999; Chapter 6 in Thompson+ 2001

PART II – for the users

Databases: catalogues & images

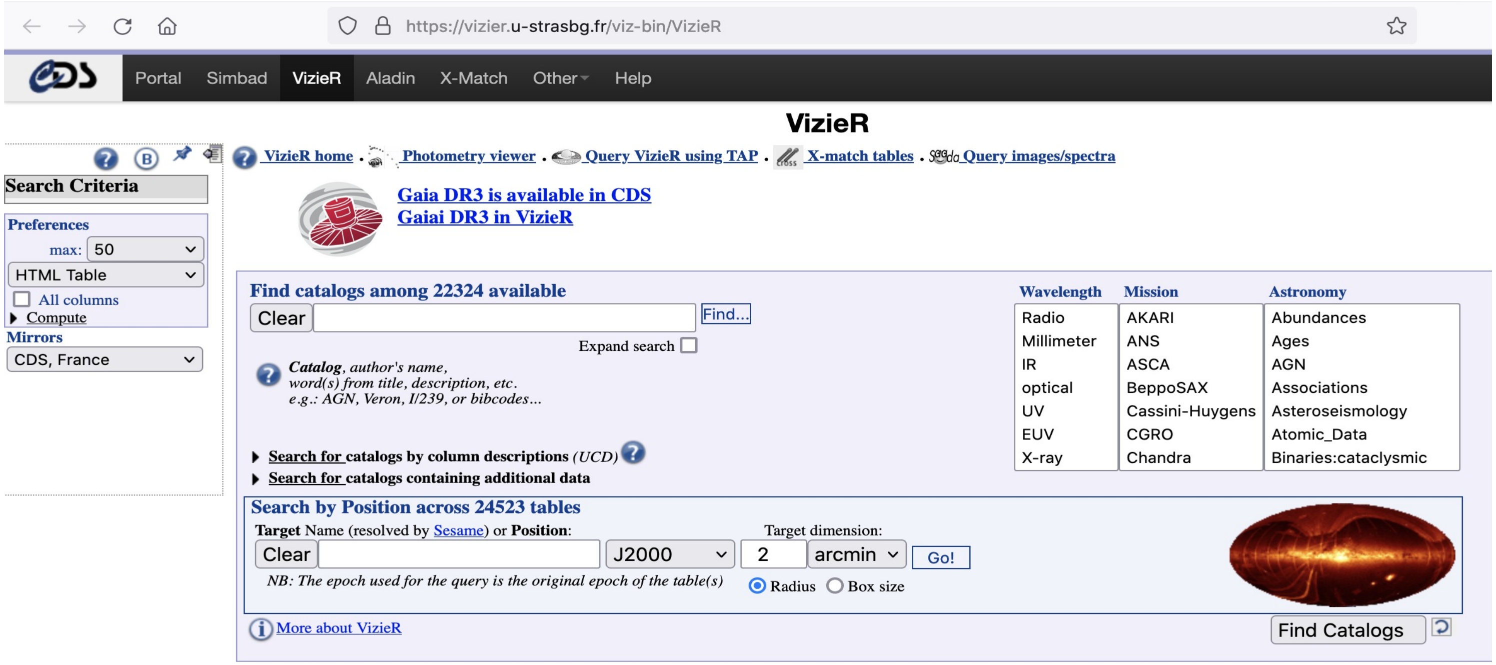
So, where do I find them?

Databases: catalogues & images

So, where do I find them?

1. Vizier catalogue database (virtually everything, minus a handful)

https://vizier.u-strasbg.fr/viz-bin/VizieR



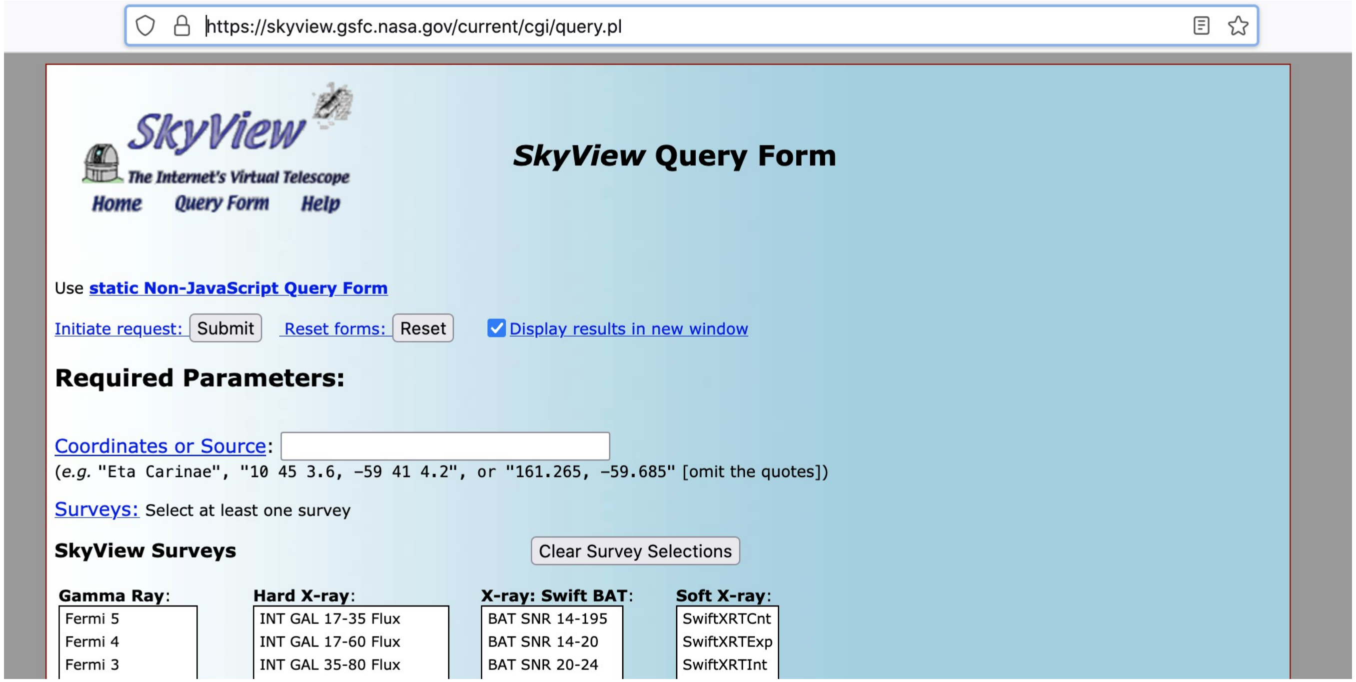
Databases: catalogues & images

So, where do I find them?

2. SkyView – compilation of accessible all-sky survey images

https://skyview.gsfc.nasa.gov/current/cgi/titlepage.pl

Query form: https://skyview.gsfc.nasa.gov/current/cgi/query.pl

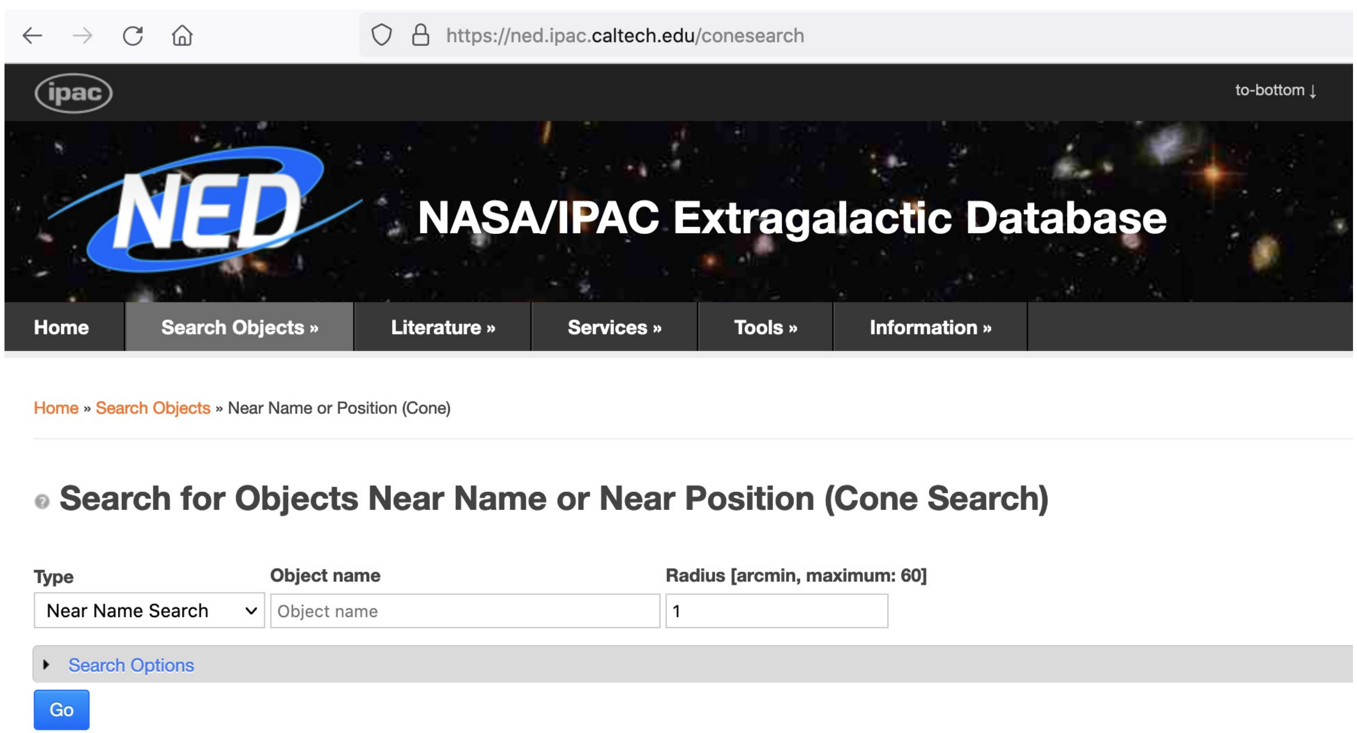


Databases: catalogues & images

So, where do I find them?

3. NED: NASA/IPAC extragalactic database

https://ned.ipac.caltech.edu/



Databases: catalogues & images

So, where do I find them?

Ad. 1. Vizier catalogue database

Ad. 3. NED: NASA/IPAC extragalactic database

A quick note on the positional accuracy/uncertainty of radio sources (extremely important when cross-matching with other catalogues of any wavelength)

Radio <u>point-source</u> positional uncertainty in each RA and Dec:

$$\sigma_{pos} \approx \frac{\sigma_{rms}\,\Theta_{ang}}{2\,S_p}$$

For more, check out the excellent discussion in Condon+1998 (yes, the NVSS paper)

Databases: catalogues & images

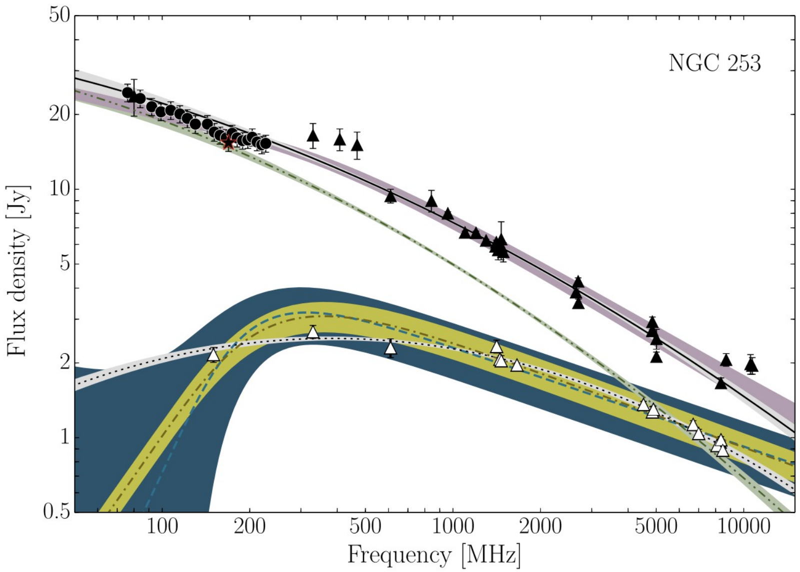
So, where do I find them?

Ad. 1. Vizier catalogue database

Ad. 3. NED: NASA/IPAC extragalactic database

A second quick note on the *absolute flux density scale* (extremely important for creating and modelling radio spectral energy distribution plots)

→ Baars 1977
→ Scaife+Heald 2012
→ Perley+Butler 2013,2017

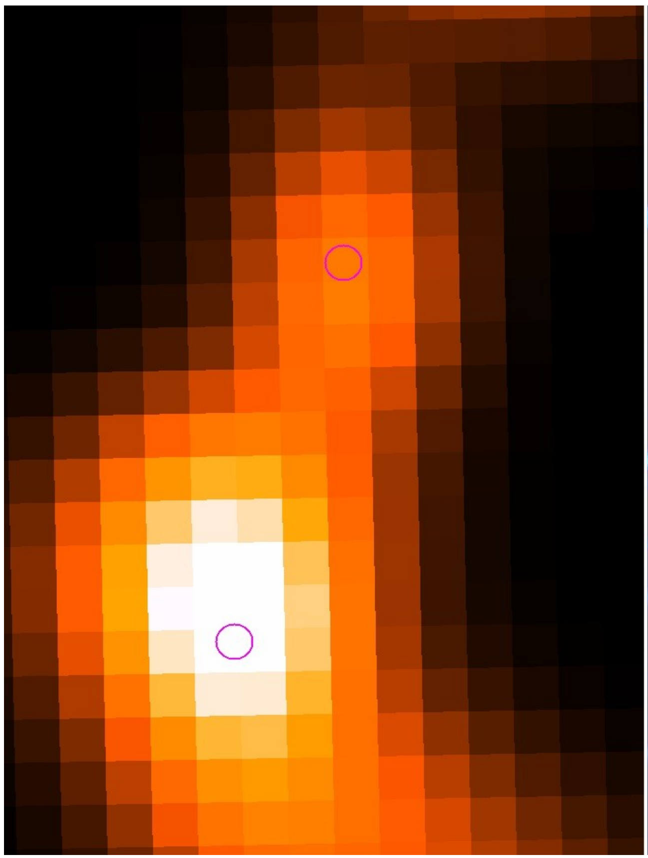


Some radio all-sky surveys to know about

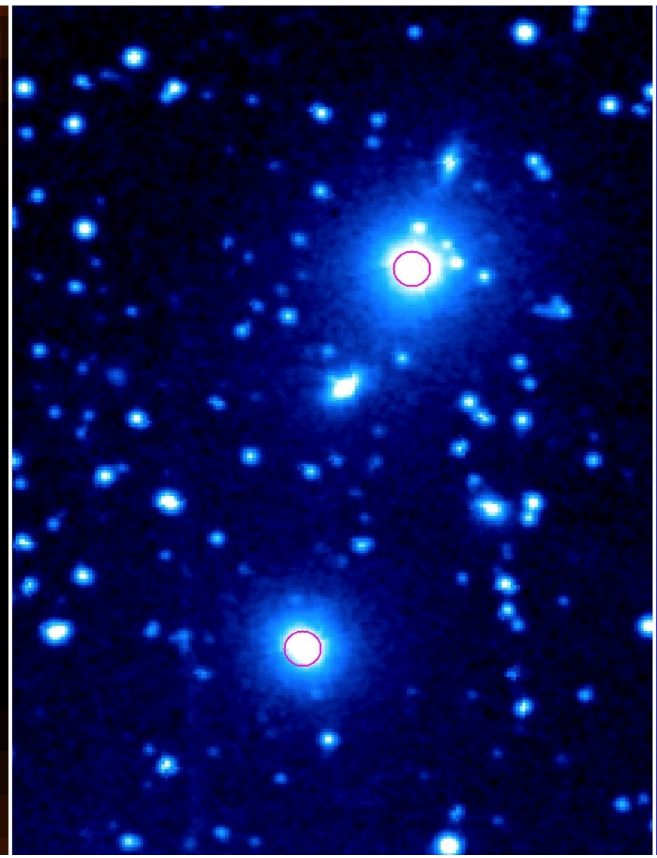
NVSS:
NRAO VLA Sky Survey
1.4 GHz, 45” resolution
0.45 mJy/bm rms

FIRST:
Faint Images of Radio Sky at Twenty centimeters
1.4 GHz, 5.4” resolution
0.15 mJy/bm rms

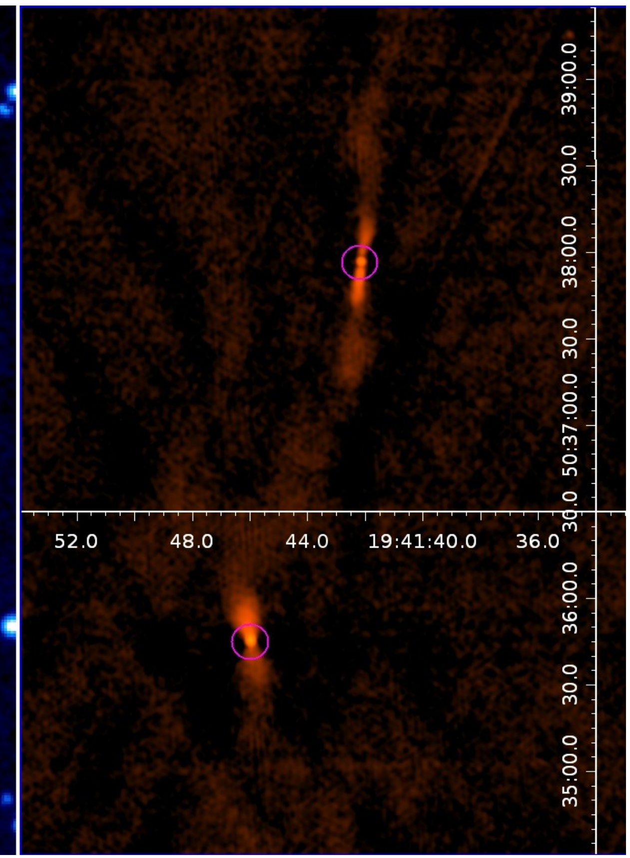
VLASS:
VLA Sky Survey
3 GHz, 2.5” resolution
0.15 mJy/bm rms



Condon+1998



Becker+1995

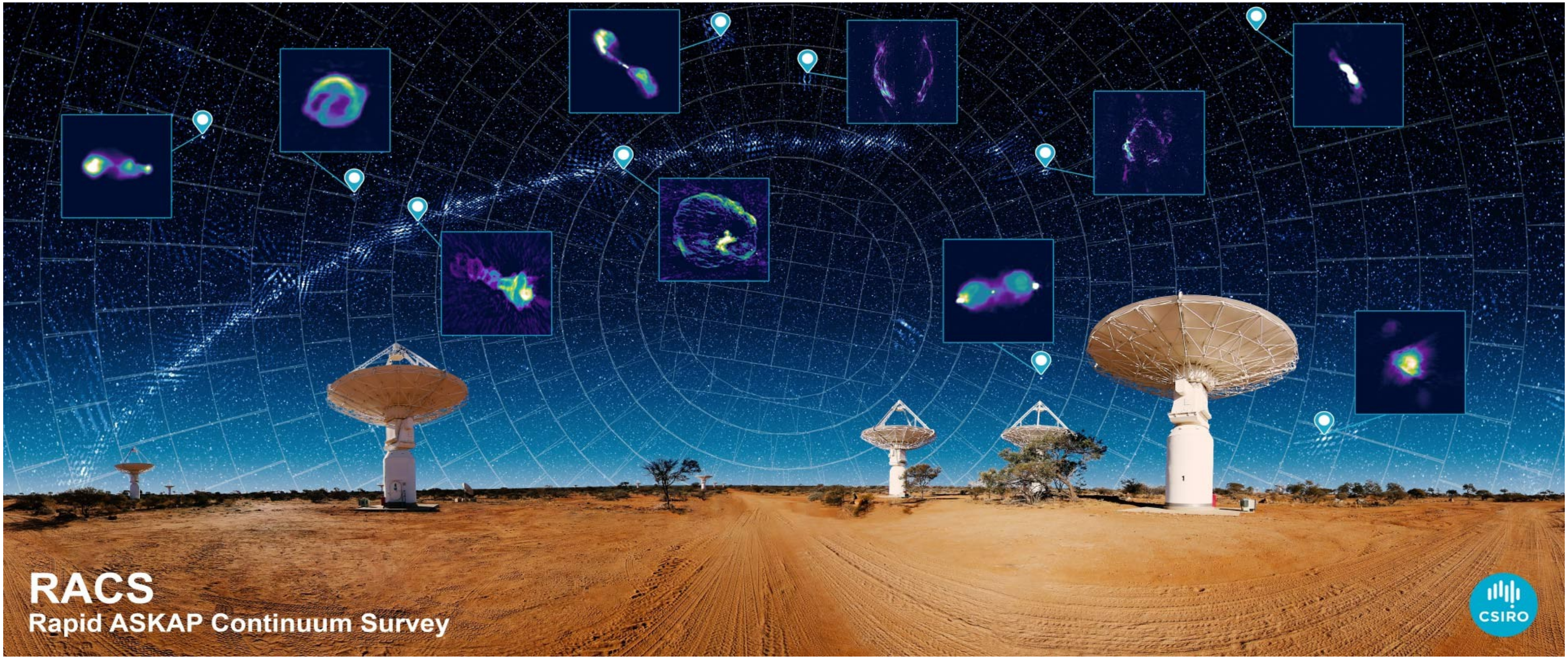


ongoing

Some radio all-sky surveys to know about

RACS:
Rapid ASKAP Continuum Survey
0.88 GHz, 15” resolution
…… mJy/bm rms

Southern,
survey telescope



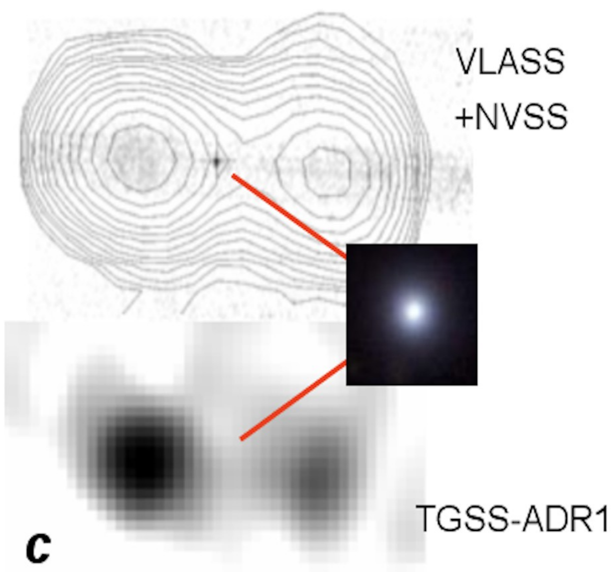
McConnell+2020

Some radio all-sky surveys to know about

Low frequency continuum radio surveys (<1 GHz)

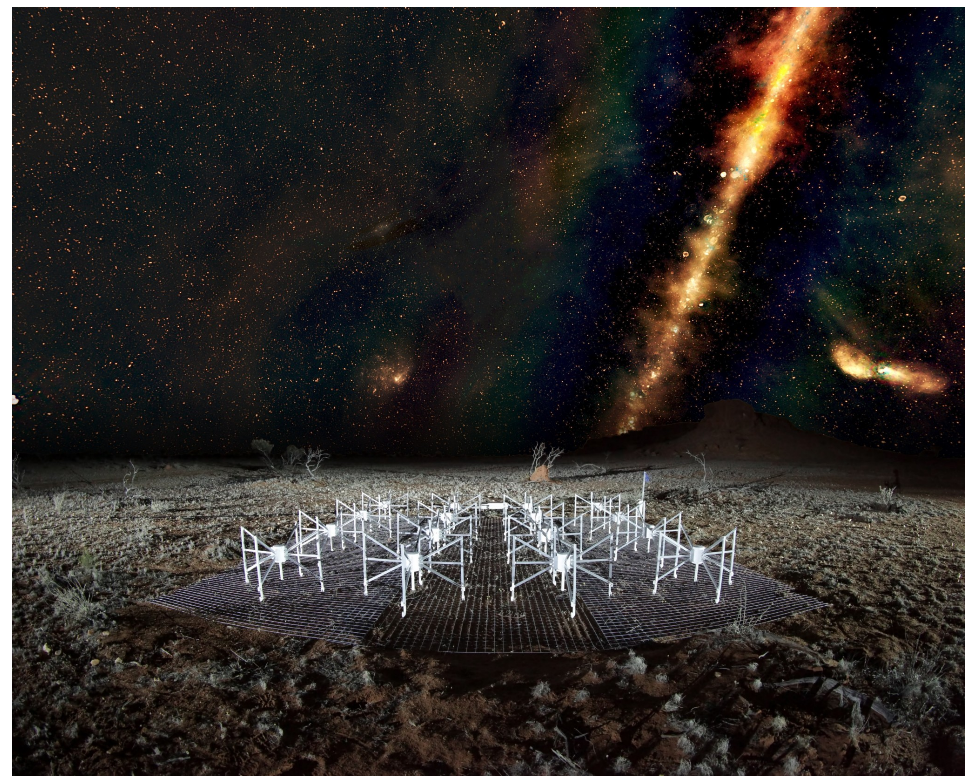
Southern,
survey telescope

TGSS:
TIFR GMRT Sky Survey
150 MHz, ~25” resolution
5 mJy/bm rms



From Villarreal Hernandez+Andernach 2018

GLEAM:
GaLactic and Extragalactic All-sky MWA survey
70–230 MHz, 2–5' resolution
~10 mJy/bm rms



TGSS: Intema+2017

GLEAM: Hurley-Walker+ 2017, 2019

Some radio all-sky surveys to know about

Single-dish radio continuum surveys

GB6:
Green Bank 6-cm survey
4.85 GHz, rms 18 mJy/bm

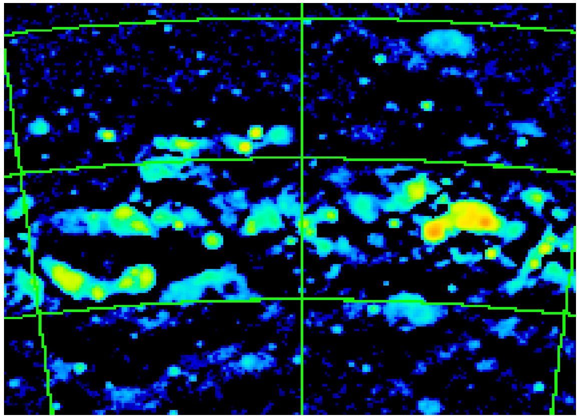
Data obtained in 2nd half of 1980s

Sky coverage:
declinations 0 to +75 deg

Technically almost truly “all-sky”, but had to use three separate radio telescopes!

PMN:
Parkes–MIT–NRAO Surveys
4.85 GHz

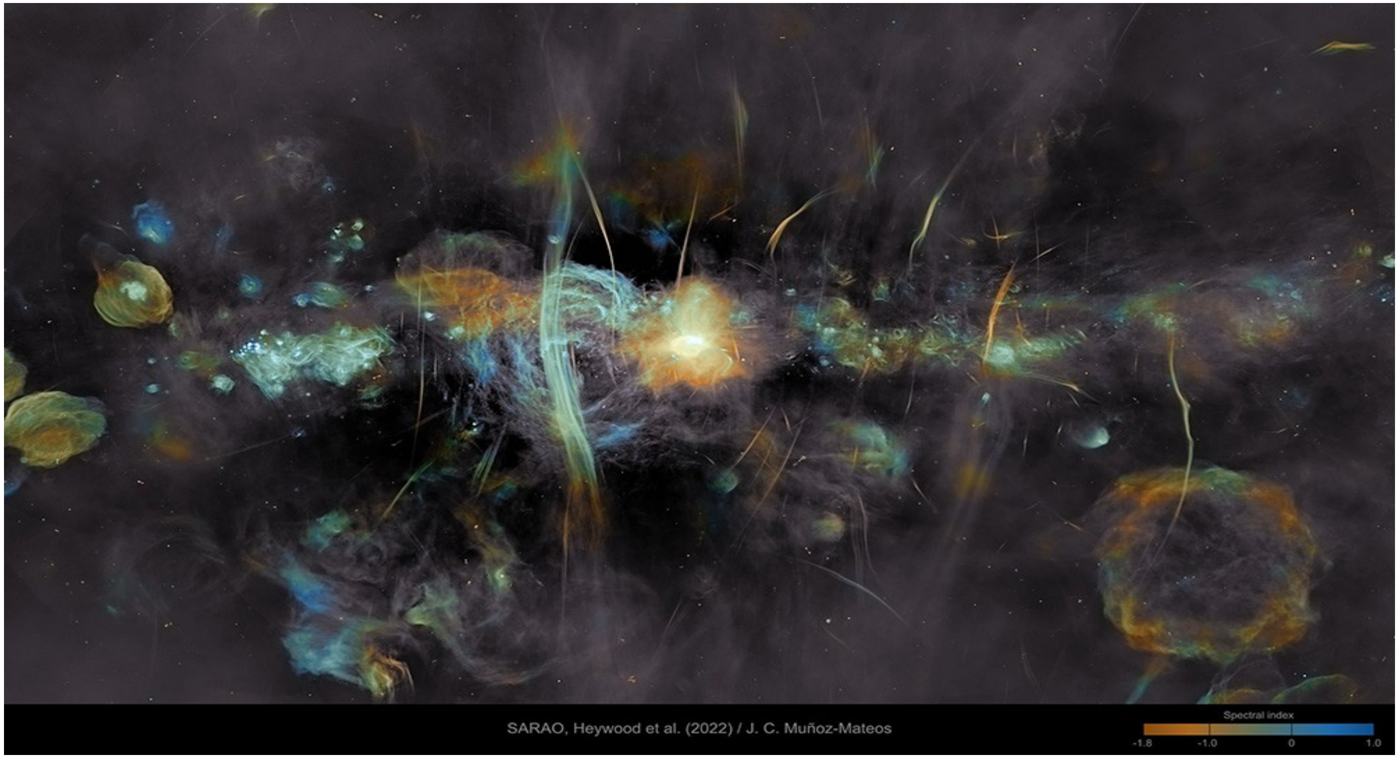
→ the southern equivalent of GB6
→ Parkes 64m Australian dish, and NRAO seven beam receiver used to cover sky between –87 to +10 deg in declination



Gregory+ 1996, Condon+ 1994

Some radio all-sky surveys to know about

Galactic Plane surveys



MeerKAT telescope

Parkes: HIPASS/HIZoA surveys of GP region (radio recombination lines)
GBT: MUSTANG Galactic Plane Survey (MGPS90; early days)
MeerKAT: MeerGAL (oncoming)
ASKAP: a few surveys targeting Galactic Plane, EMU for continuum, POSSUM for polarisation, GASKAP for HI and OH lines (near future)

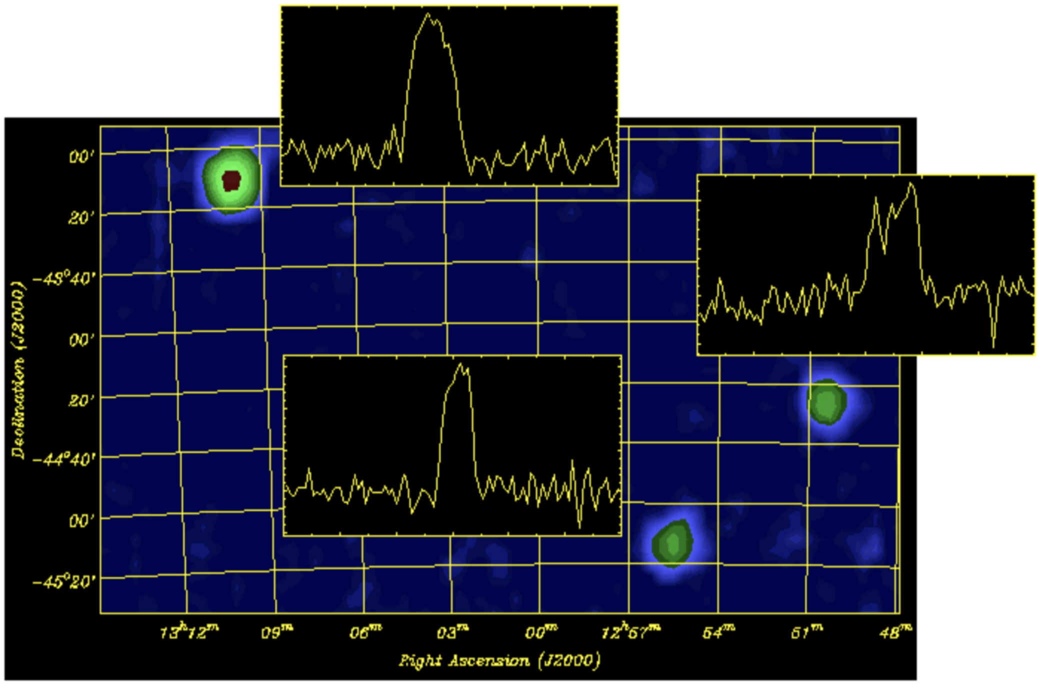
Hydrogen
HI lines

Some radio all-sky surveys to know about

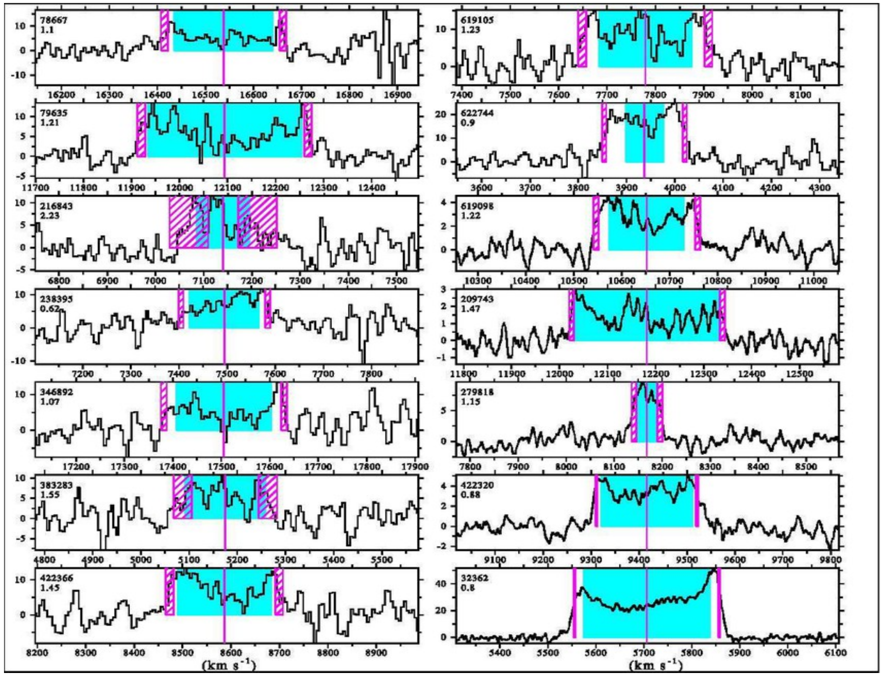
Non-continuum: HI and others

Southern

HIPASS:
HI Parkes All-Sky Survey



ALFALFA:
Arecibo Legacy Fast ALFA survey



ALFALFA HI profiles from Cecil+2015

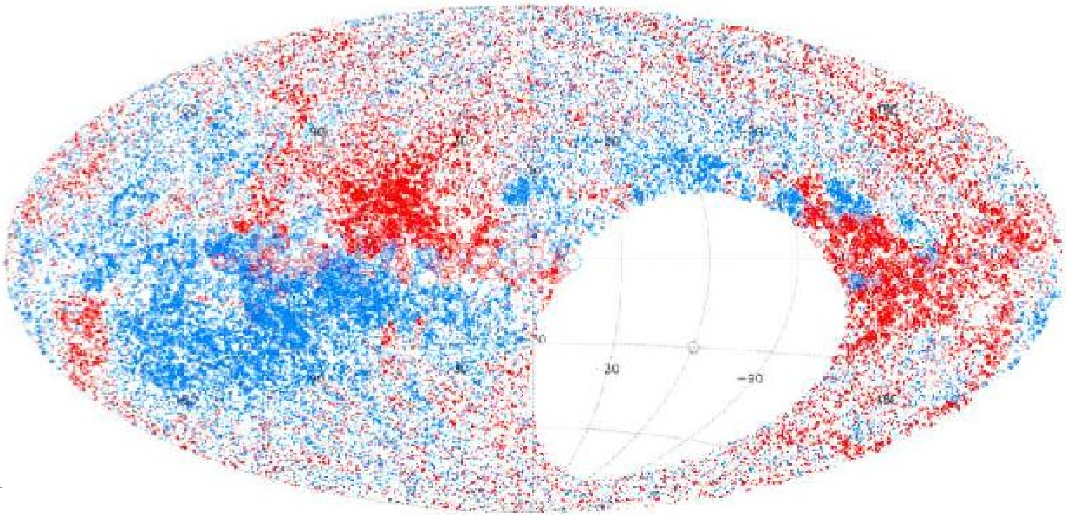
Some radio all-sky surveys to know about

Surveys providing polarisation measurements: Rotation Measures; Q and U Stokes measurements, etc

→ NVSS measured polarisation properties of its catalogues sources, e.g. Rotation Measures (RM) of NVSS radio sources

Red: negative
Blue: positive

From Akahori+ 2016
See also Taylor+ 2009



In the works (keep an eye on these):

– from VLA telescope (3 GHz; part of VLASS)
– from LOFAR telescope (~140MHz; “cosmic magnetism” team)
– from ASKAP telescope (~800–1400 MHz; POSSUM survey)
– *MeerKAT?*

And ngVLA? You'll be building it :)

Something extra:

Big data astronomy & survey mining

Improvements in instrument hardware and software has been allowing for much larger datasets to be produced from radio observations, with truly wide band, wide field capabilities.

Enormous amounts of data are being produced, at it only will get worse (or shall we say better from scientific point of view? :))

We are at about the limit of solely human data mining and classification!

→ citizen science projects for data classification have been great over the past 1.5 decades, but we will need 10x more with oncoming surveys (for radio check out Radio Galaxy Zoo)

→ we NEED machine learning methods to take on bulk of this work

→ but there is still some space for good ol' eyeballing your images...

...ORCs??