Surveying the sky for radio galaxies

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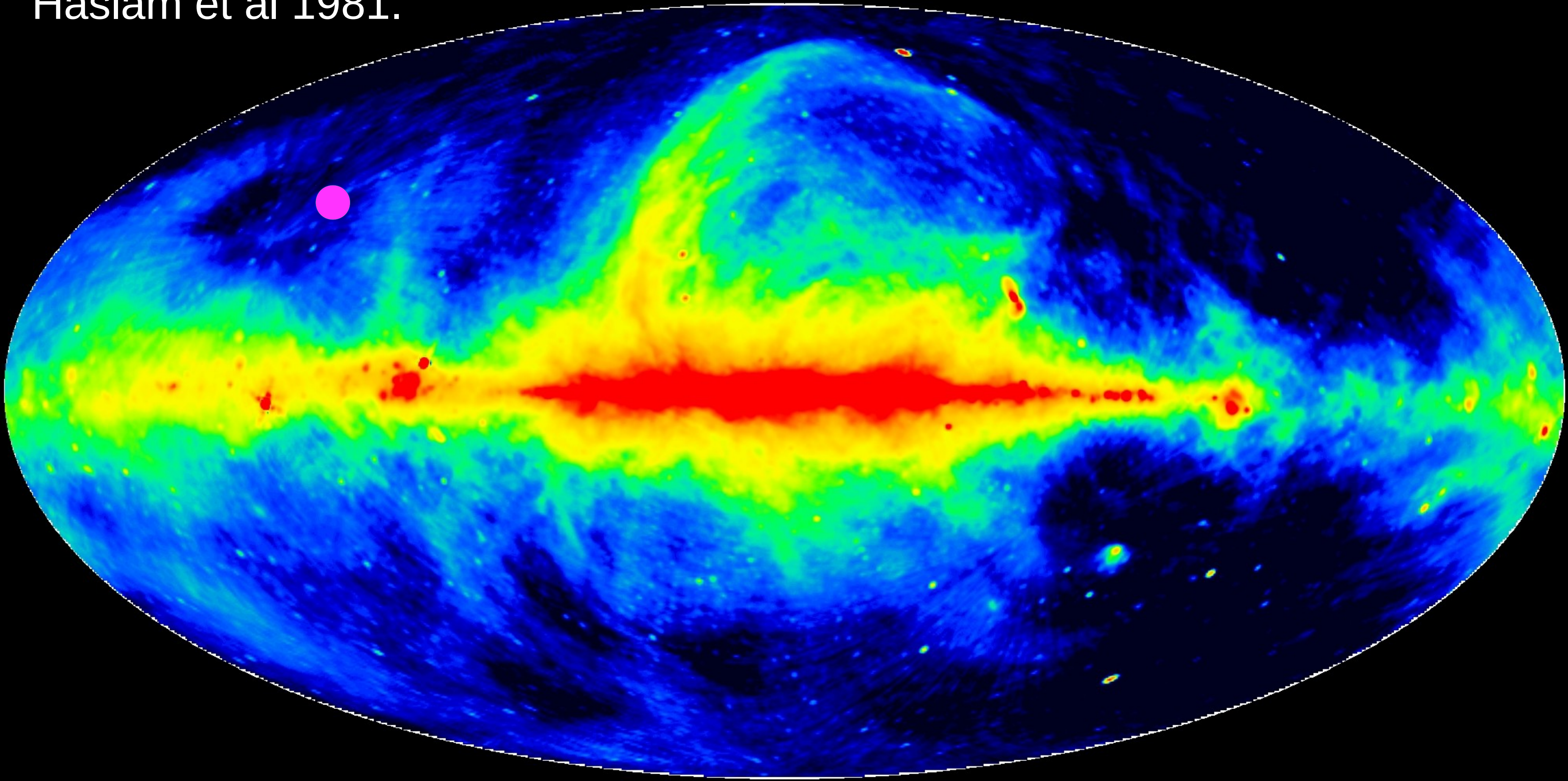
Surveying the radio sky

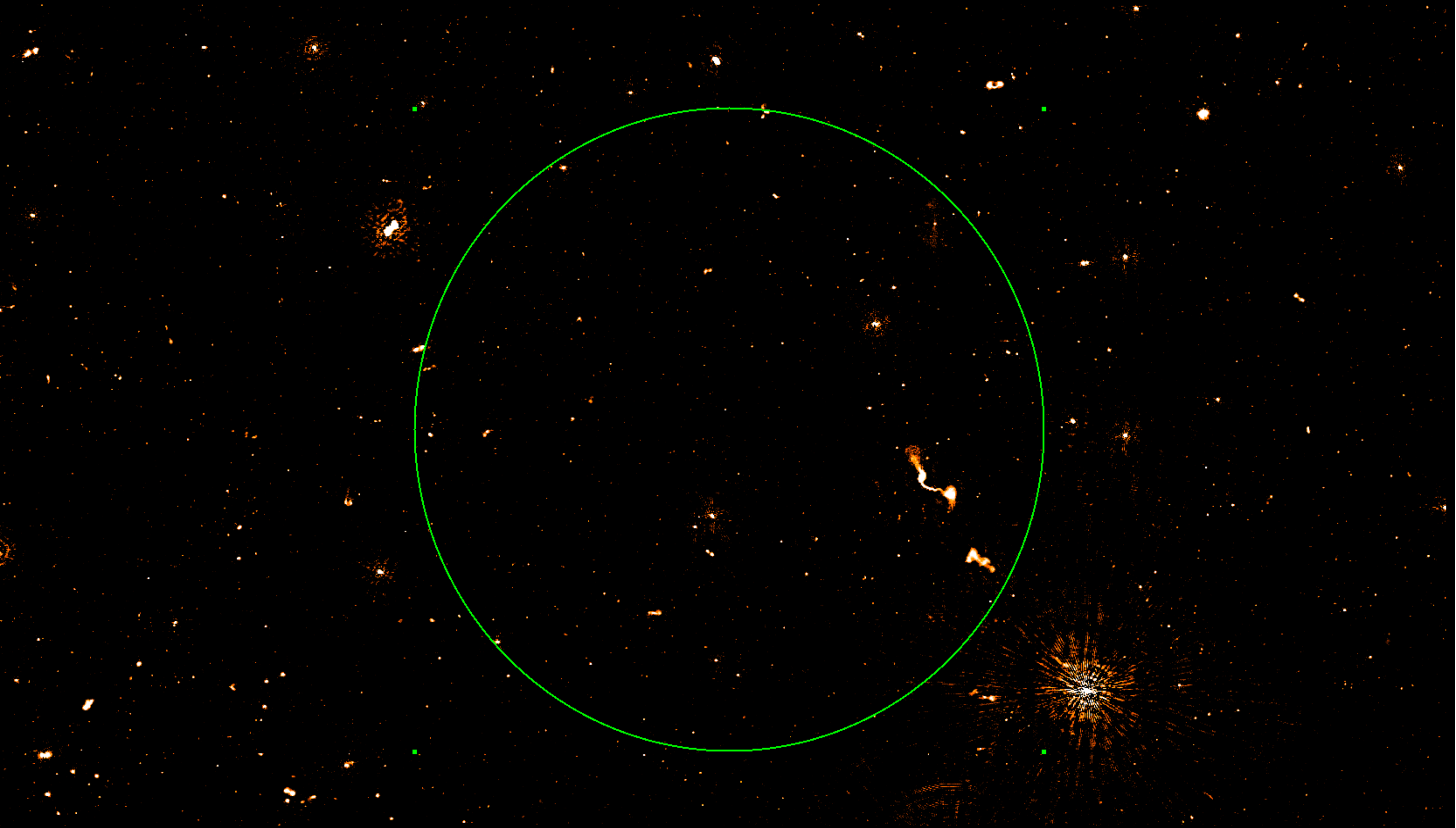
4C array at Lord's Bridge: credit Wikipedia

The first radio surveys

Right: replica of Jansky’s radio telescope used to discover MW radio waves in 1933. Below: 408-MHz survey of the sky in Galactic co-ordinates by Haslam et al 1981.



… to now



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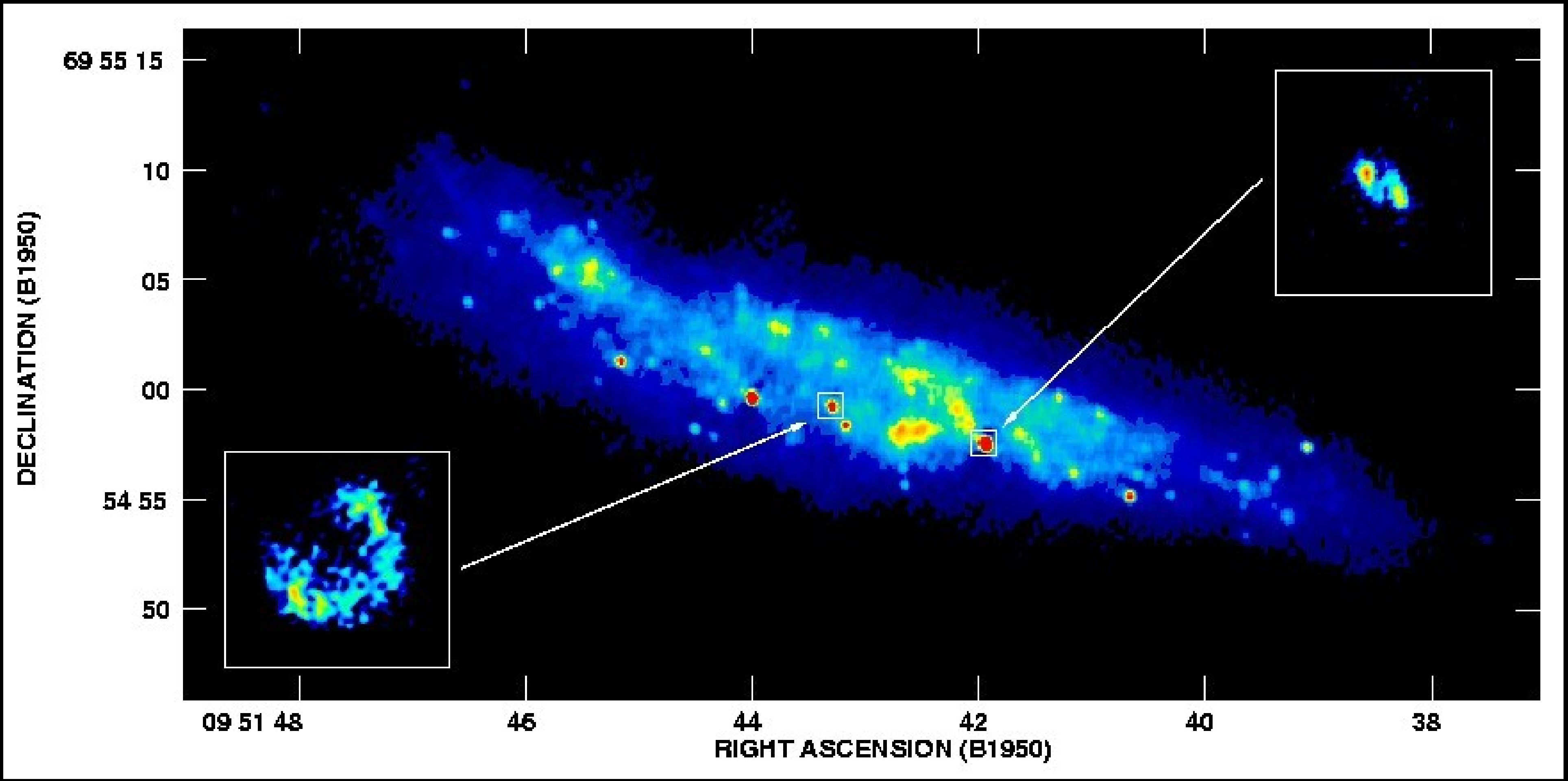
Normal star-forming galaxies

M82 HST

Normal star-forming galaxies



M82 MERLIN+VLA:
Muxlow+

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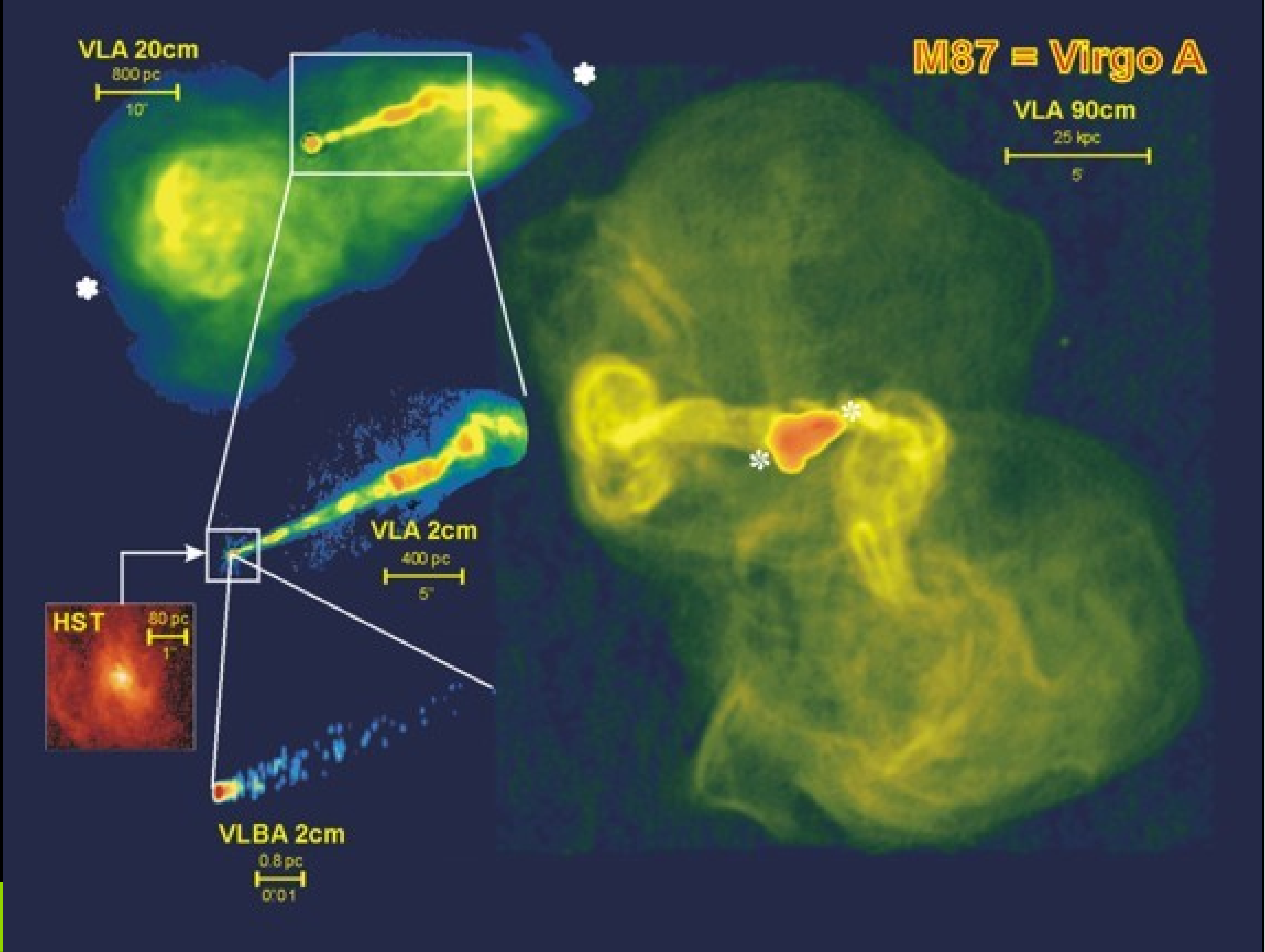
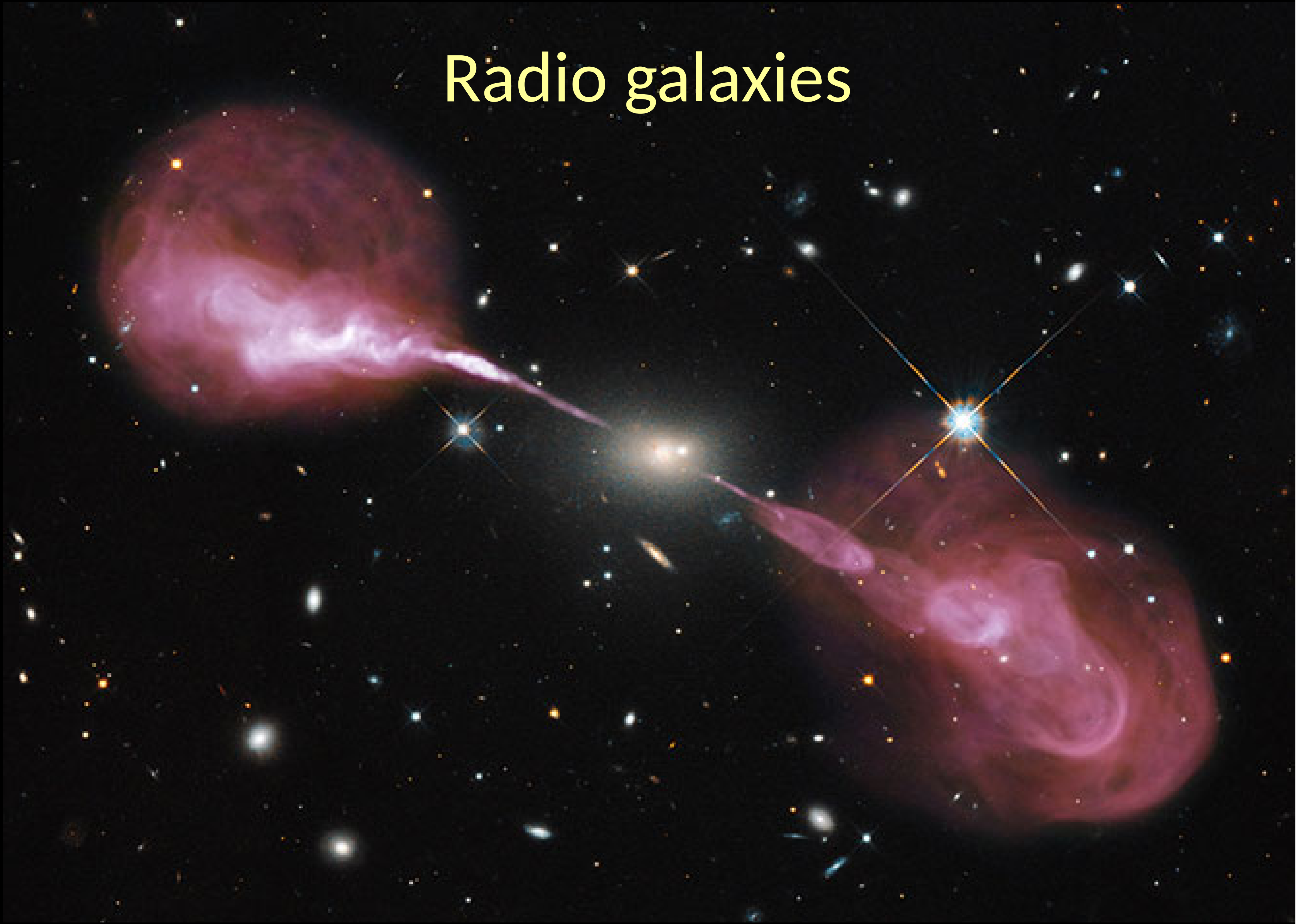
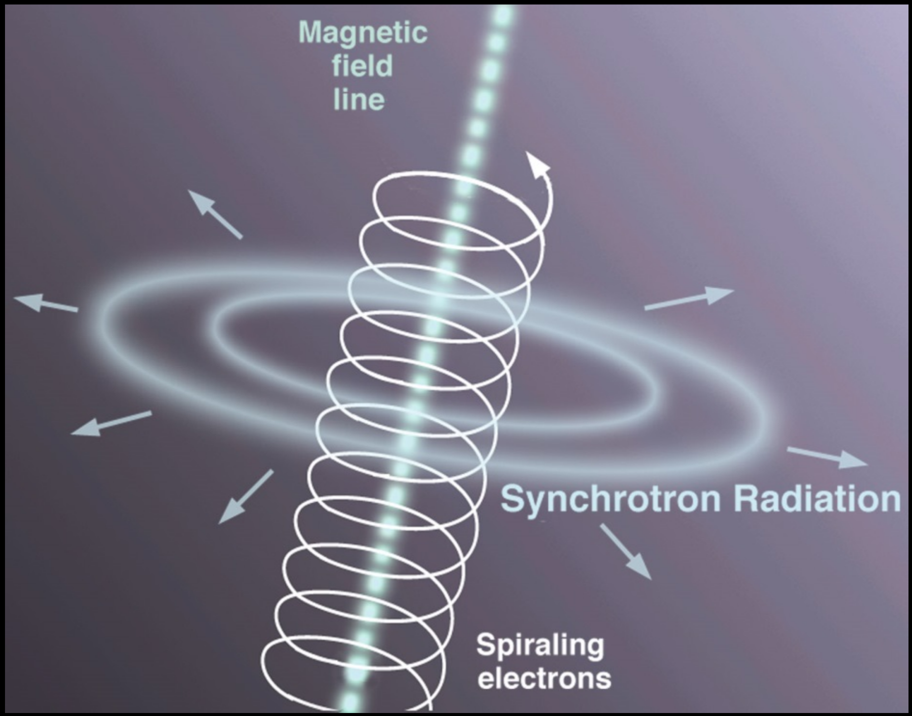
Active galaxies


M87 = Virgo A
VLA 20cm
800 pc
10"
VLA 90cm
25 kpc
5'
VLA 2cm
400 pc
5"
HST
80 pc
1"
VLBA 2cm
0.8 pc
0"01

Radio galaxies

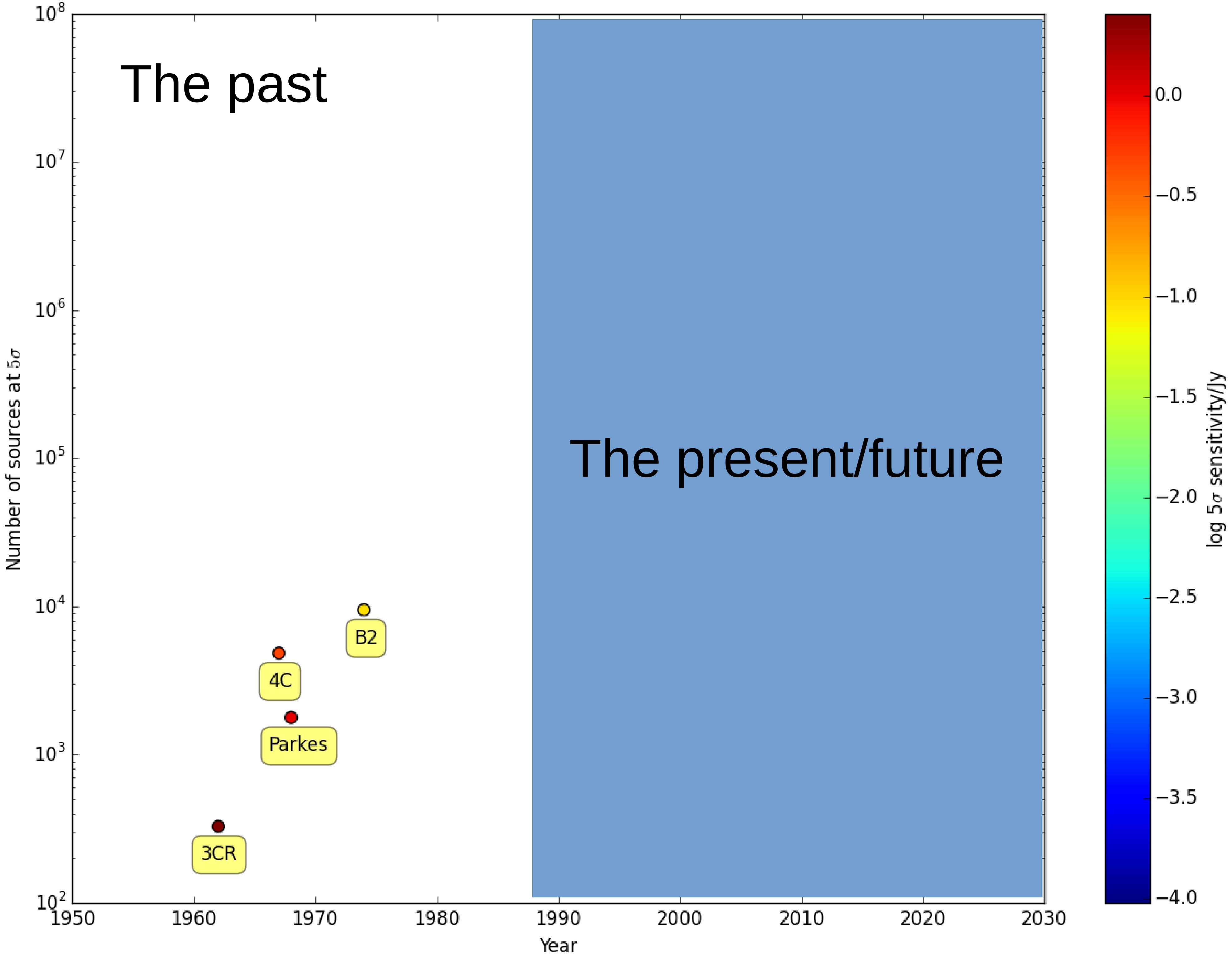


Why radio?


Magnetic
field
line
Synchrotron Radiation
Spiraling
electrons

Back to radio sky surveys

4C array at Lord's Bridge: credit Wikipedia


The past
The present/future
Number of sources at 5σ
Year
log 5σ sensitivity/Jy
3CR
4C
Parkes
B2
1950
1960
1970
1980
1990
2000
2010
2020
2030
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
−3.5
−4.0

Why the gap?

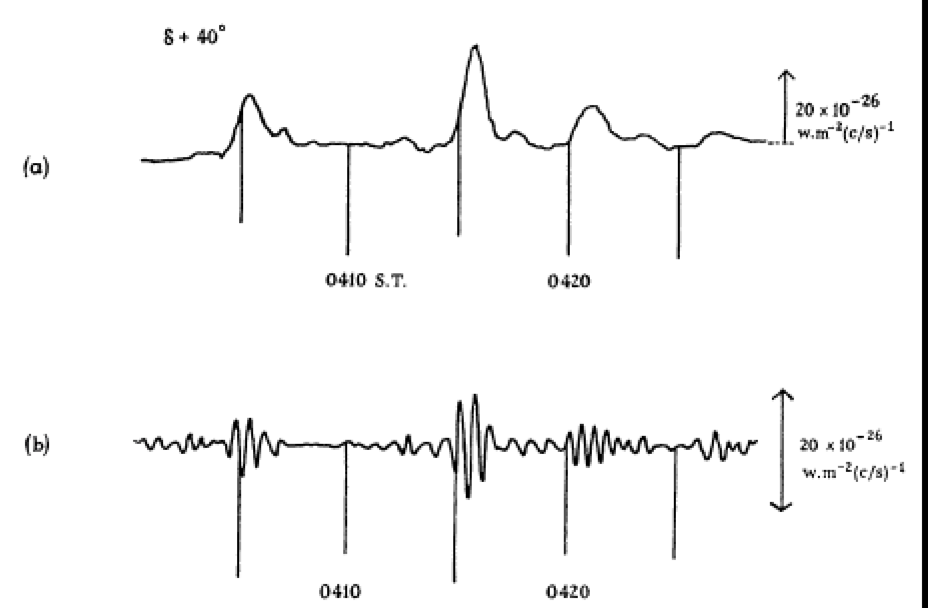


FIG. 4.—*Sections of typical record taken with (a) the total power system and (b) the interferometric system.*

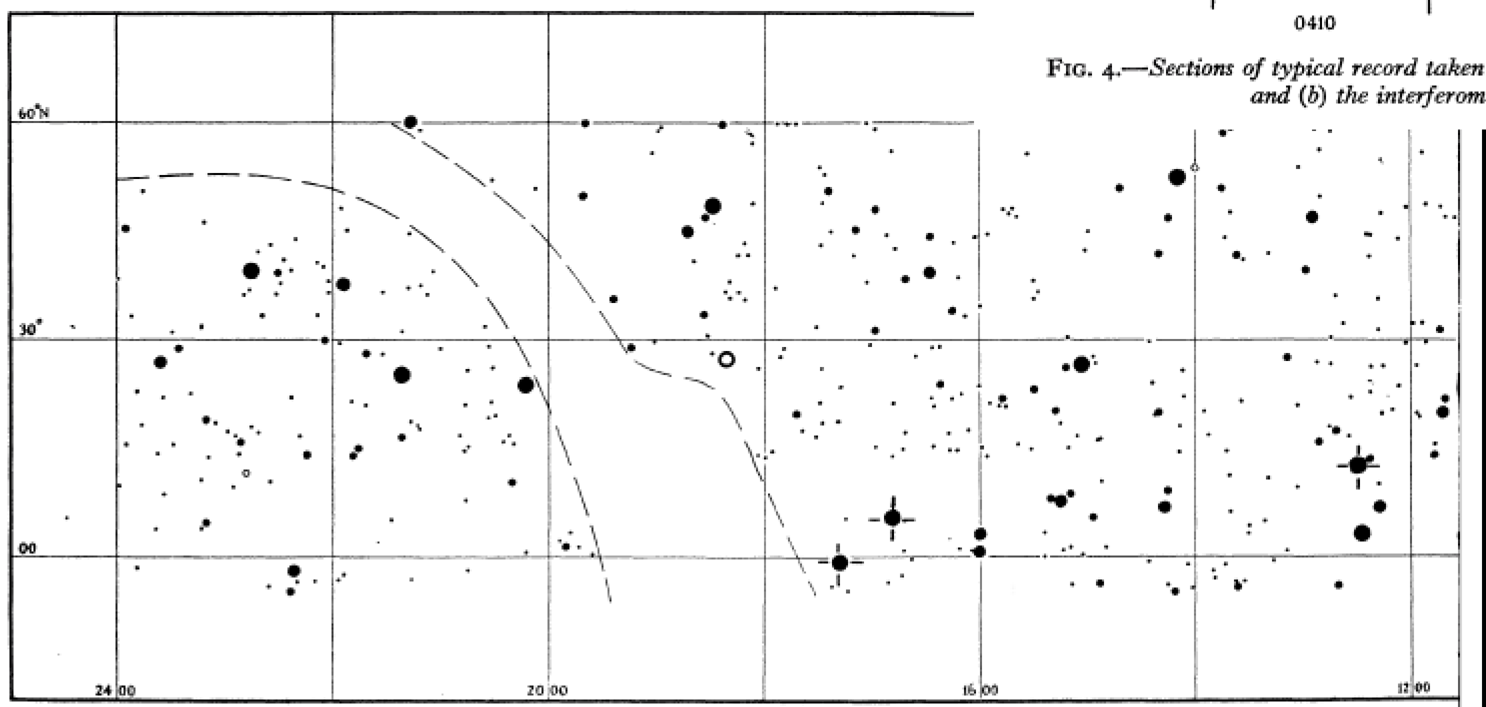


FIG. 7.—*Map showing the positions of all sources observed. Open circle*

Leslie 1961

Why the gap?

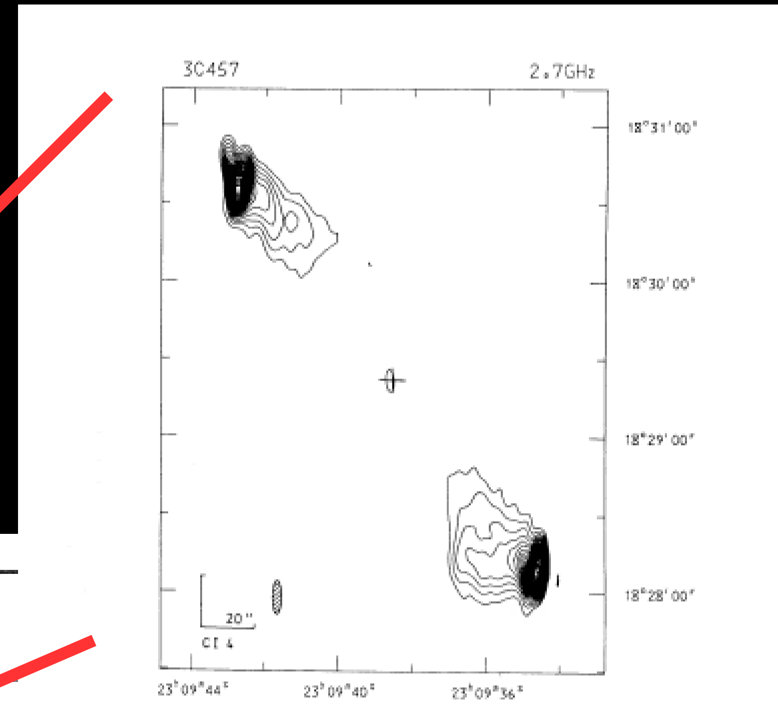


Figure A11. 3C 457. The cross marks the position of a 19.5 mag galaxy.

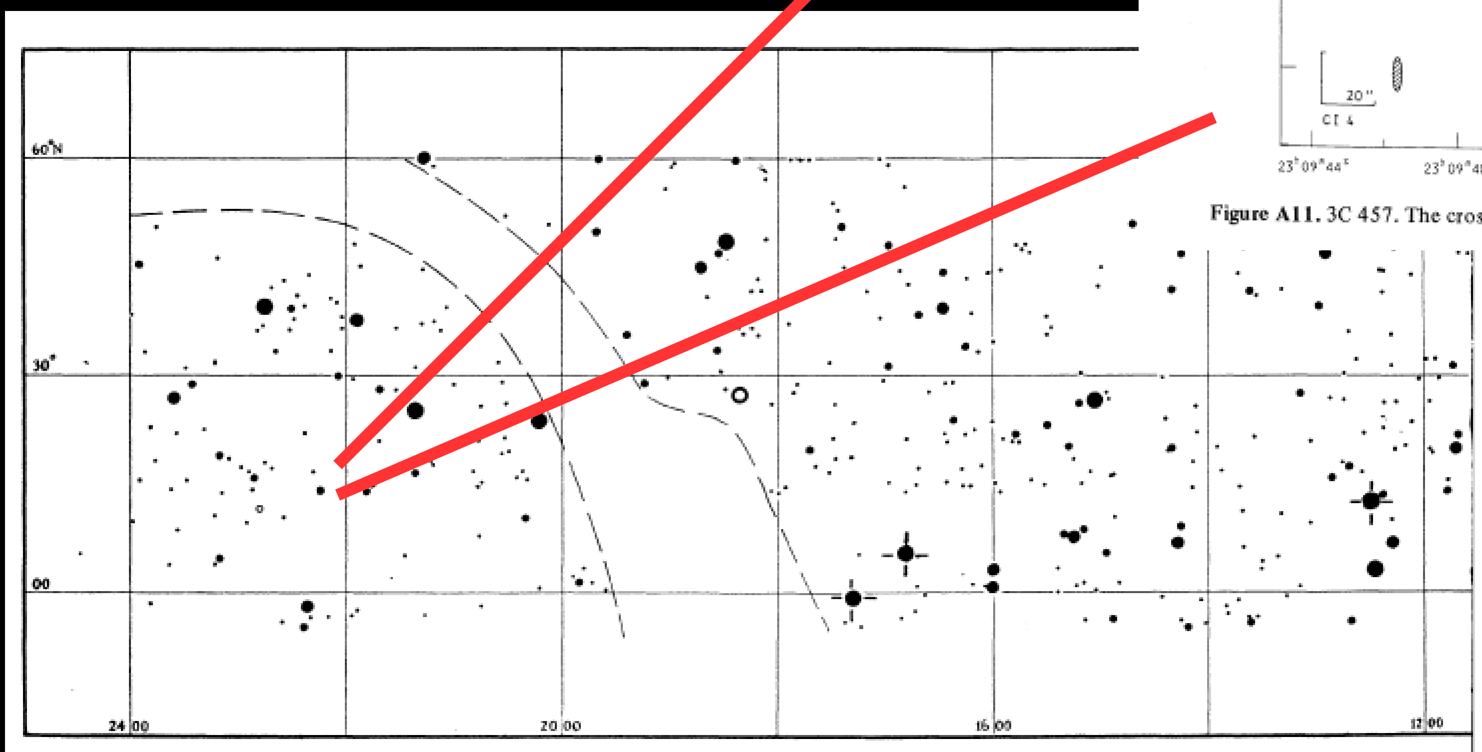


FIG. 7.—*Map showing the positions of all sources observed. Open circle*

Laing et al 1983

The next generation – 1979-now

The VLA

- 27 25-m dishes
- 4 configurations
- Frequencies from 74 MHz to 43 GHz
- Resolution is frequency and configuration dependent – at GHz frequencies it is sub-arcsec
- *Sensitivity to extended structure* is also configuration-dependent
- Field of view is small

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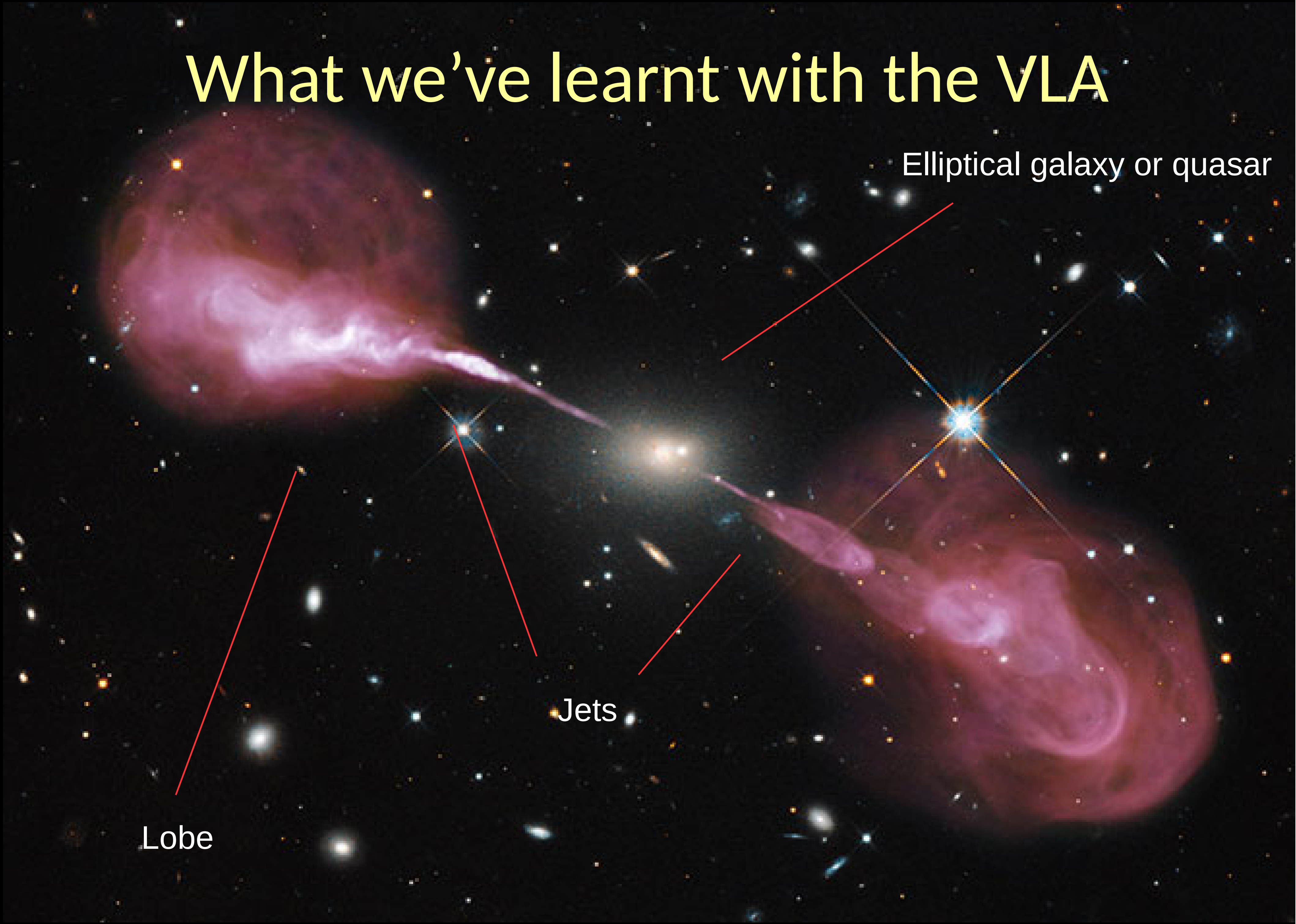
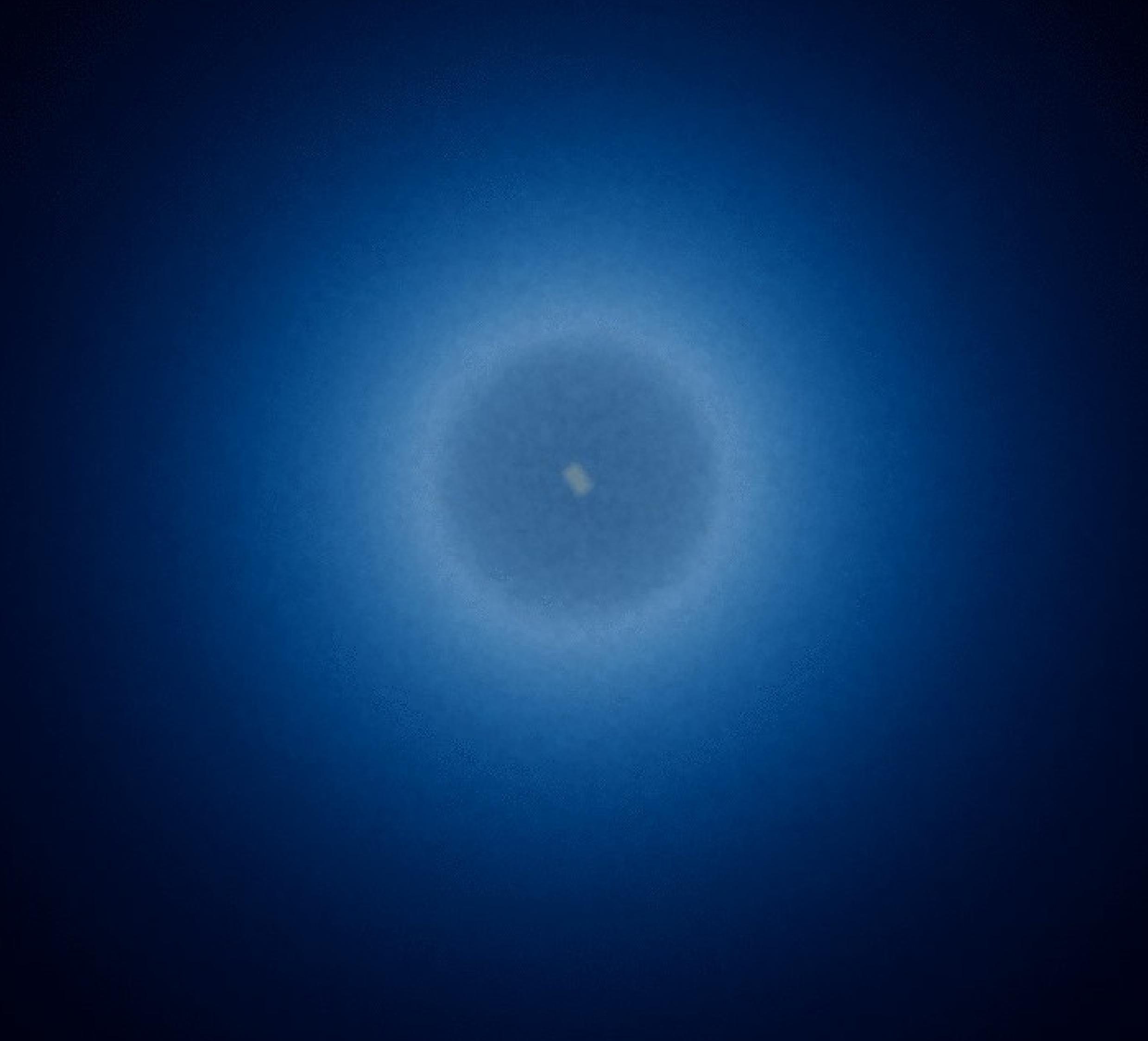
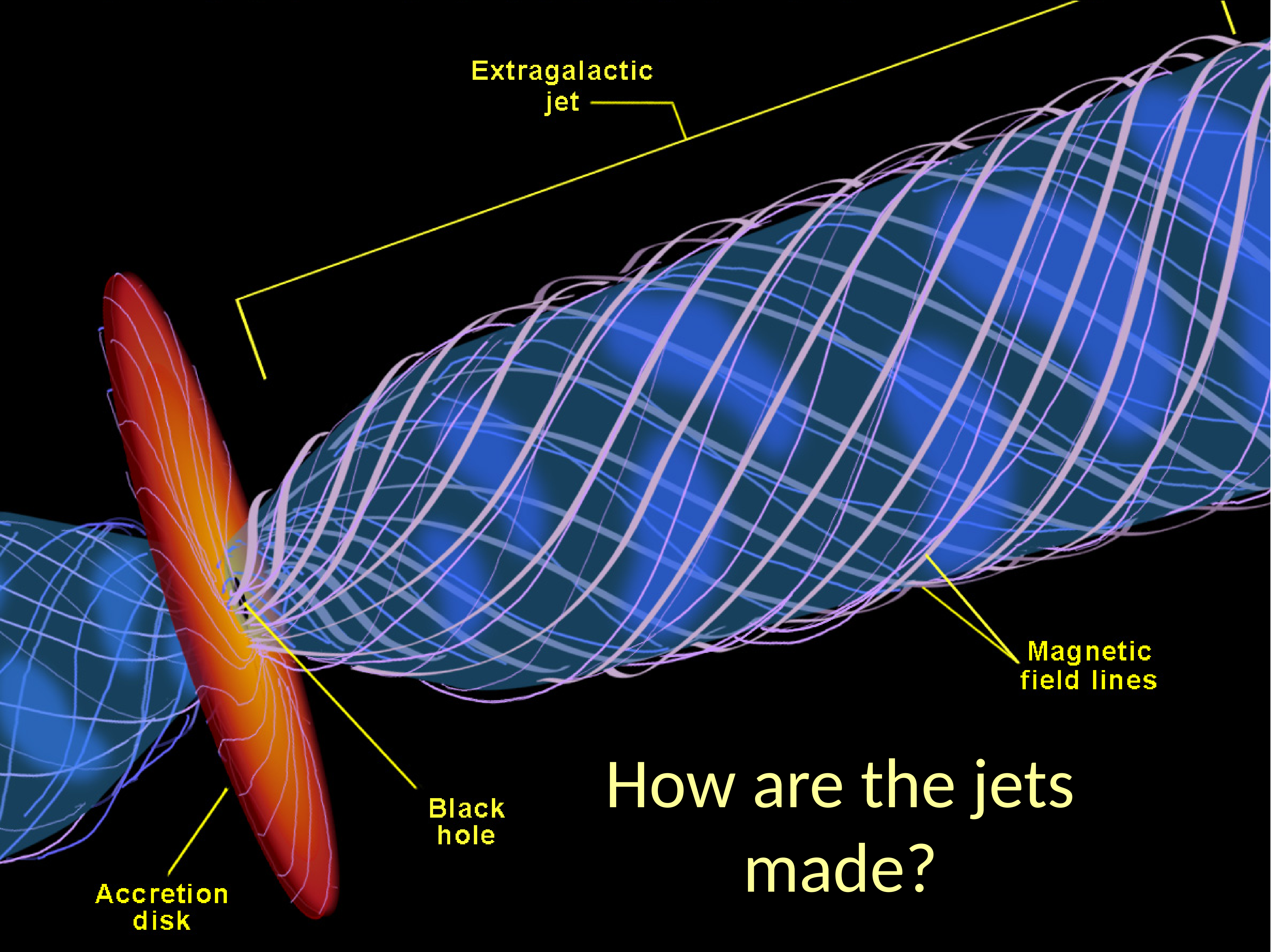
What we've learnt with the VLA



How radio galaxies work



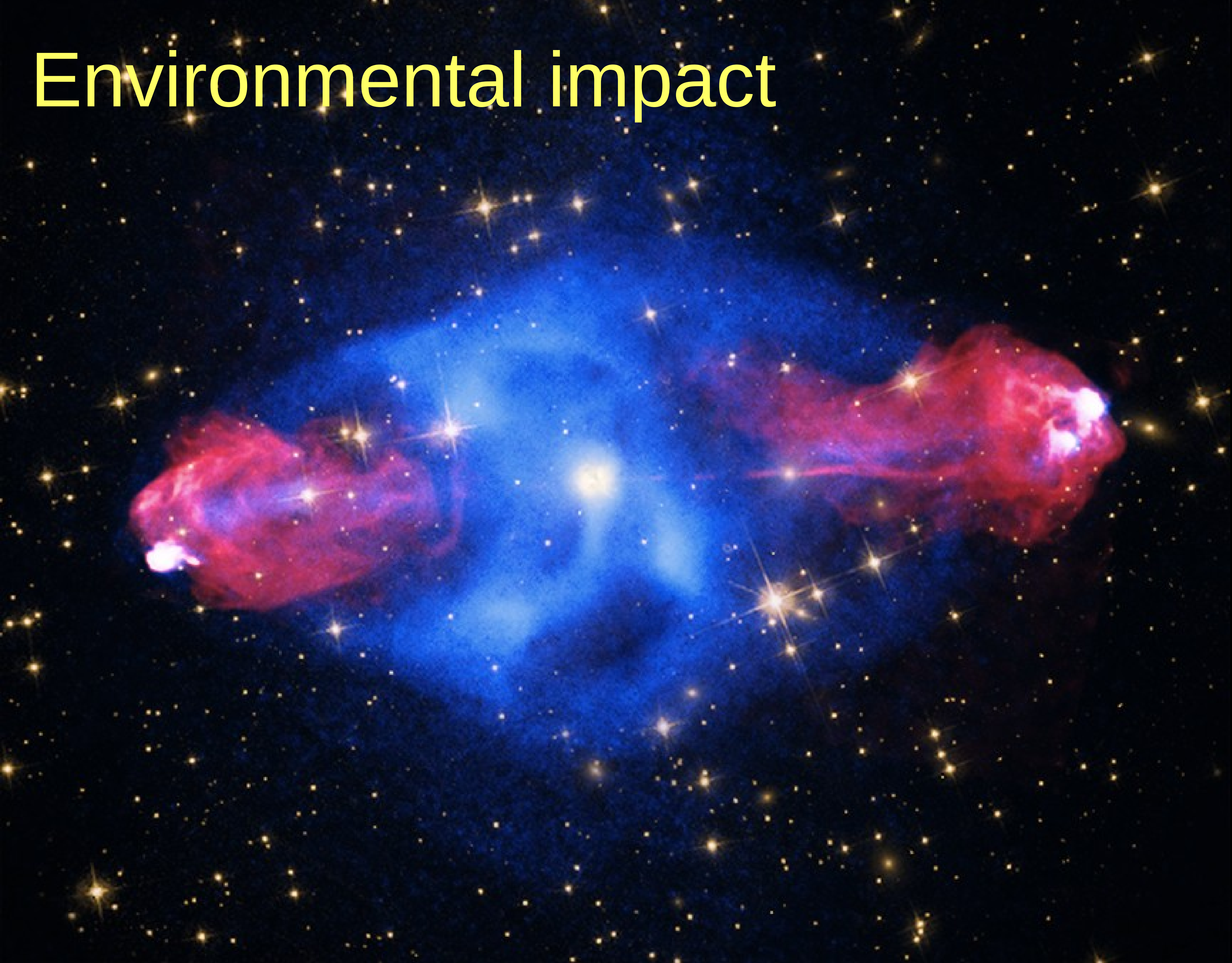


How are the jets made?

What’s falling in to the black hole?

How do they look at other wavelengths?

Environmental impact



What we still don’t know

- What makes an object a radio-loud AGN?
- How does radio activity relate to host galaxy properties? (type, star formation rate, environment)
- How does radio activity affect host galaxy/environment properties (feedback, jet-induced star formation...)?
- How do radio structures evolve?
- What happens when a jet turns off?
- How does all of the above depend on radio power, redshift...?

… NEED LARGE SAMPLES!

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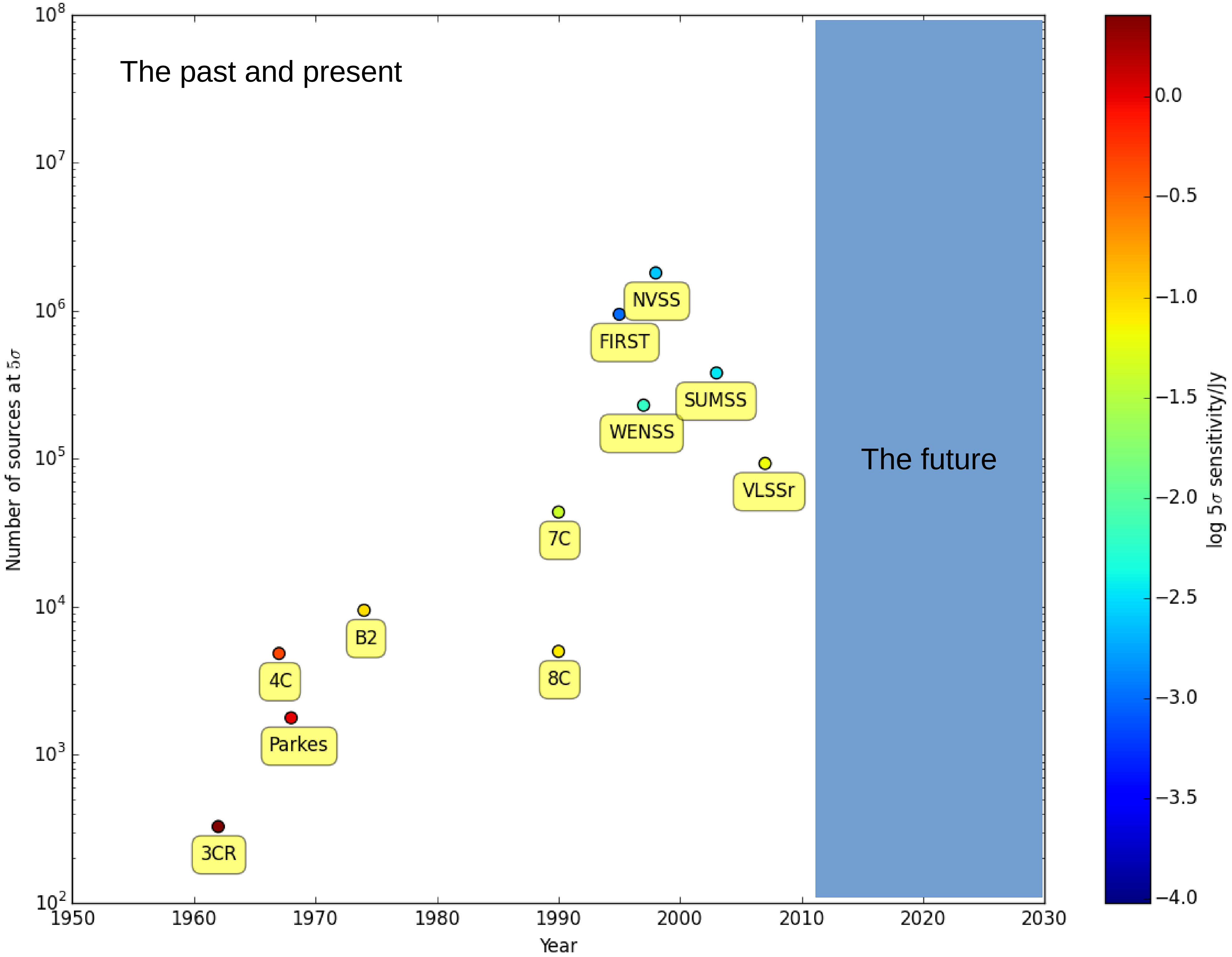
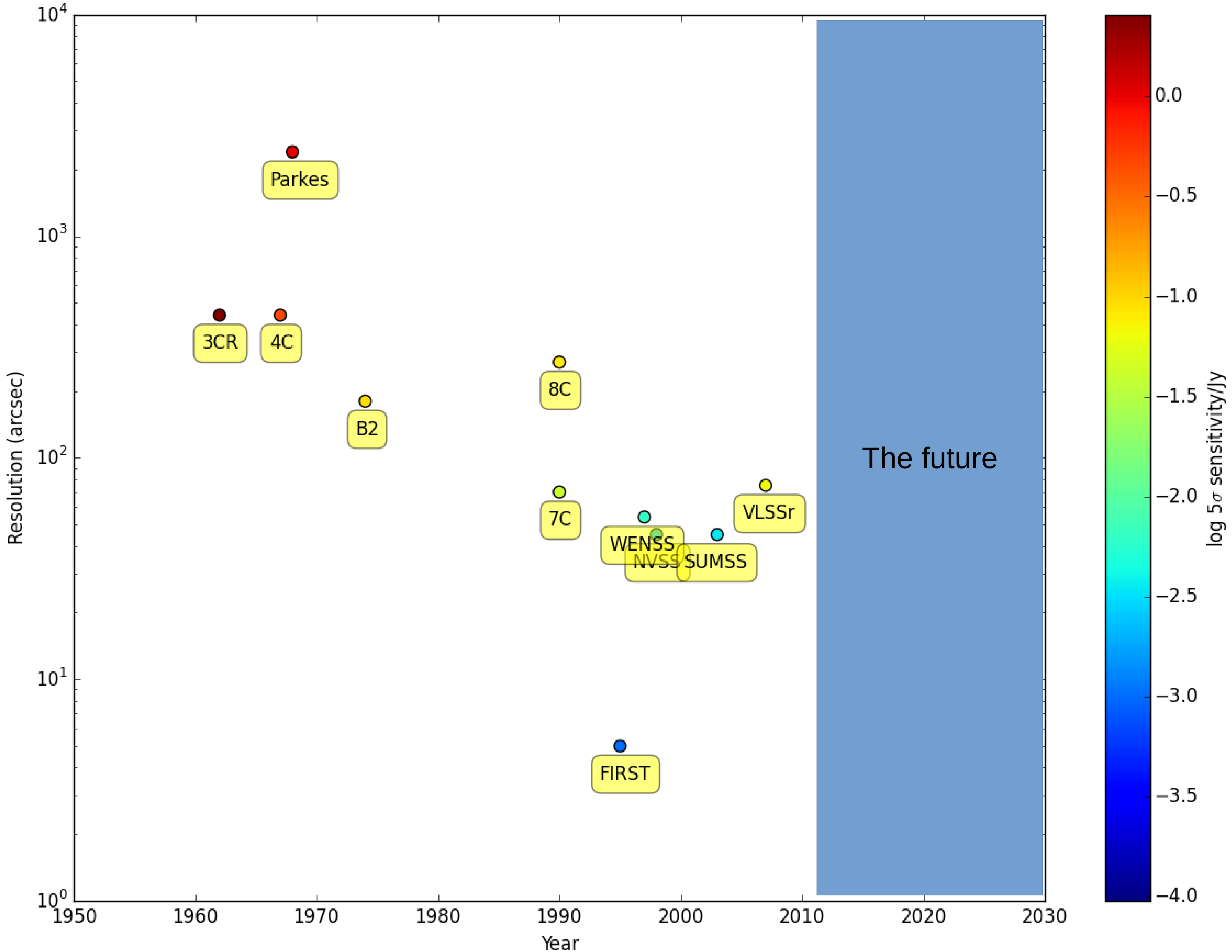


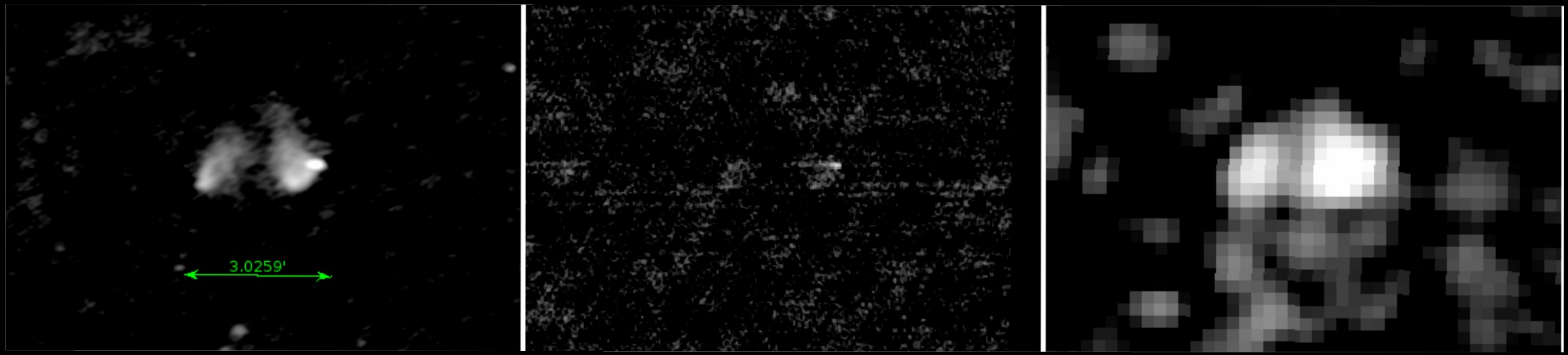
The past and present
The future
3CR
4C
Parkes
B2
7C
8C
FIRST
NVSS
WENSS
SUMSS
VLSSr
Number of sources at 5σ
Year
log 5σ sensitivity/Jy
1950
1960
1970
1980
1990
2000
2010
2020
2030
10^2
10^3
10^4
10^5
10^6
10^7
10^8
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
−3.5
−4.0



Parkes
3CR
4C
B2
8C
7C
WENSS
NVSS
SUMSS
VLSSr
FIRST
The future
Resolution (arcsec)
Year
log 5σ sensitivity/Jy

What’s wrong with VLA surveys?

- NVSS has too low resolution: can’t identify sources
- FIRST has high resolution but low sensitivity to extended structure
- Fundamental limitation of the VLA
- Need to build telescopes in a different way!

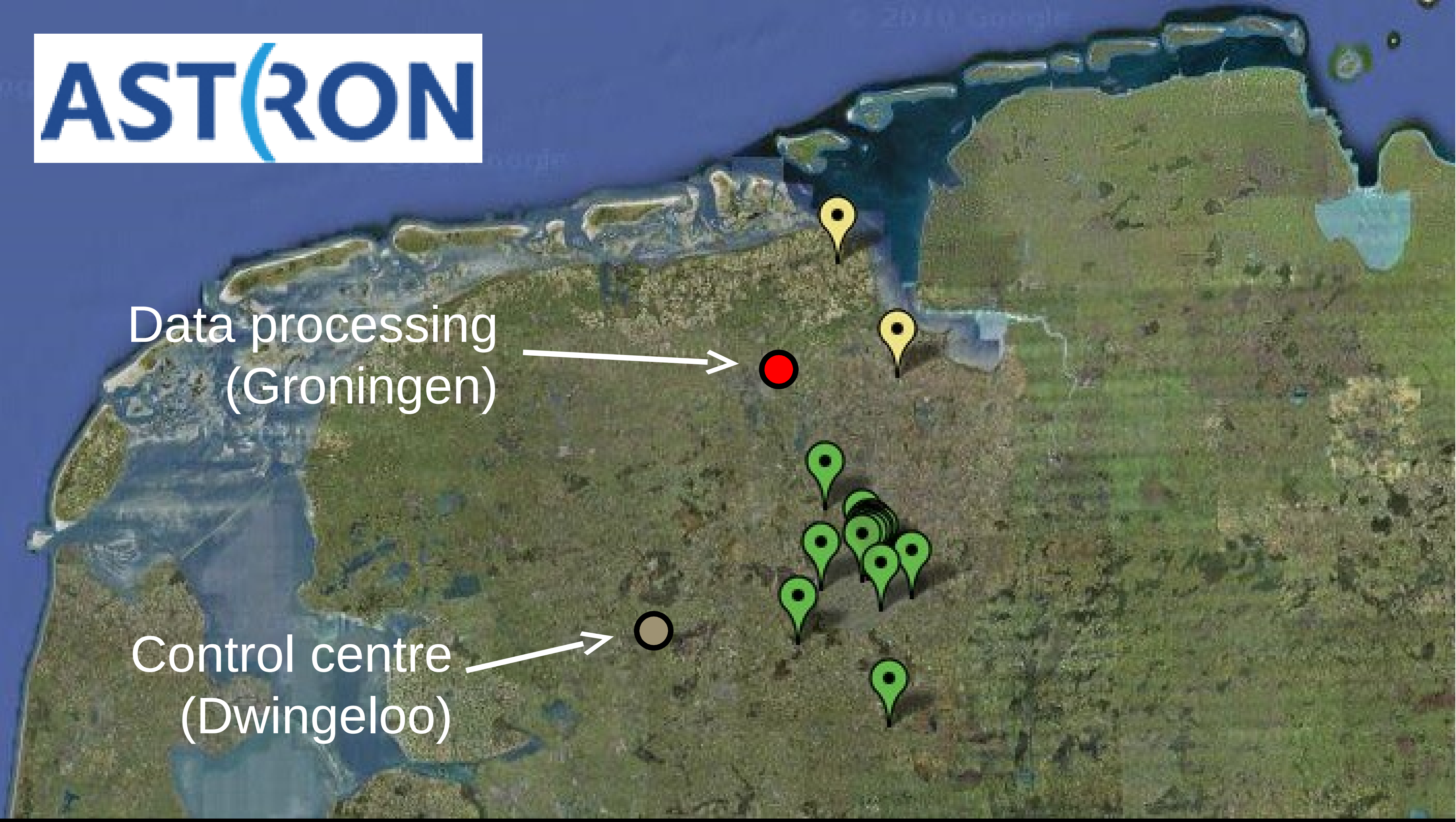


What’s really there What FIRST sees What NVSS sees

LOFAR – a next-generation radio telescope

- LOFAR – the LOw Frequency ARray.
- Low frequencies (30-200 MHz):
  - Mostly unexplored
  - Excellent for finding radio galaxies which get brighter as you go to lower frequencies
- But:
  - Fighting with human-generated interference
  - Need long baselines for resolution
  - Sensitivity requires many telescopes and high bandwidth => lots of data

LOFAR stations 2018



- Heart of the facility
  - ASTRON (Dwingeloo, Exloo, Groningen)

- Main Antenna Array near Buinen/Exloo
  - 24 core stations, 16 remote stations

- At the heart of this is the Superterp
  - The equivalent of 6 core stations

- Core station
  - 96 LBA + 2×24 HBA

- LBA (Low Band Array) 30-80 MHz
  - Angled dipole, ground plane, LNAs

LOFAR design

- Cheap, simple components:
- But lots of them (around 5000 LBA antennas)
- No moving parts
- Pointing done in software
- Hardware is dumb, software is clever.
- Many small antennas combined to make one station.

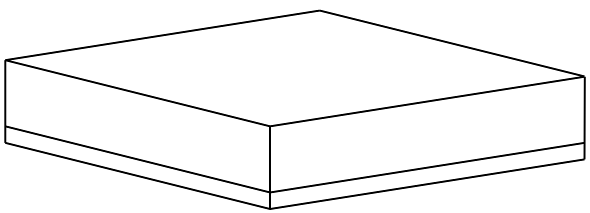
LOFAR-UK

- Why a UK station?
  - Long baselines => science
  - Strong UK tradition of radio astronomy
  - Pathway to future (SKA)
- Largest astronomy collaboration in the UK
  - (funds from 22 universities + funding from STFC)
- Everything must be cheap!

LÖF ÅR

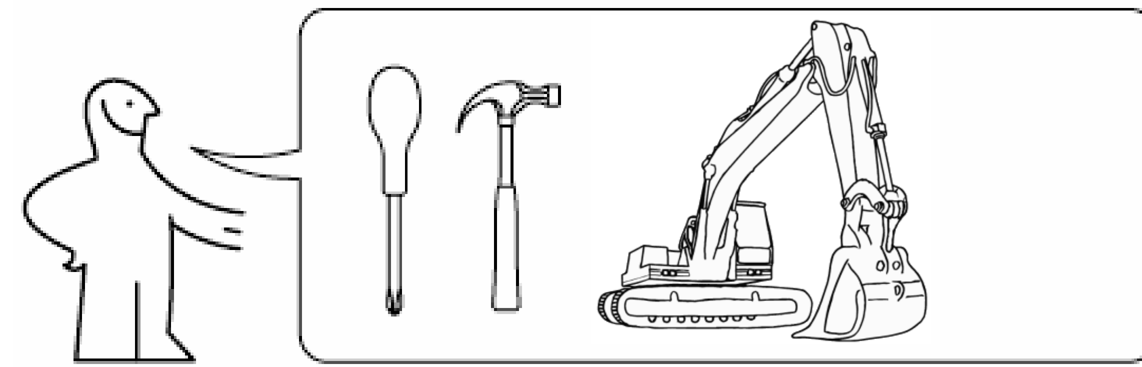
112649-1

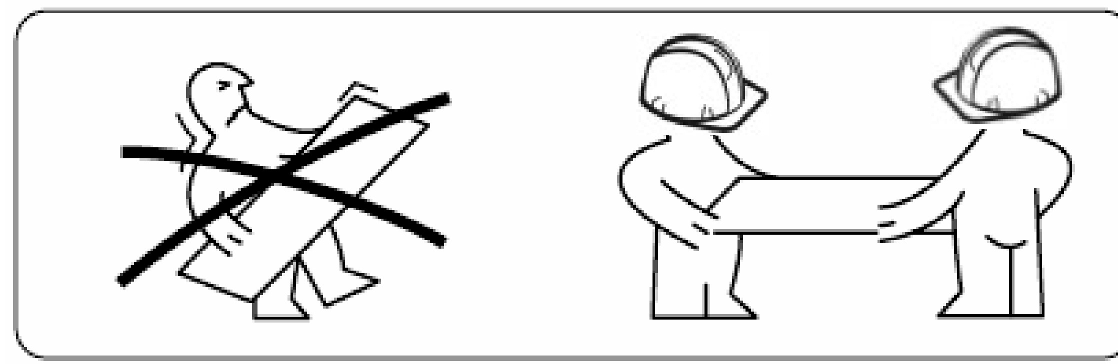
96x

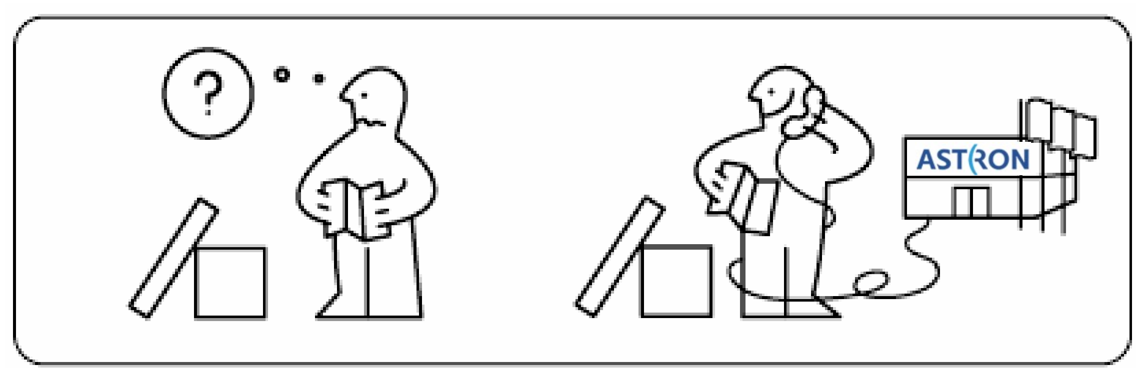
501163-2

96x

743133-7

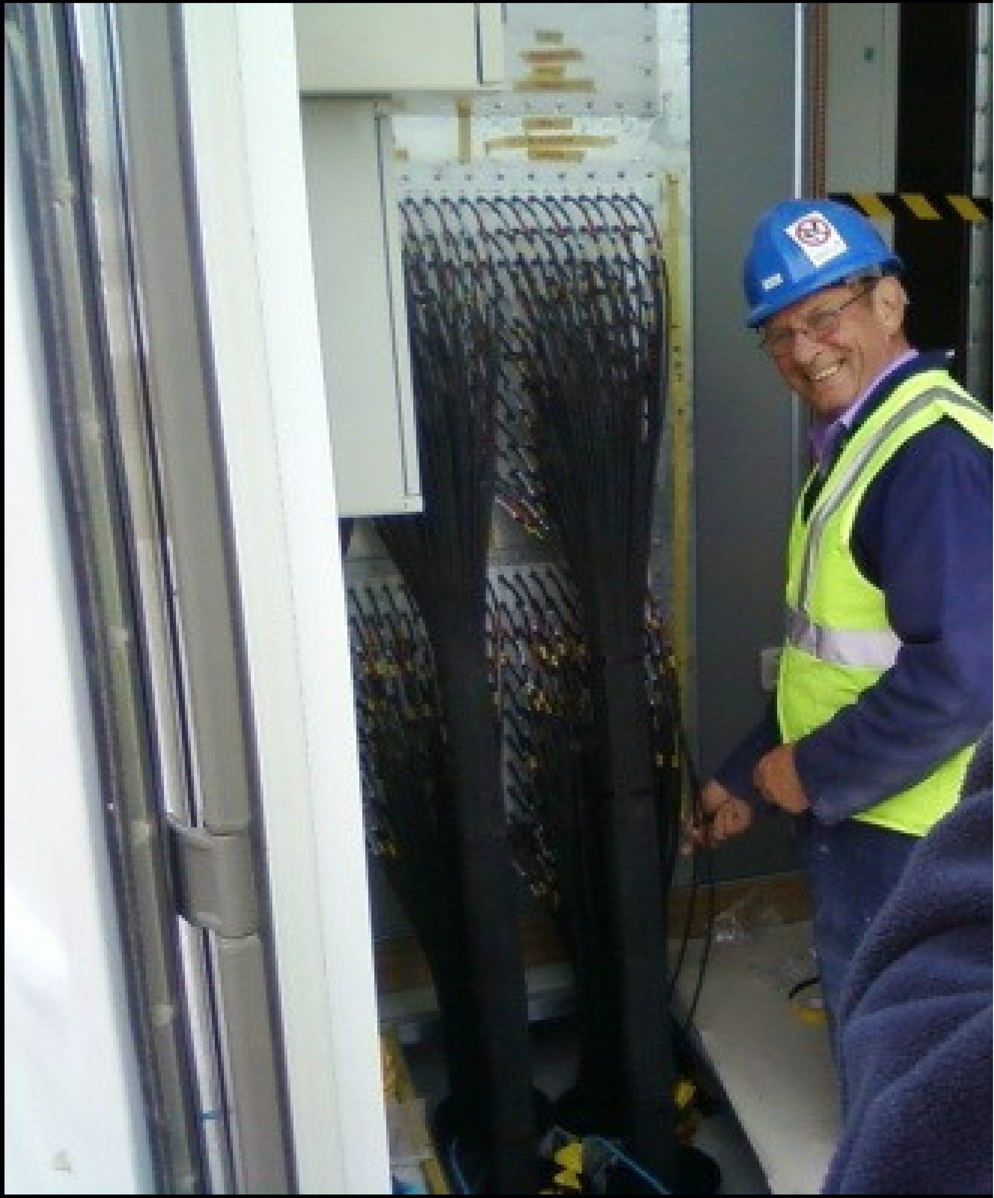
1x







Connecting it up

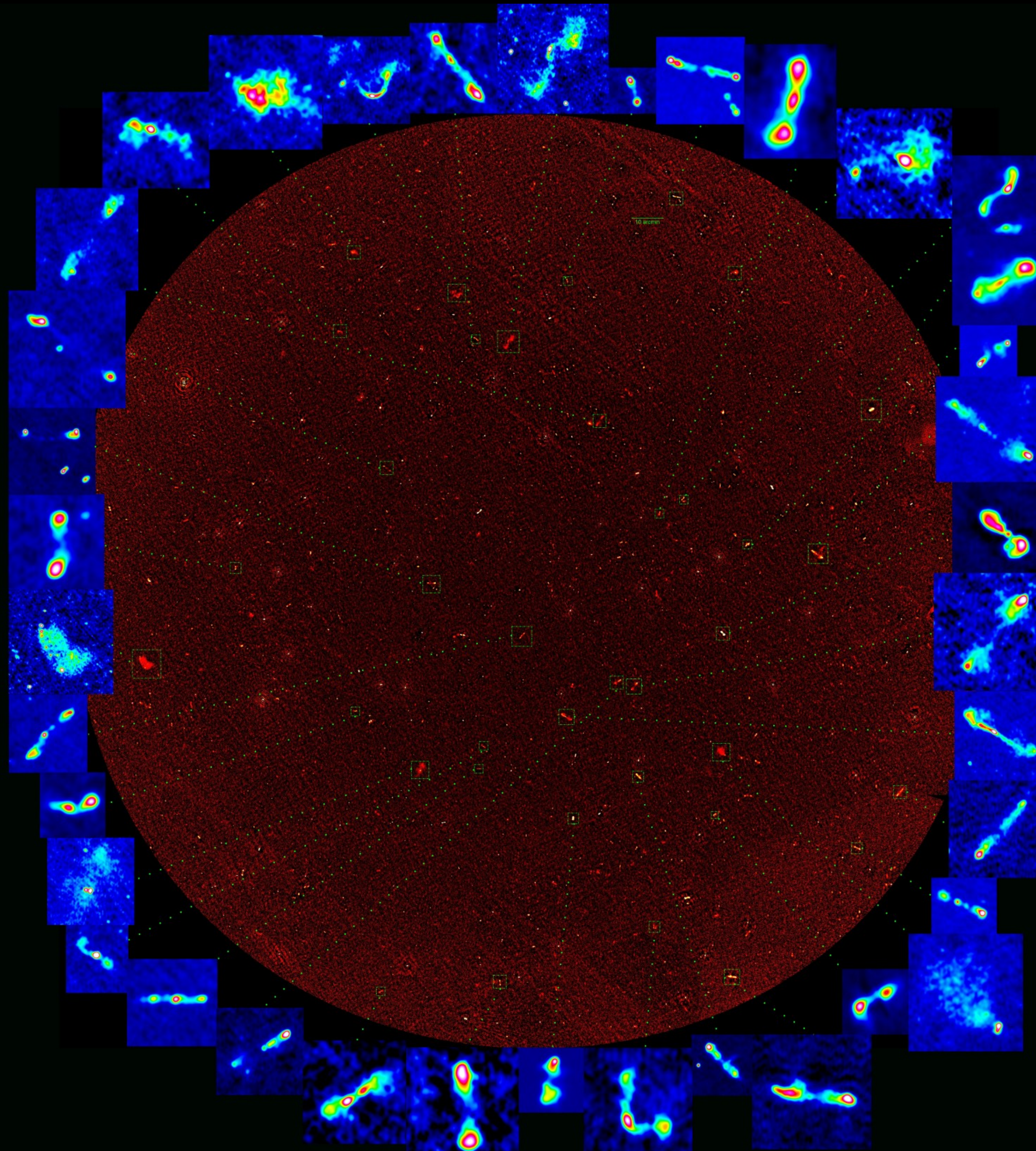


LOFAR-Chilbolton

LOFAR surveys

Bootes field: Williams+ 2016

H-ATLAS field: Hardcastle+ 2016



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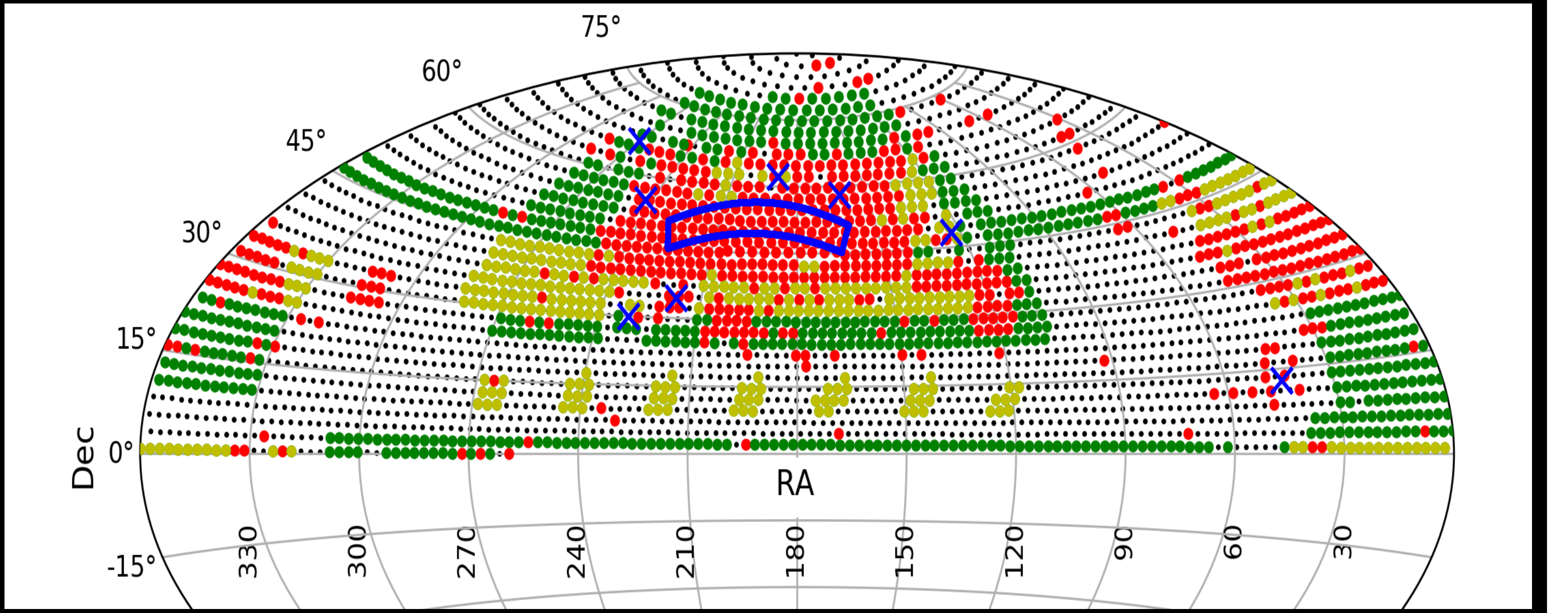
A LOFAR all-sky survey

- Survey all of the Northern sky (south not visible to LOFAR) at frequencies between 120 & 168 MHz with 6 arcsec resolution
- Requires 3,170 separate pointings with LOFAR
- Each pointing is 8h and we can observe 2 at a time
- Would require 1.5 years of telescope time at 100% efficiency with exclusive use of the telescope!
- A long-term project...



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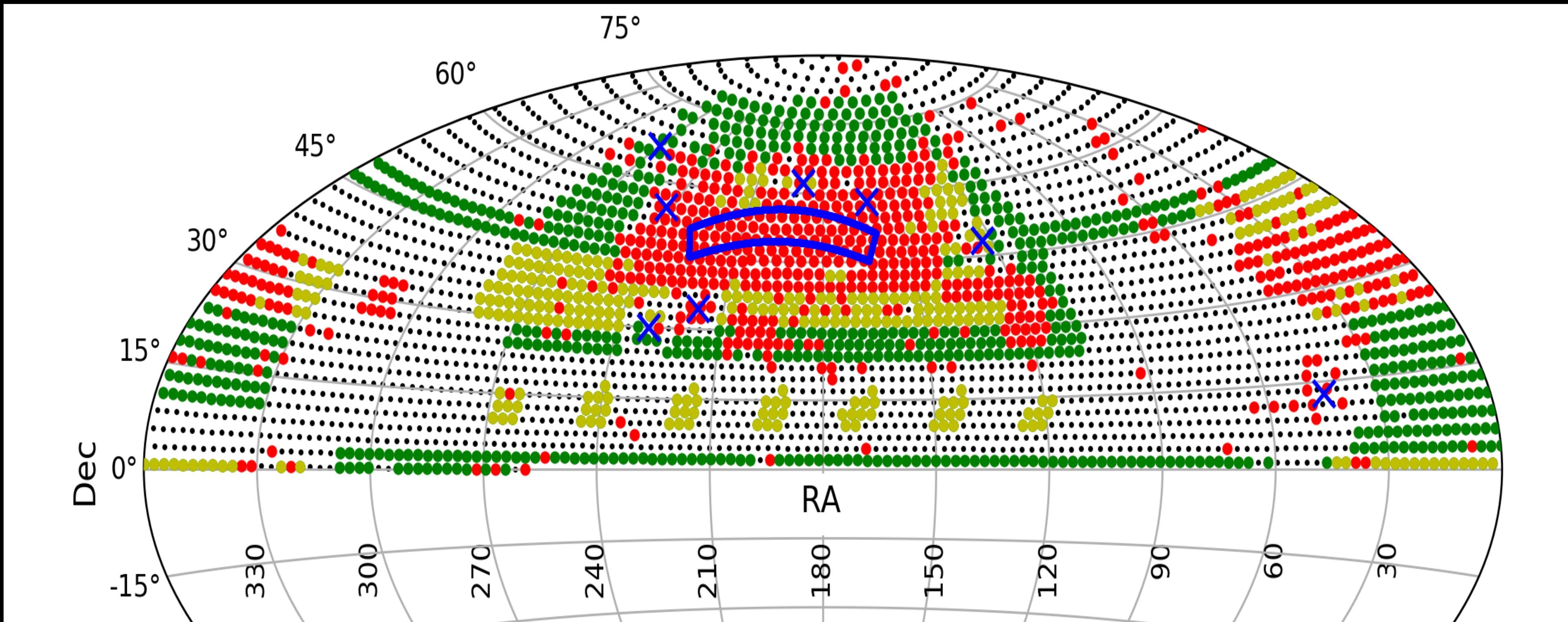
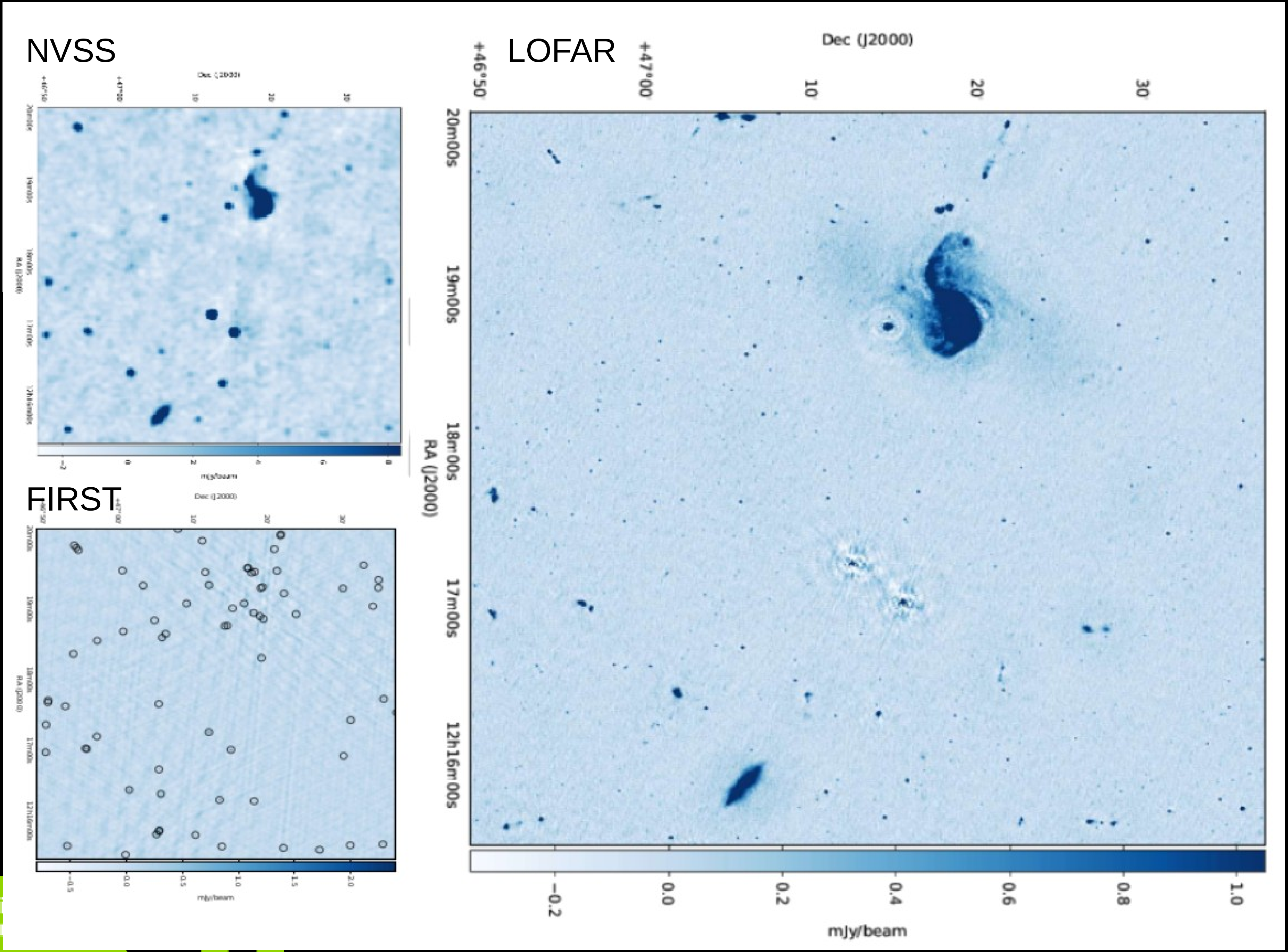
The HETDEX field



How to do a radio survey

- Schedule the observations and take the data
  - raw data size is 16 TB per 8-h observation
- Calibrate and image the data
  - data transport, new software methods, pipeline development, find computing resources
- Find the sources in the images
- Figure out which sources go together to make physical objects
  - human visual inspection needed!
- Carry out optical identifications
- Find galaxy properties and redshifts
- Science!

LoTSS imaging quality



Pan-STARRS

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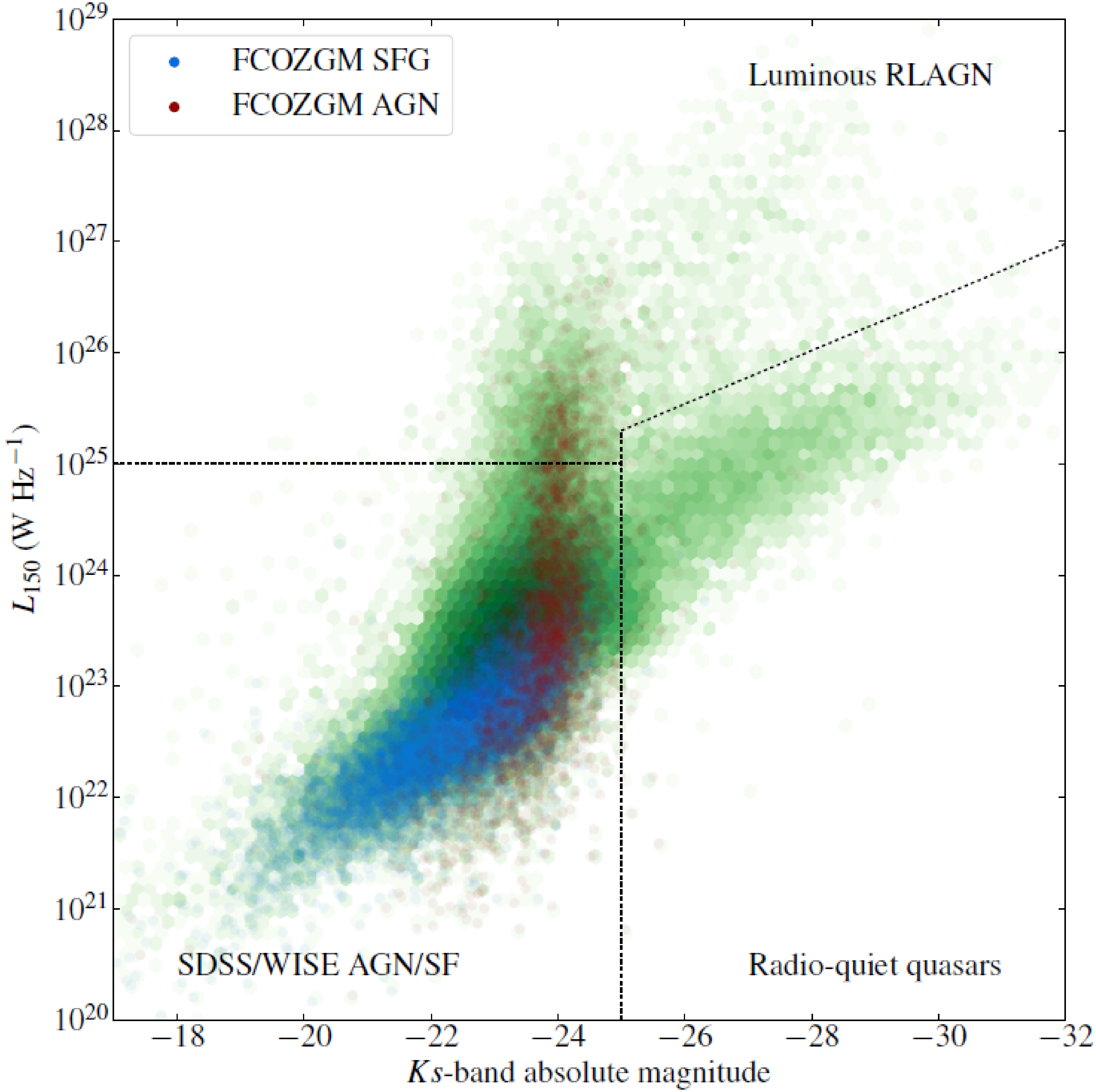
LOFAR + FIRST on PanSTARRS

HETDEX facts and figures

- 420 square degrees of sky
- 58 8-h LOFAR pointings processed
- 928 TB of raw data
- 200,000 CPU-hours processing time for imaging
- 33 GB of final images
- 325,000 'sources' detected
- 319,000 actual objects catalogued
- 229,000 have some sort of optical counterpart
- 161,000 have some sort of redshift estimate
- 33,000 extended sources

Statistics: optical vs radio



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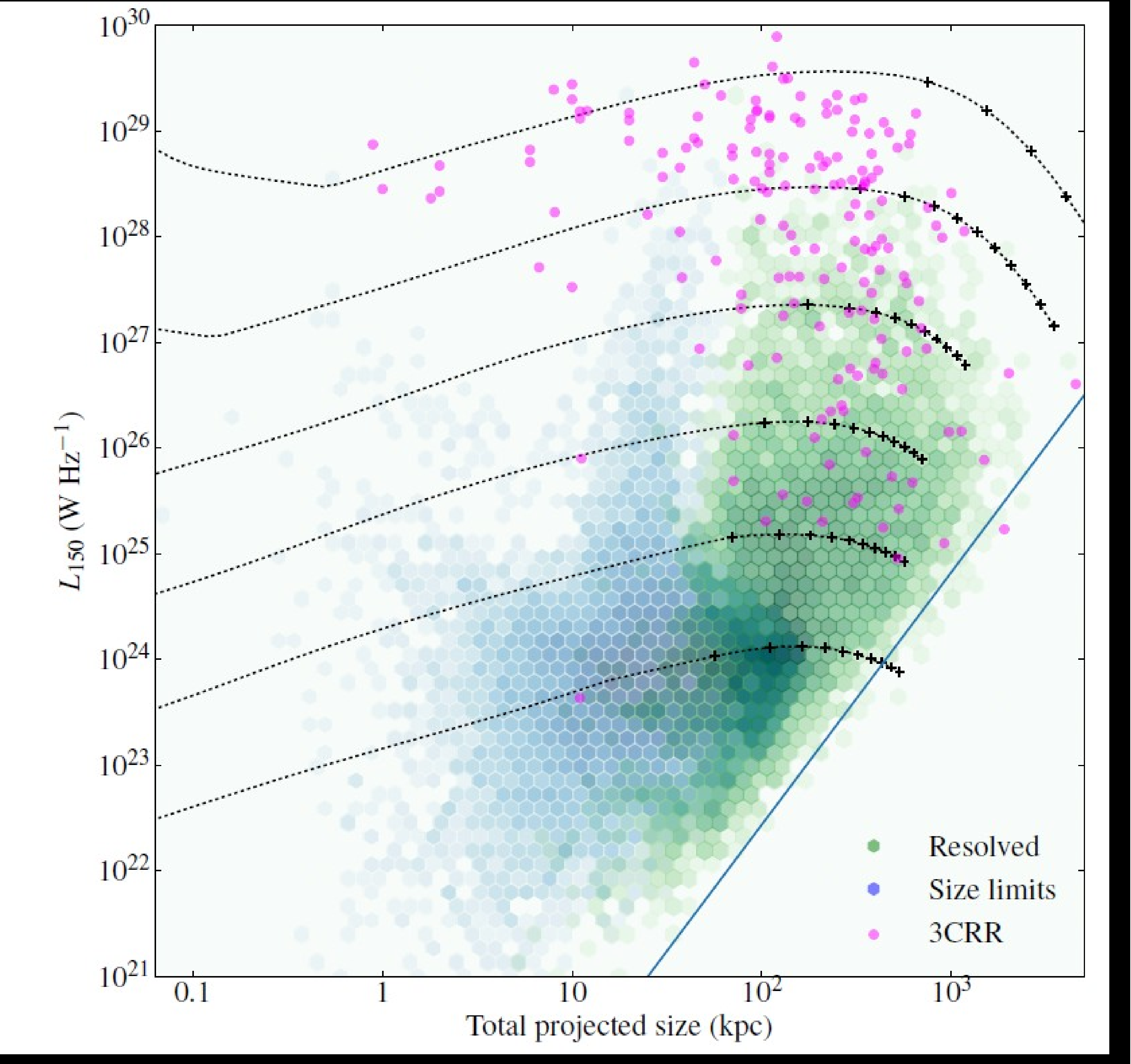
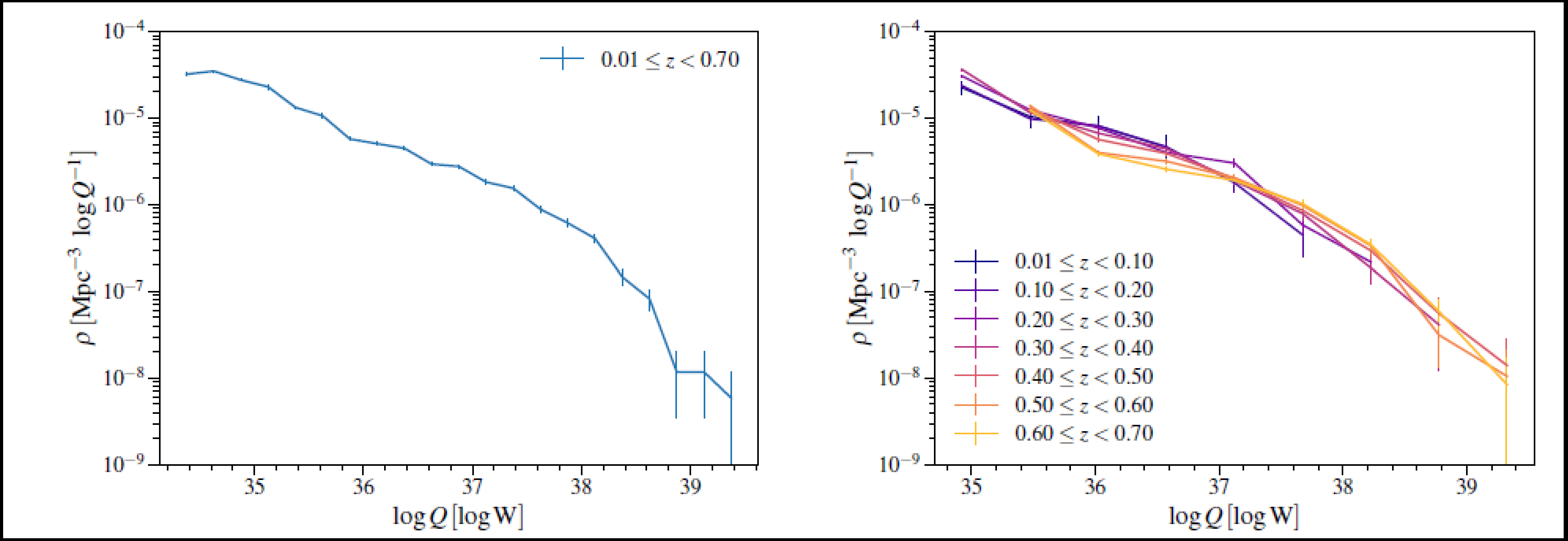
Statistics: power vs size



Statistics:
the jet kinetic luminosity function



$$\int Q\rho(Q)\mathrm{d}Q = 7 \times 10^{31}\ \mathrm{W\ Mpc}^{-3}$$

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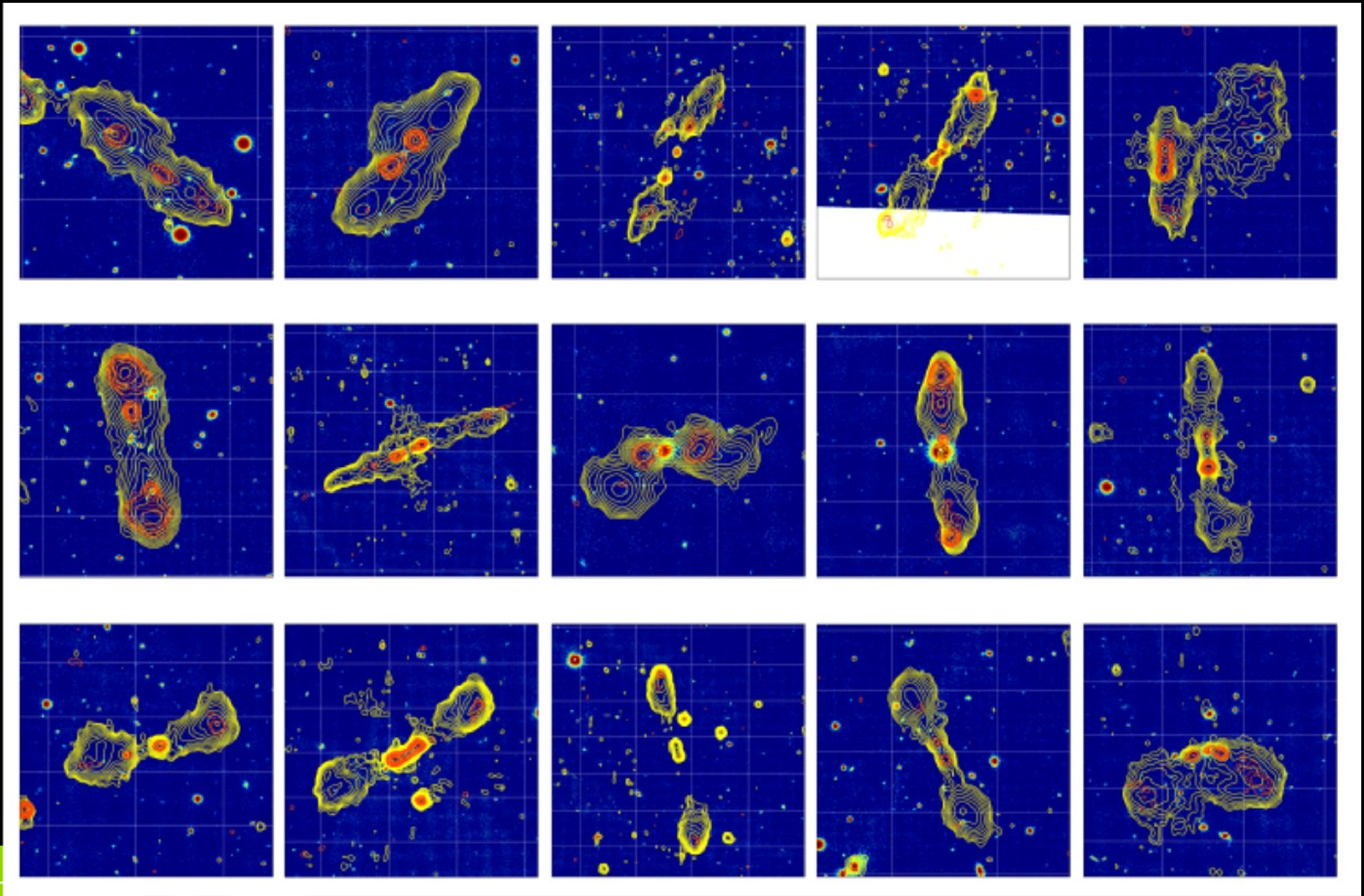
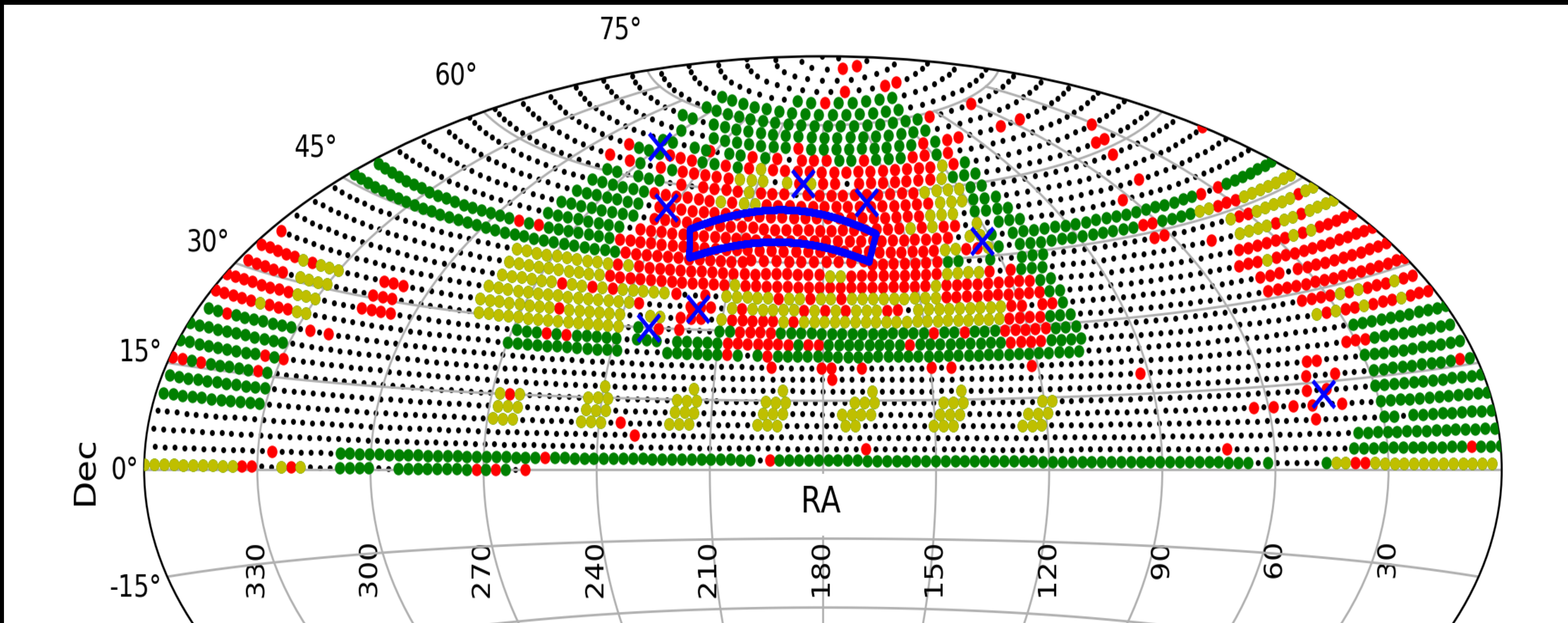
Rare objects: restarting sources



Next: 10,000 sq. degrees



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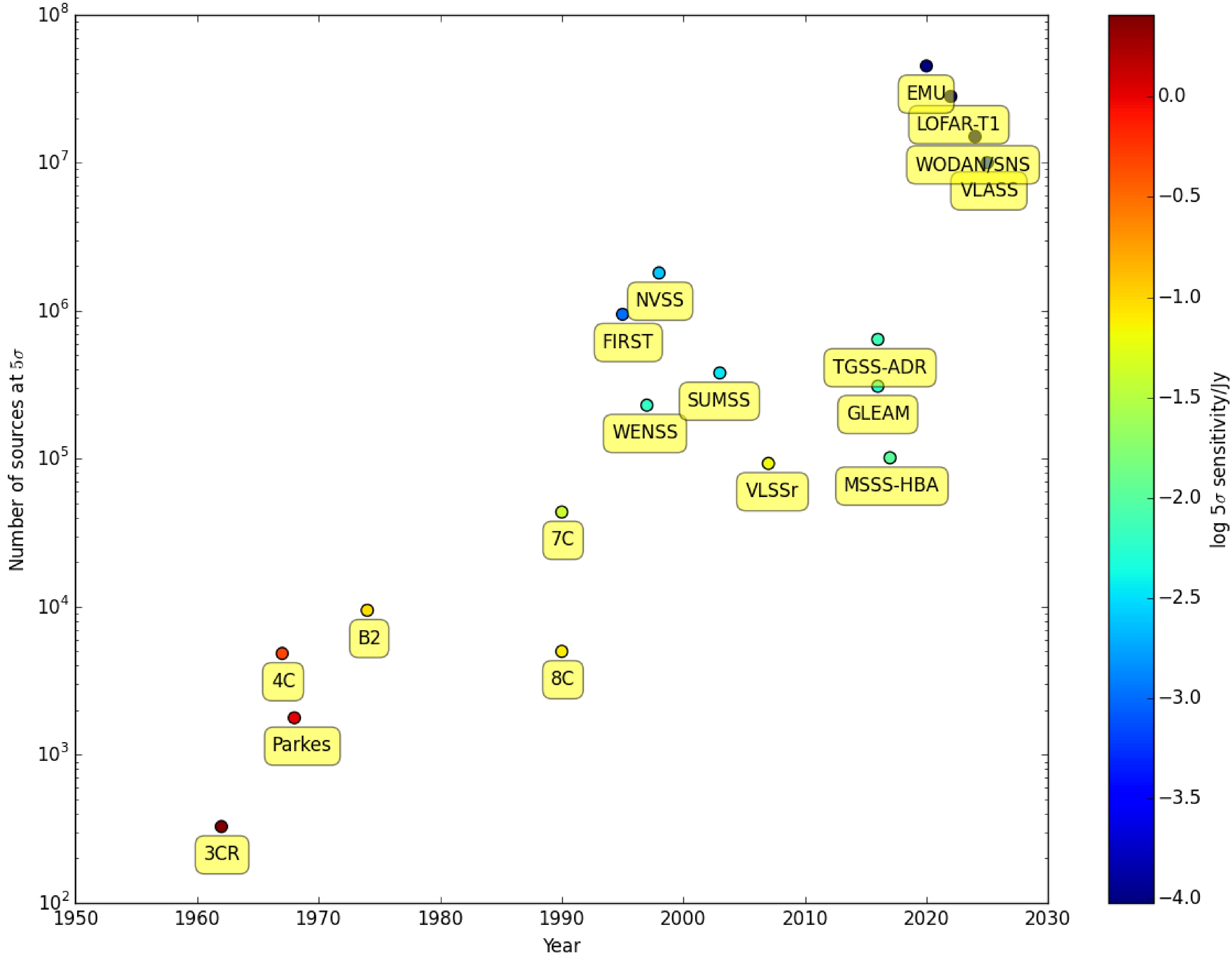
Next: WEAVE/LOFAR on WHT



Number of sources at 5σ
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3CR
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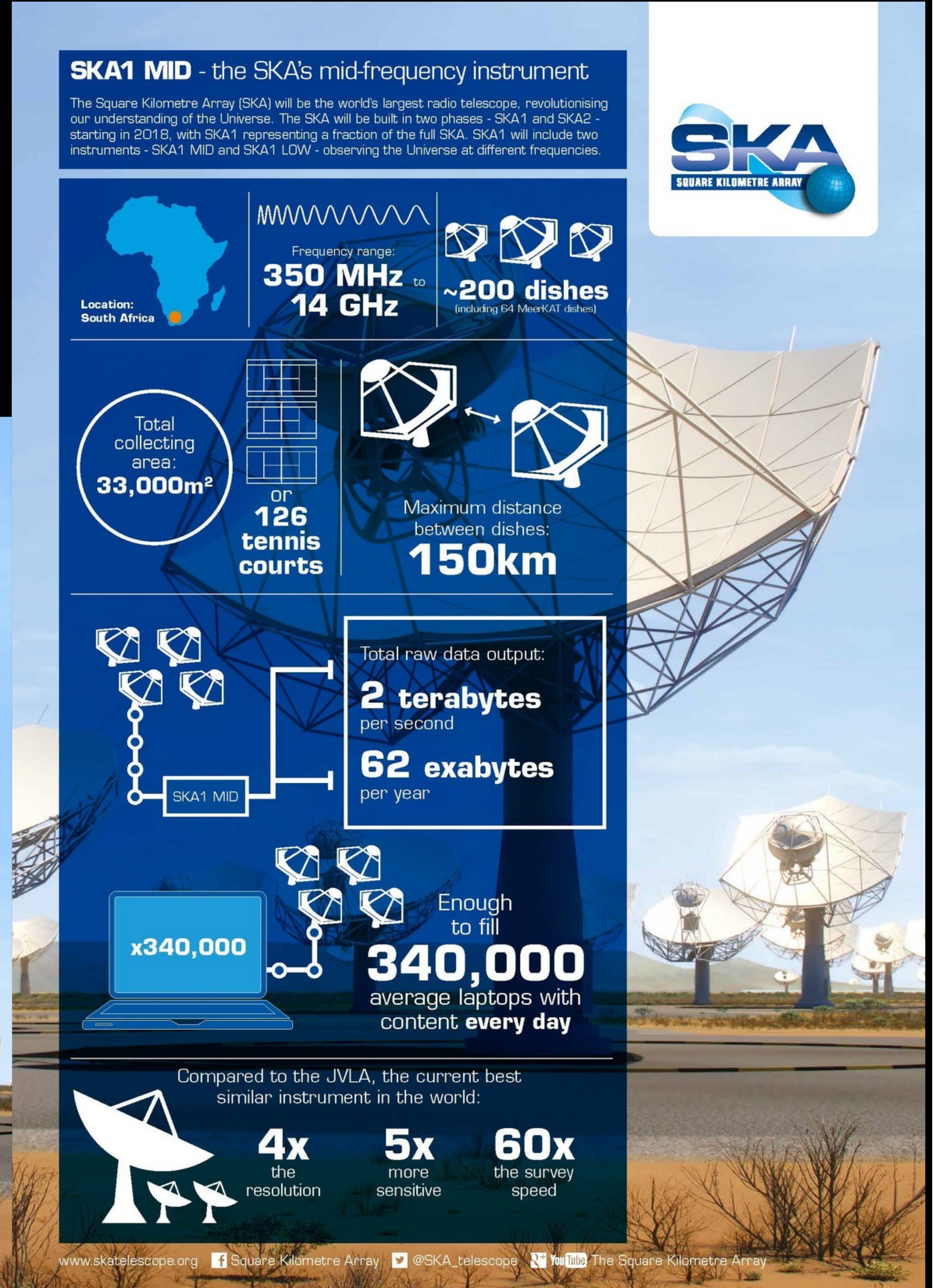
VLSSr
TGSS-ADR
GLEAM
MSSS-HBA
EMU
LOFAR-T1
WODAN/SNS
VLASS

The SKA



SKA1 MID - the SKA's mid-frequency instrument
The Square Kilometre Array (SKA) will be the world's largest radio telescope, revolutionising our understanding of the Universe. The SKA will be built in two phases - SKA1 and SKA2 - starting in 2018, with SKA1 representing a fraction of the full SKA. SKA1 will include two instruments - SKA1 MID and SKA1 LOW - observing the Universe at different frequencies.
SKA
SQUARE KILOMETRE ARRAY
Location: South Africa
Frequency range: 350 MHz to 14 GHz
~200 dishes (including 64 MeerKAT dishes)
Total collecting area: 33,000m²
or 126 tennis courts
Maximum distance between dishes: 150km
SKA1 MID
Total raw data output:
2 terabytes per second
62 exabytes per year
x340,000
Enough to fill 340,000 average laptops with content every day
Compared to the JVLA, the current best similar instrument in the world:
4x the resolution
5x more sensitive
60x the survey speed
www.skatelescope.org Square Kilometre Array @SKA_telescope The Square Kilometre Array

How does SKA1 compare with the world's biggest radio telescopes?

The Square Kilometre Array (SKA) will be the world's largest radio telescope, revolutionising our understanding of the Universe. The SKA will be built in two phases - SKA1 and SKA2 - starting in 2018, with SKA1 representing a fraction of the full SKA. SKA1 will include two instruments - SKA1 MID and SKA1 LOW - observing the Universe at different frequencies.

A telescope's capacity to receive faint signals - called sensitivity - depends on its collecting area, the bigger the better. But just like you can't compare radio telescopes and optical telescopes, comparison only works between telescopes working in similar frequencies, hence the different categories above.

The collecting area is just one aspect of a telescope's capability though. Arrays like the SKA have an advantage over single dish telescopes: by being spread over long distances, they simulate a virtual dish the size of that distance and so can see smaller details in the sky, this is called resolution.

www.skatelescope.org Square Kilometre Array @SKA_telescope The Square Kilometre Array