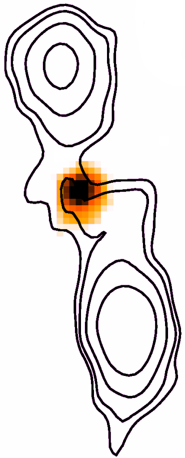
# Active Galactic Nuclei: a low frequency perspective



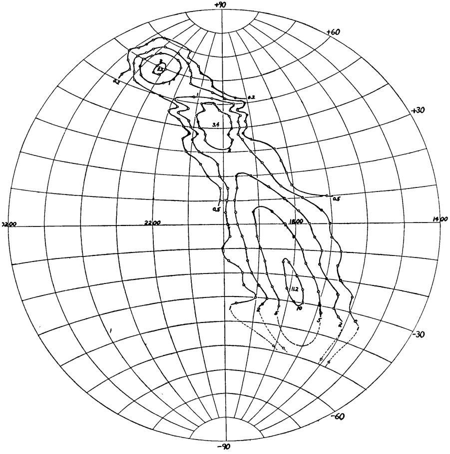
**Jodrell Bank Centre for Astrophysics Colloquium**
**1 May 2019**


UNIVERSITY OF OXFORD

**Dr. Leah Morabito**

**Hintze Fellow, Millard & Lee Alexander Fellow**

# The first map of the radio sky




*a*

*Reber (1944)*

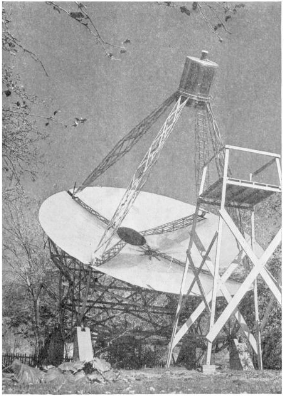


FIG. 1.—Sheet-metal mirror, 31.4 feet in diameter, 20 feet in focal length, used for collecting cosmic static

$\theta = 12°$
$\nu = 160\,\mathrm{MHz}$

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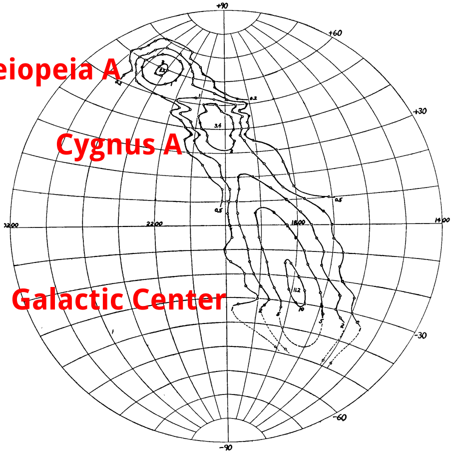

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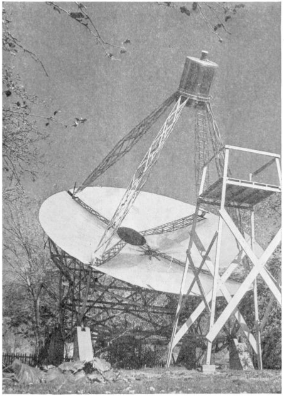

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# The radio nature of Cygnus A

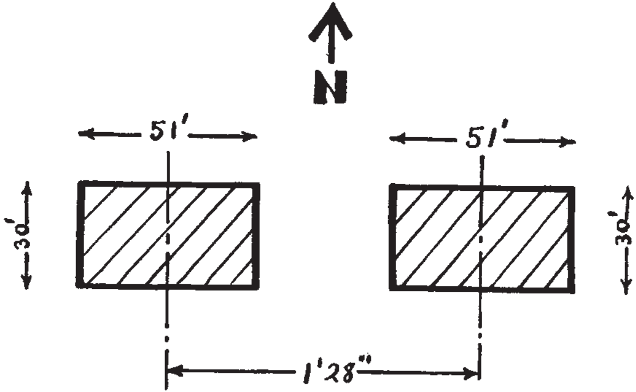
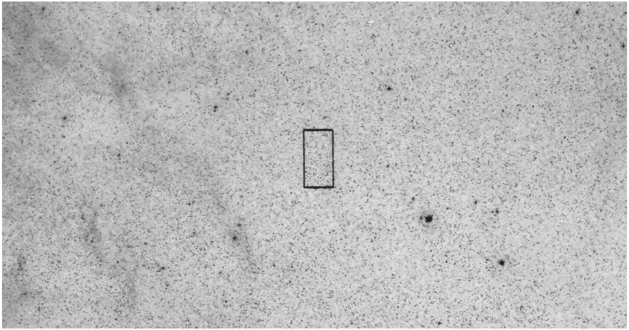



Fig. 2. Approximate intensity distribution of the extra-terrestrial radio source in Cygnus

*Jennison & Das Gupta (1953)*

# The extragalactic nature of Cygnus A

Positions from several studies narrowed the location to 18’ in RA and 10’ in Dec



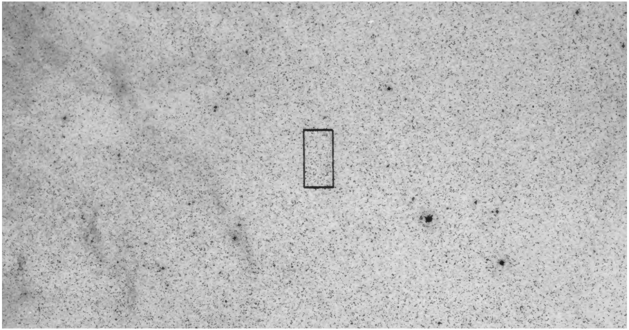
*Baade & Minkowski (1954)*

# The extragalactic nature of Cygnus A

Positions from several studies narrowed the location to 18’ in RA and 10’ in Dec

Within the field is a rich cluster of galaxies

The radio position coincided with one of the brightest in the cluster – which turned out to be two merging galaxies



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# The discovery of quasars

1040 NATURE March 16, 1963 VOL. 197

3C 273: A STAR-LIKE OBJECT WITH LARGE RED-SHIFT

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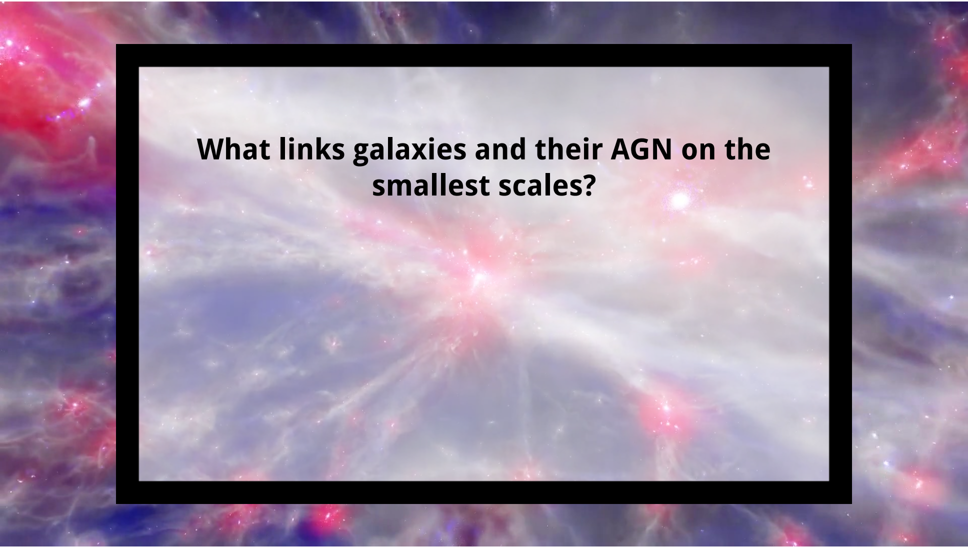
By 1965, an entire class of **quasars** – from **Q**uasi-**S**tellar **R**adio sources – had been identified.
Quasars are a subset of **A**ctive **G**alactic **Nuclei** (AGN).

# Active galactic nuclei (AGN) and the growth of galaxies

*the EAGLE simulation*
*http://icc.dur.ac.uk/Eagle/*

# Active galactic nuclei (AGN) and the growth of galaxies

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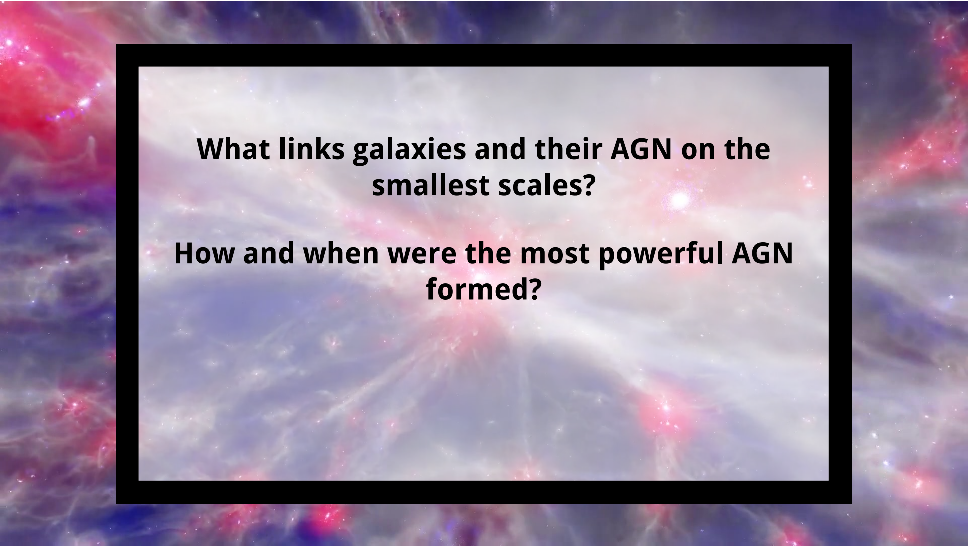


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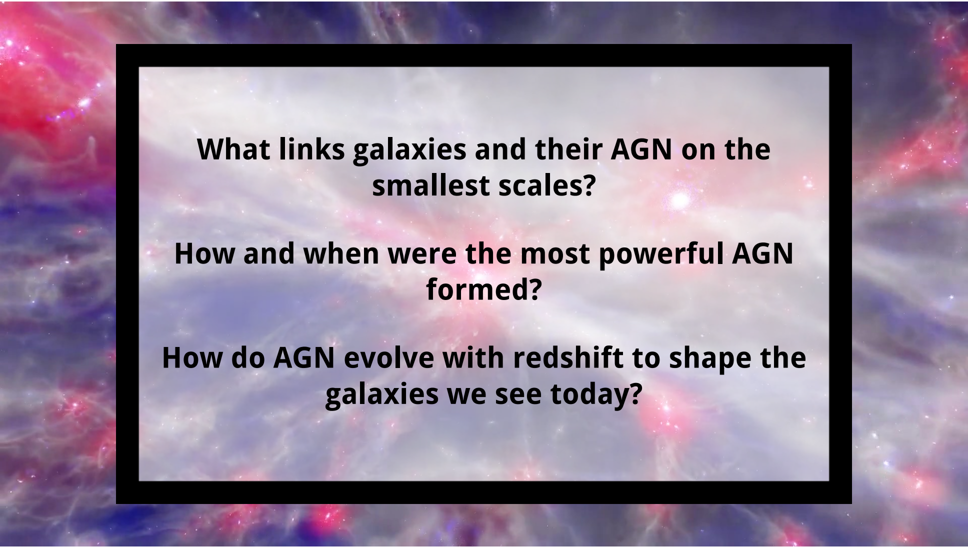


**What links galaxies and their AGN on the smallest scales?**

**How and when were the most powerful AGN formed?**

**How do AGN evolve with redshift to shape the galaxies we see today?**

*the EAGLE simulation*
*http://icc.dur.ac.uk/Eagle/*

## Overview

- What is an active galactic nuclei (AGN)?
- Focusing on radio AGN
  - Radio loud
  - Radio quiet
- Radio interferometry
- The LOw Frequency ARray (LOFAR)
- The LOFAR Two-metre Sky Survey
- High resolution surveying with LOFAR

# What is an AGN?

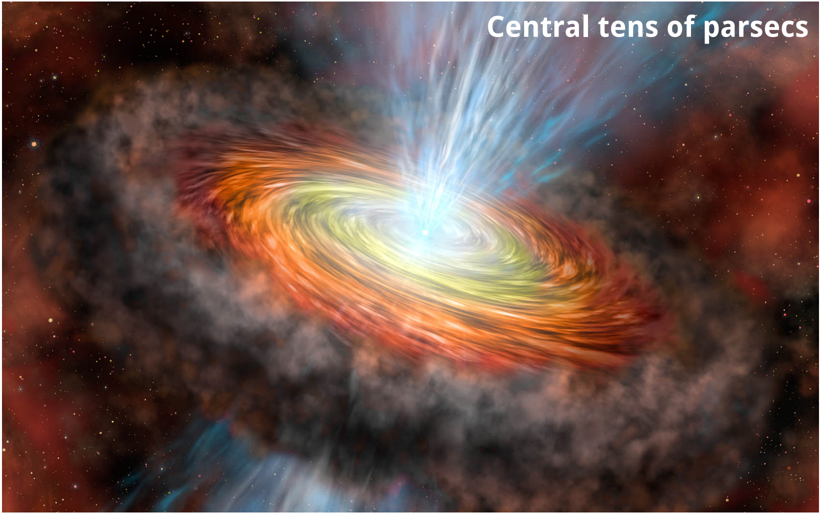
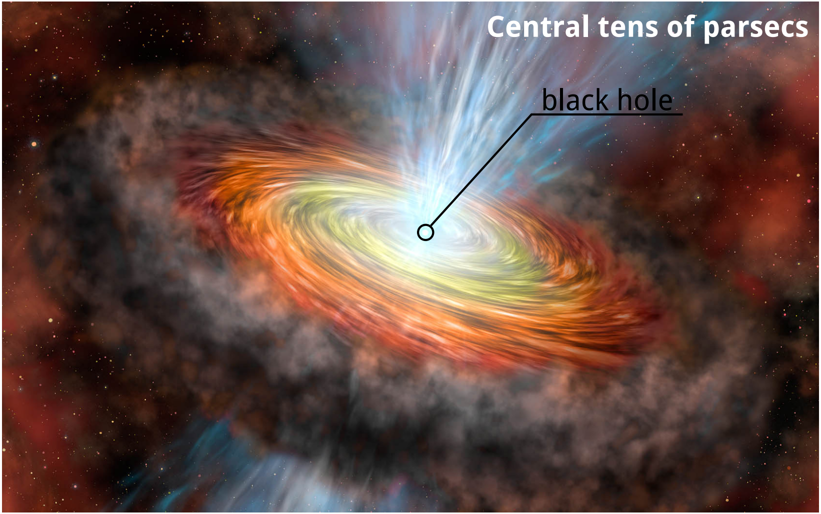



*Image credit: Gemini Observatory / Lynette Cook*

# What is an AGN?

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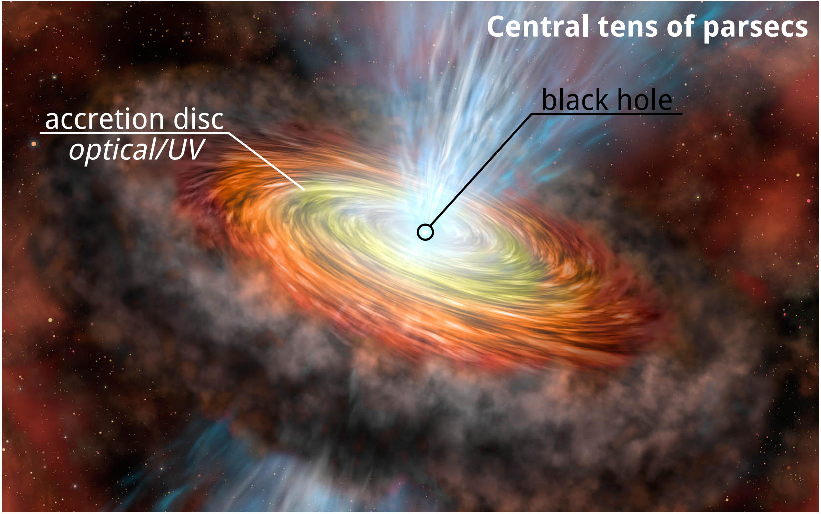


*Image credit: Gemini Observatory / Lynette Cook*

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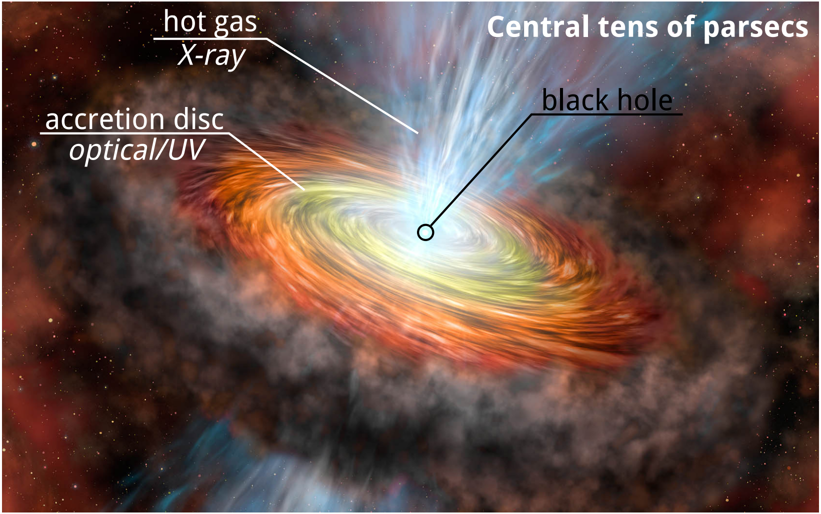


*Image credit: Gemini Observatory / Lynette Cook*

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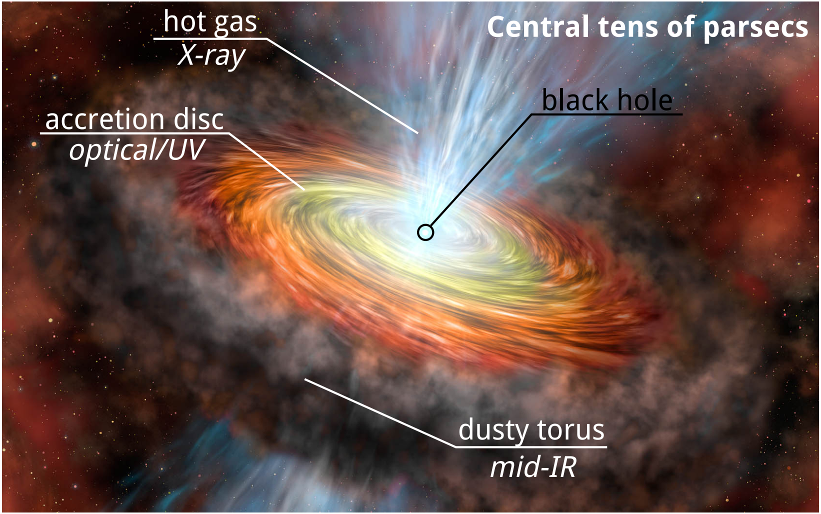


*Image credit: Gemini Observatory / Lynette Cook*

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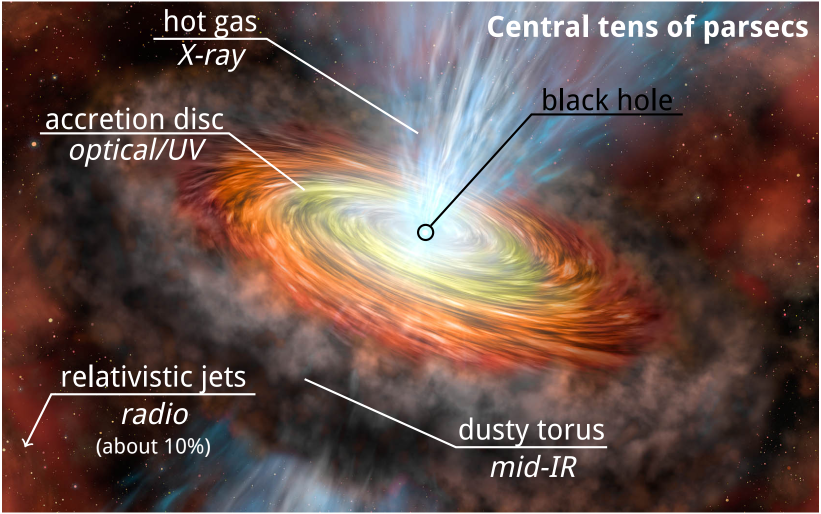
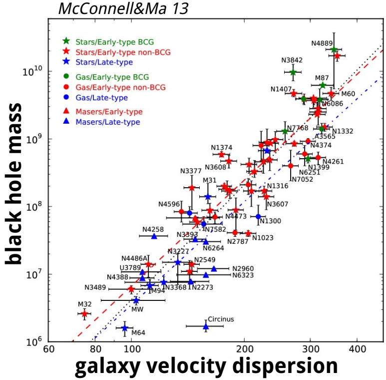
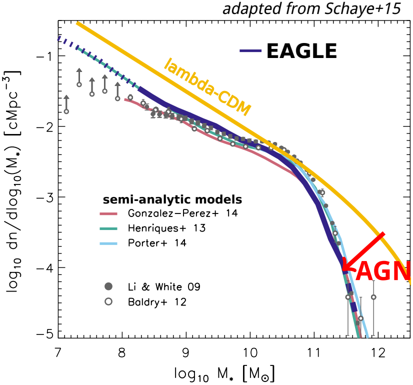



*Image credit: Gemini Observatory / Lynette Cook*

# AGN are closely linked to host galaxies

***feedback***: the process by which a system changes in response to its own effects / products




**observations:** strong correlation between black hole mass and galaxy properties, but <u>*indirect*</u> evidence biased by selection effects

*Ferrarese&Merritt 00, Gebhardt+00, Kormendy&Ho 13, Batcheldor 10, **Morabito**&Dai 12, Shankar+19*

**simulations:** cosmological simulations, semi-analytic models can reproduce high-mass cutoff by introducing *AGN feedback*

*Bower+06, Croton+06, Schaye+15, Vogelsberger+14, Slyz+16, Volonteri+16*

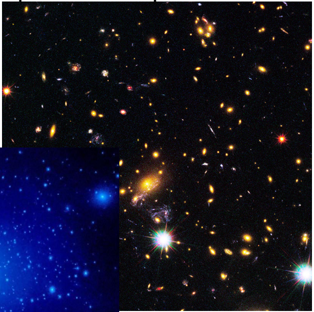
# How AGN regulate galaxy growth

**Outflows**
multi-phase
metallicity distribution
gas temp / pressure

**Radiation**
gas ionisation state
gas temperature

**Jets**
gas pressure
metallicity distribution
turbulence

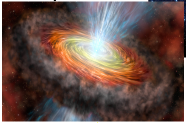
**galaxy cluster**
up to a few Mpc



**galaxy halo**
$10^2$ kpc

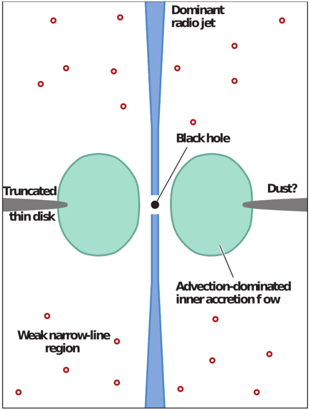
**galaxy disk**
1 – 10 kpc

**nucleus**
<10 pc



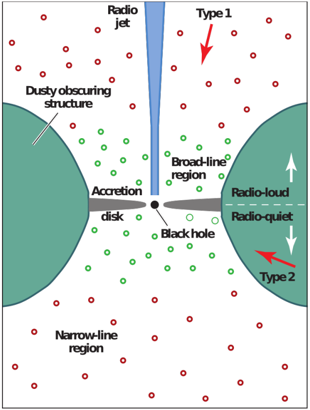
# Focusing on radio AGN

radiatively inefficient




Heckman&Best 14

radiatively efficient



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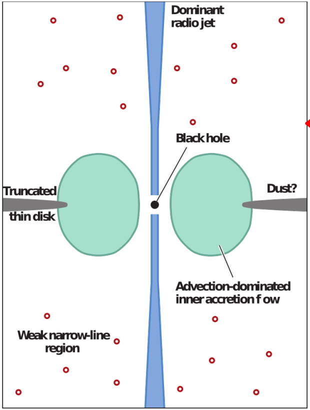


Heckman&Best 14

?

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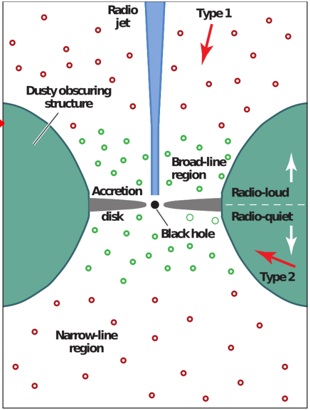

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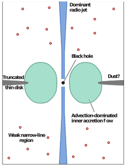


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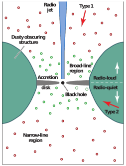


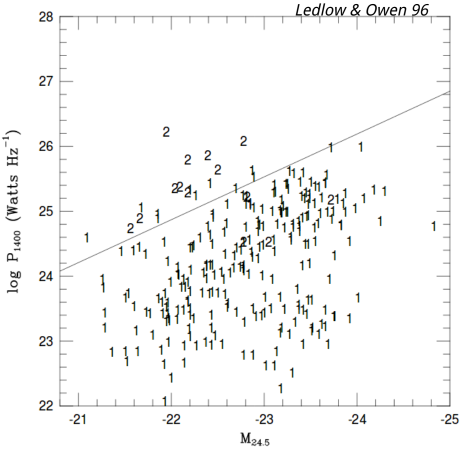

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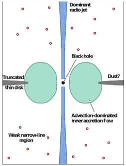


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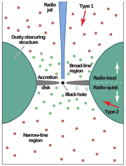
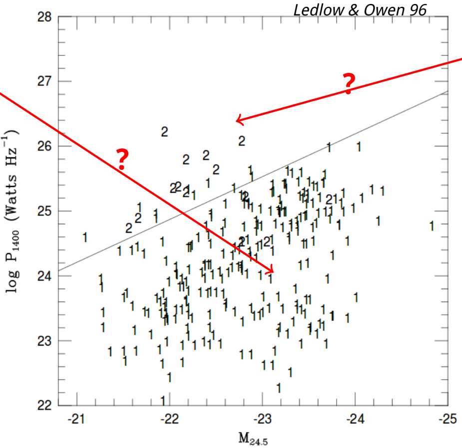


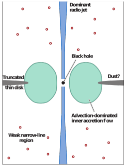



# Focusing on radio AGN

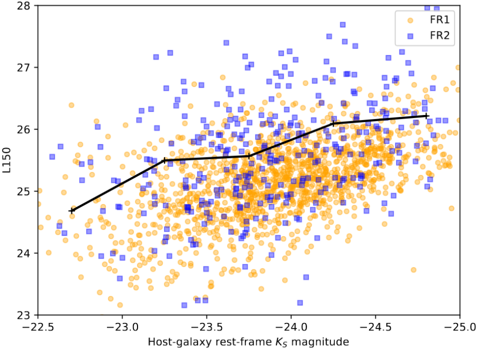
a spectrum of accretion in radio AGN

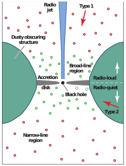
radiatively inefficient

radiatively efficient




*Mingo+**LM**+in prep*

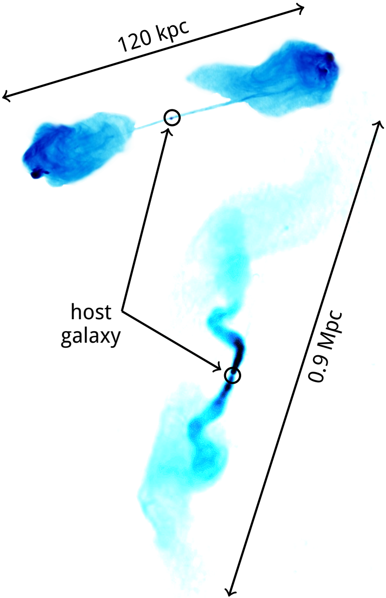


# Radio loud AGN

We know a lot about **nearby** radio loud AGN:

- the most massive AGN are always radio loud
  *Best+05, Brown+2011 Sabater+**LM**+19*
- generally found in cluster environments
  *Best+05, Sabater+13, Croston+**LM**+19*
- consistent with Unification Theory
  *Barthel 89, **Morabito**+17*



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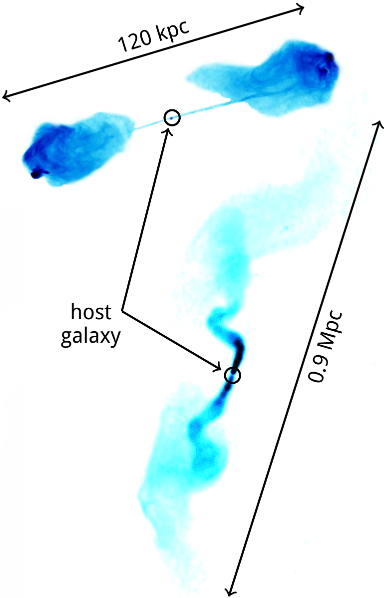
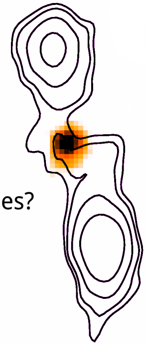



radio loud AGN out to $z \sim 6$:

- how did they form so early?
- do they have the same properties?



***Morabito**+16*
*4C 43.15*
$z = 2.49$

# Radio loud AGN

Characteristics of **high-*z*** radio loud AGN:

- At the centres of proto-clusters
  *e.g., Röttgering+96,Carilli+97,Pentericci+06*
- Optical alignment (outside galaxy)
  *Chambers+87,McCarthy+87,Pentericci+99*
- Embedded in halos of ionised gas
  *e.g., Fynbo+99,Steidel+00,Dey+05*
- Observed ultra-steep radio spectra
  *Tielens+79, Blumenthal & Miley 79*

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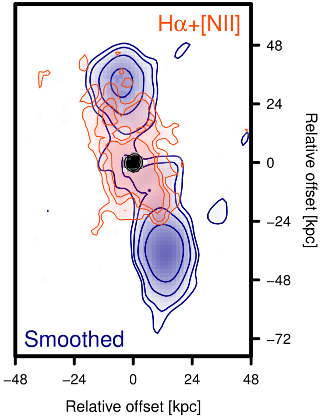
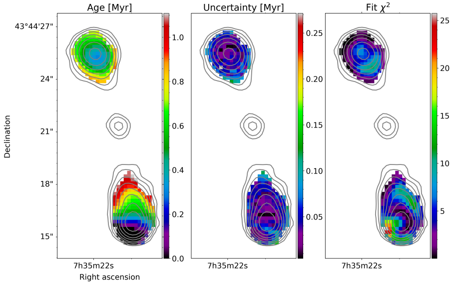
4C 43.15, at $z = 2.429$



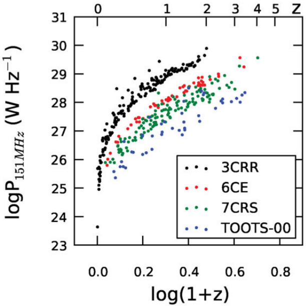

***Morabito***+16
ionised gas from *Motohara+00*




*Sweijen+**LM**+in prep*

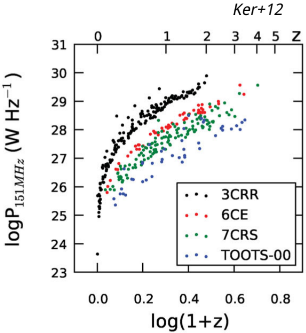
# Radio loud AGN: populations

*Ker+12*




It is difficult to break degeneracies amongst critical observable parameters $P, \alpha, D, z$

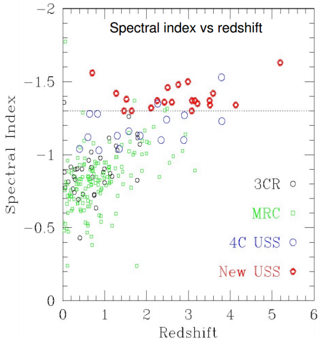
# Radio loud AGN: populations




It is difficult to break degeneracies amongst critical observable parameters $P, \alpha, D, z$

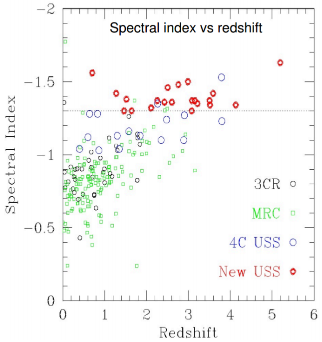
We need wide area, sensitive surveys. Particularly important for high redshift population – for which our current samples are heavily **biased** due to spectral index selection

# Radio loud AGN: populations




*de Breuck+00*

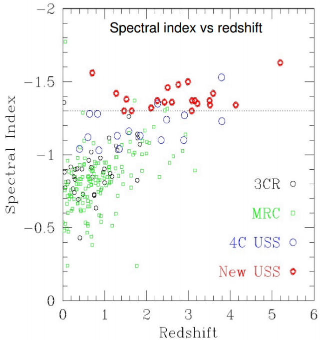
# Radio loud AGN: populations




*de Breuck+00*

Why is there a correlation?
Is it due to evolution?

# Radio loud AGN: populations




*de Breuck+00*

Why is there a correlation?
Is it due to evolution?

<u>several theories proposed:</u>

Probing different rest frequencies
*Afonso+ (2011), Klamer+ (2006), Athreya+ (1998)*

Higher ambient density at high-$z$
*Klamer+ (2006), Miley & De Breuck (2008), Athreya+ (1998)*

$L - \alpha$ relation + flux limits
*Blundell+ (1999)*

$z$-dependent inverse Compton losses
*Krolik & Chen (1991)*

# Radio loud AGN: populations

Previous studies used samples from $\leq$2 observed frequencies
there is a degeneracy between redshift and age

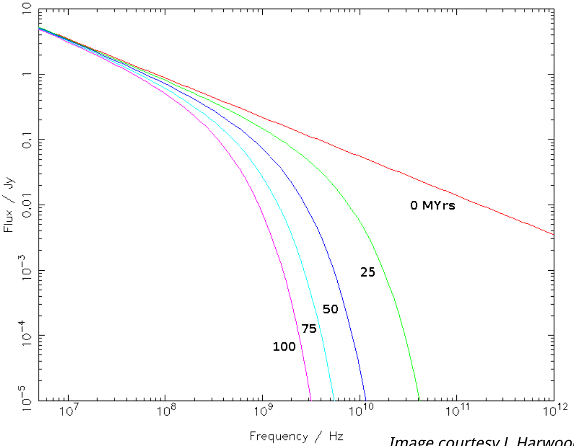



*Image courtesy J. Harwood*

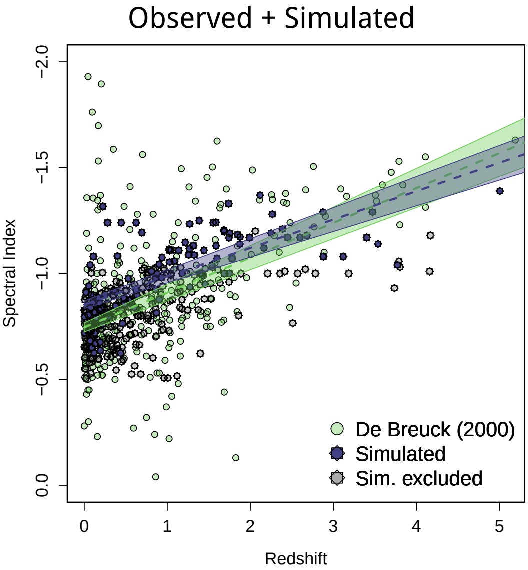
# Radio loud AGN: populations

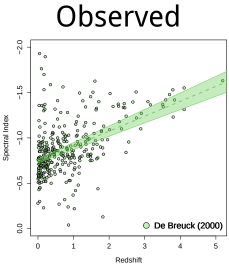
Previous studies used samples from $\leq$2 observed frequencies

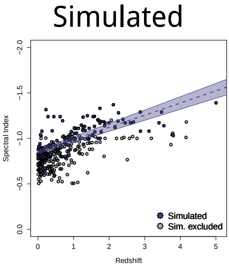
there is a degeneracy between redshift and age

1. Use spectral modelling to determine properties of low-redshift sample
   - Broadband Radio Astronomy Tools *Harwood+13,15*
2. Simulate a population with the same properties, but across redshifts matching observed sample
   - Increased scattering from CMB photons due to increased magnetic field density at higher redshift
3. "Observe " the simulated sample and measure the $\alpha - z$ relation

# Radio loud AGN: populations

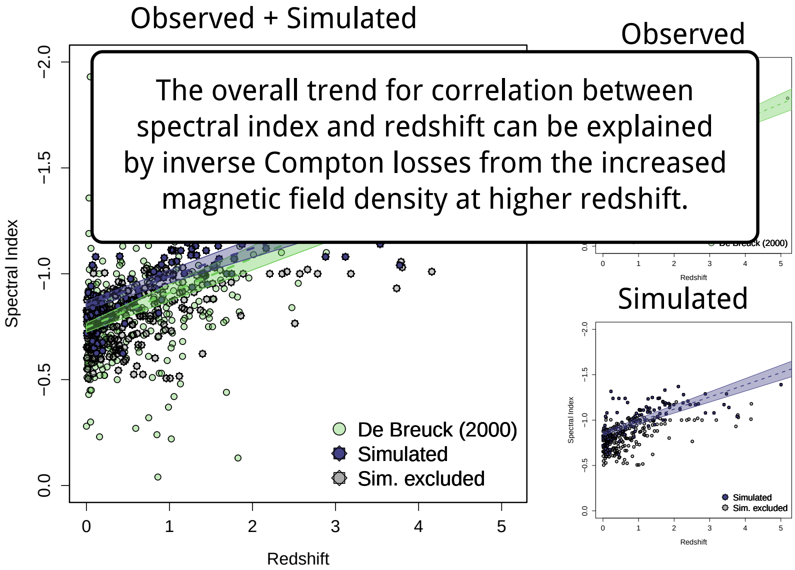



*Morabito & Harwood (2018)*

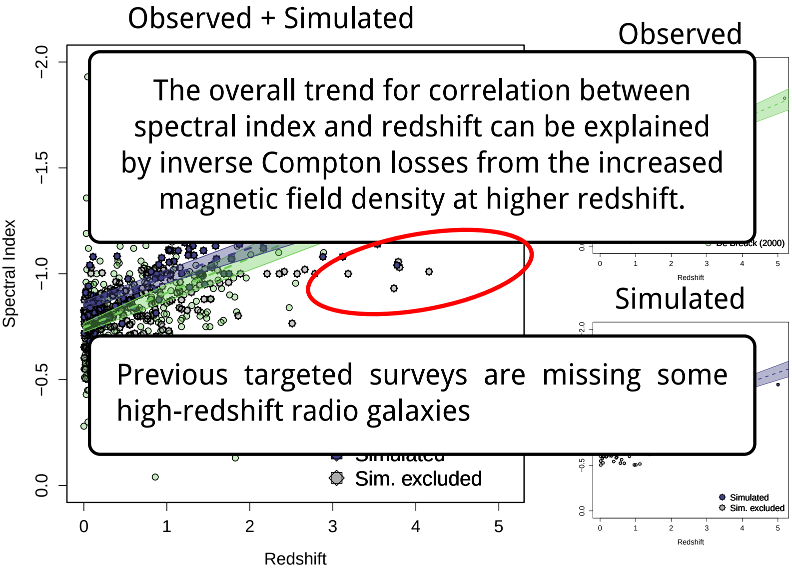
# Radio loud AGN: populations




The overall trend for correlation between spectral index and redshift can be explained by inverse Compton losses from the increased magnetic field density at higher redshift.

*Morabito & Harwood (2018)*

# Radio loud AGN: populations

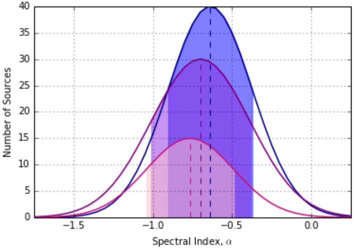


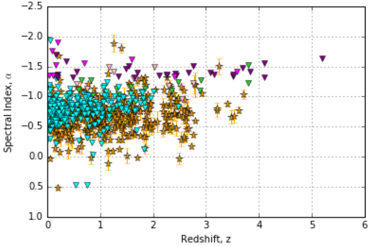

The overall trend for correlation between spectral index and redshift can be explained by inverse Compton losses from the increased magnetic field density at higher redshift.

Previous targeted surveys are missing some high-redshift radio galaxies

*Morabito & Harwood (2018)*

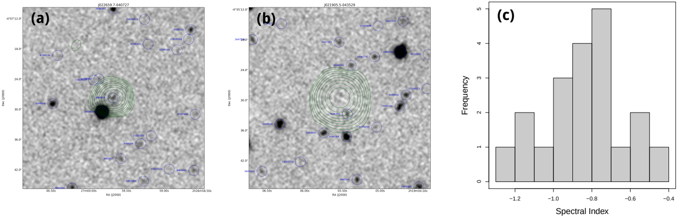
# Radio loud AGN: populations



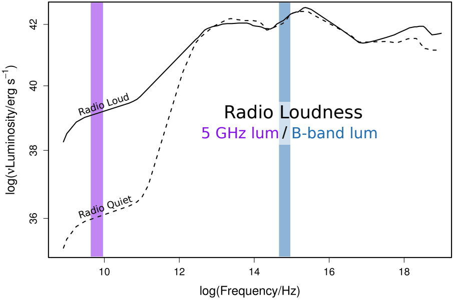




*Phipps+ in prep.*

High-*z* candidates for spectroscopic confirmation using VLT



# Radio quiet AGN



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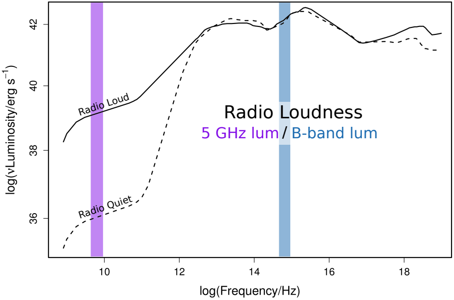



within a single galaxy, there can be radio emission from:

**Star formation** – synchrotron from electrons in supernova remnants

*e.g., Padovani+15, Kimball+11, Bonzini+13*

**AGN activity** – galaxy scale jets, disk winds, ... ?

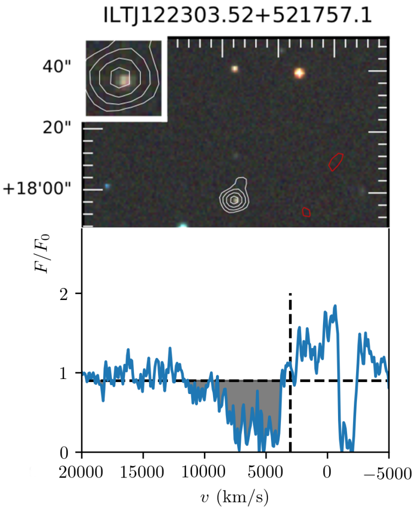
*e.g., White+15,17, Zakamska&Greene 14, **Morabito**+19*

*difficult to distingush because both processes can produce power law synchtrotron spectra*

# Radio quiet AGN

## **B**road **A**bsorption **L**ine **Q**uasars (BALQSOs)

Broad absorption lines are evidence for fast outflowing winds in our line of sight to the centres of active galaxies



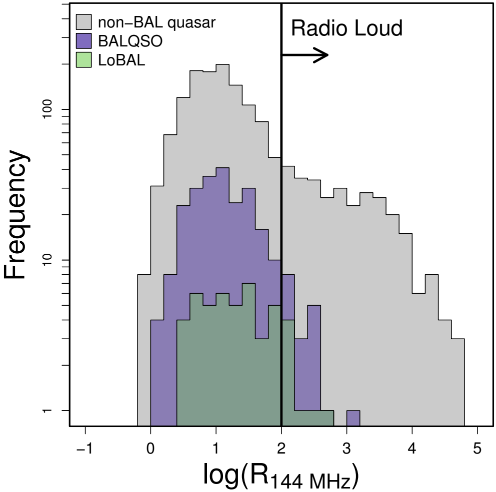

Are these an **evolutionary link** between ULIRGs/obscured quasars and unobscured quasars?

Do all quasars have these outflows and we only see them at particular **orientations**?

# Radio quiet AGN

## **B**road **A**bsorption **L**ine **Q**uasars (BALQSOs)

Most are radio quiet ... but what drives the radio emission?




*Morabito+19*

# Radio quiet AGN

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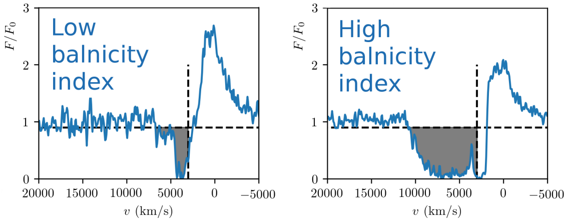
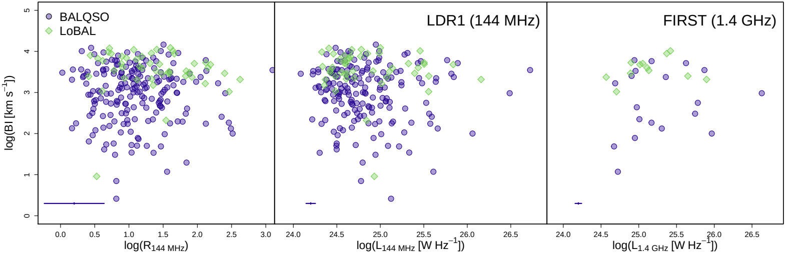



***Morabito***+19

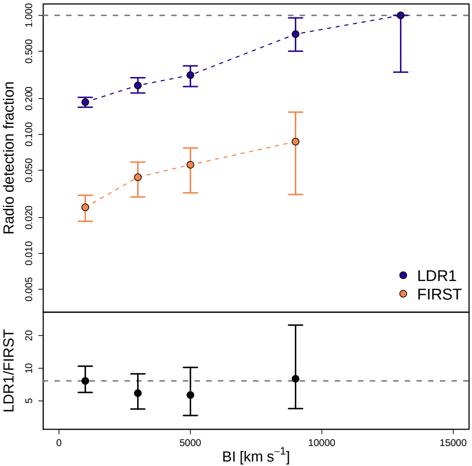



No evidence for a correlation between balnicity index and radio properties

# Radio quiet AGN

## **B**road **A**bsorption **L**ine **Q**uasars (BALQSOs)

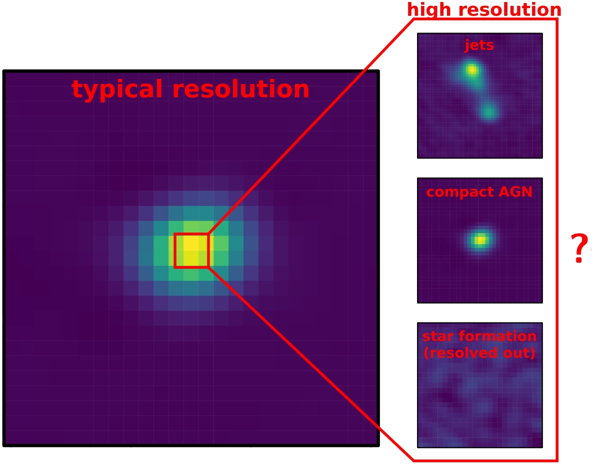
***Morabito****+19*




Radio detection fraction increases with balnicity index ... is there perhaps a faint AGN component to the radio emission hidden by scatter in radio emission from star formation?

# Radio quiet AGN

the only way to *unambiguously* separate and simultaneously measure star formation and AGN activity is via **high resolution** radio imaging



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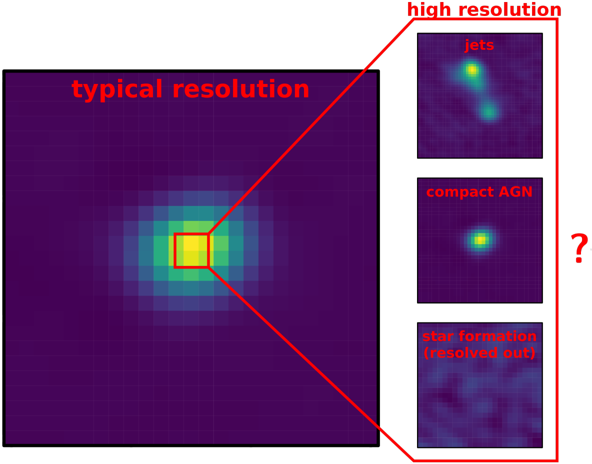


*brightness temperature*

$$T_B = 1.38 \times 10^{24} \frac{S}{\theta^2 \nu^2}$$

$T_B \gtrsim 10^5$ K $\rightarrow$ AGN, *not* star formation

*(e.g., Condon+91)*

# Radio quiet AGN

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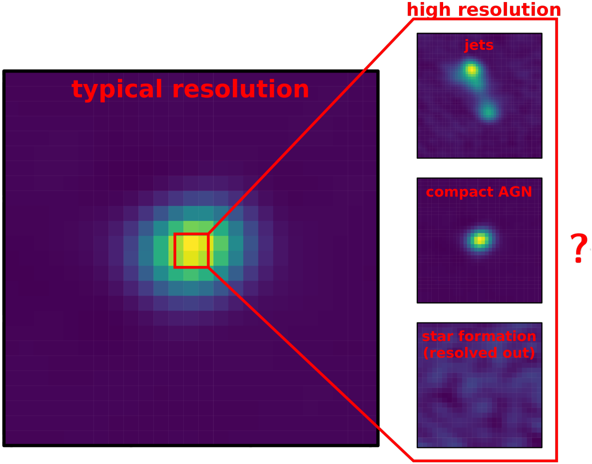


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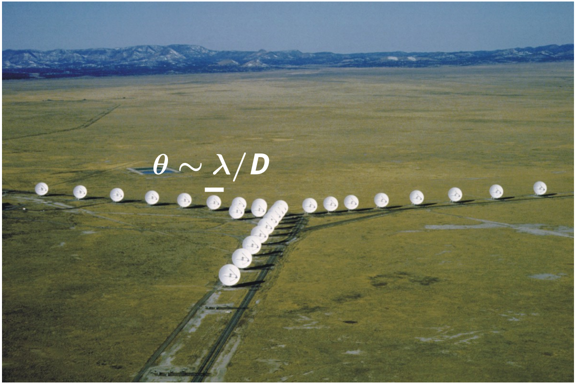
*(e.g., Condon+91)*

at GHz frequencies $\rightarrow$ need milliarcsec resolution
at 150 MHz $\rightarrow$ only need tenths of arcsec resolution

# Radio Observations: interferometry

*The Very Large Array*

# Radio Observations: interferometry




*The Very Large Array*

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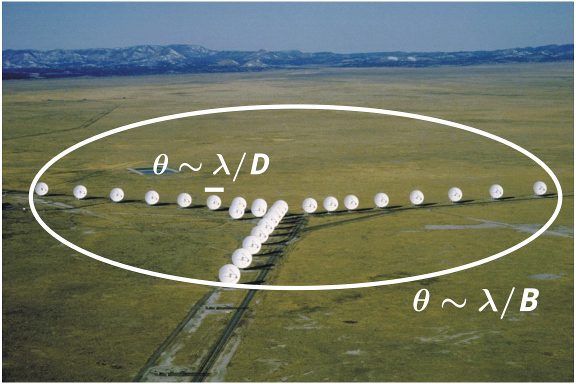
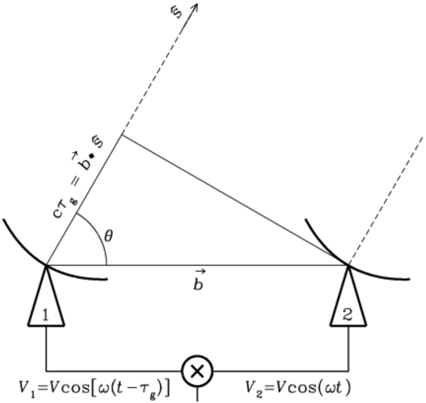



*The Very Large Array*

# Radio Observations: interferometry

Van Cittert-Zernike Theorem

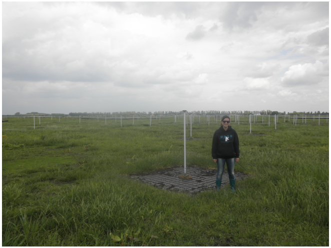
$$\Gamma_{12}(u, v, 0) = \int\int I(l, m) e^{-2\pi i(ul+vm)} \mathrm{d}l \mathrm{d}m$$



# Radio Interferometers

# Radio Interferometers

LOFAR



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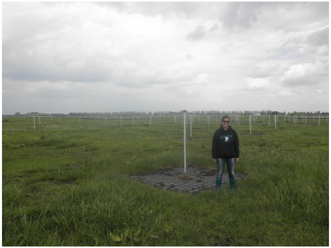
LOFAR

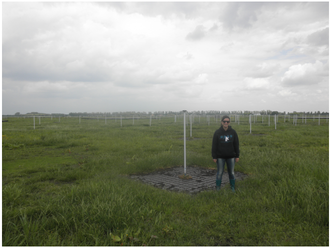


VLA

# Radio Interferometers

Meerkat

LOFAR



VLA

# Radio Interferometers

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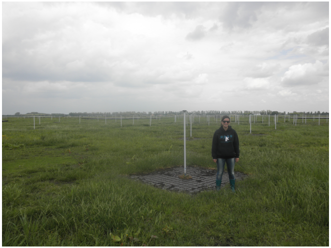
LOFAR



VLA

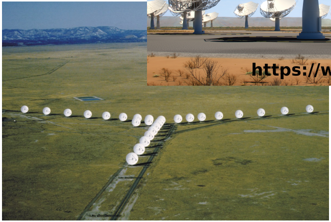
Passive Detection System

# Radio Interferometers

LOFAR

Meerkat


V



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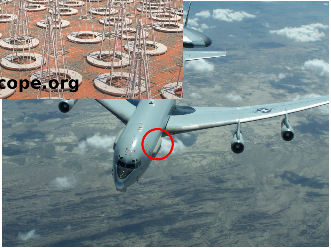
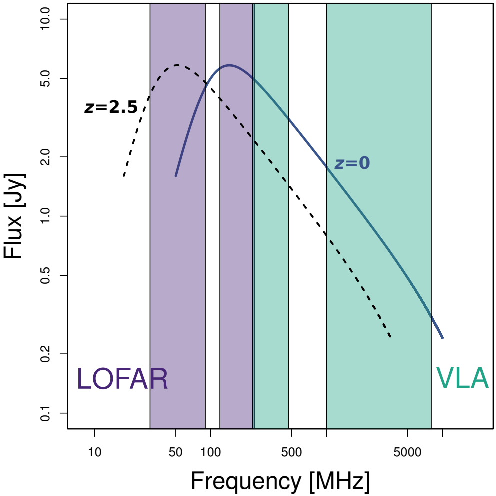
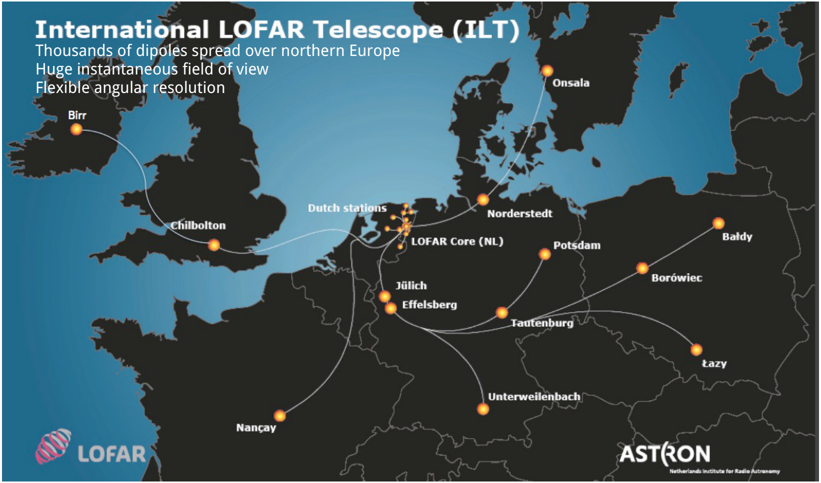


# Observing frequency matters!

Typical radio sources will be brighter at low frequencies, and the turnover at ∼100 MHz is important to measure to understand physical conditions of the emission region(s). Complementary mid-frequency observations will yield spectral index information.



# The Low Frequency Array



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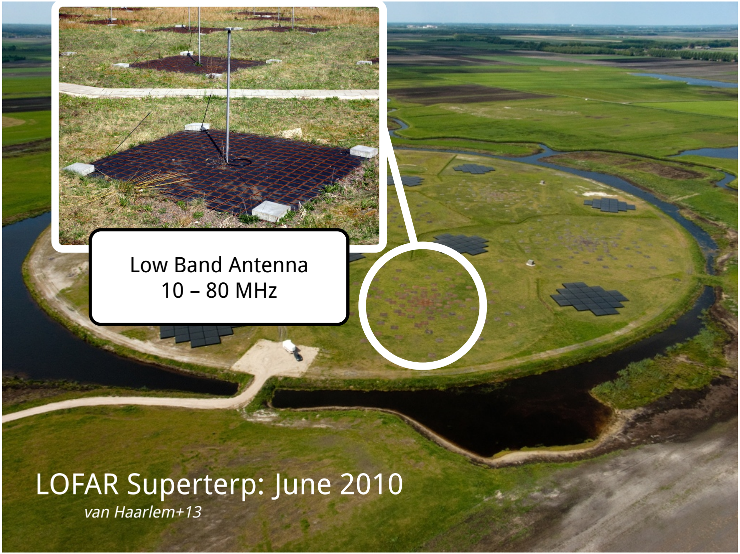

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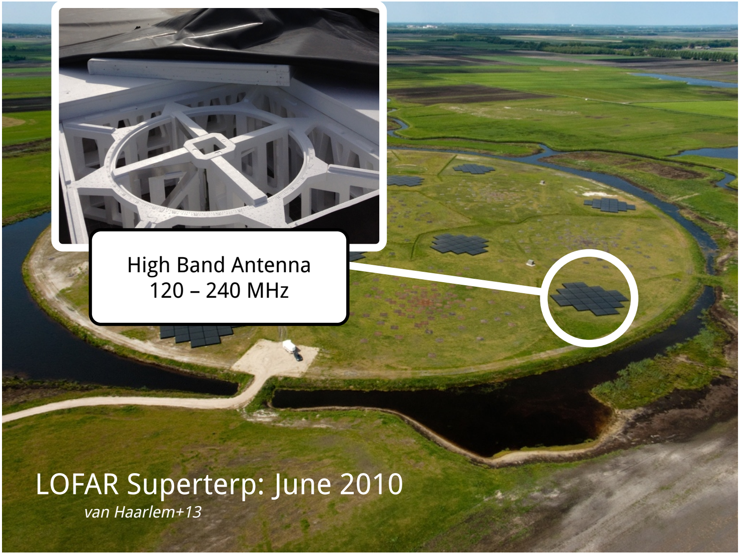
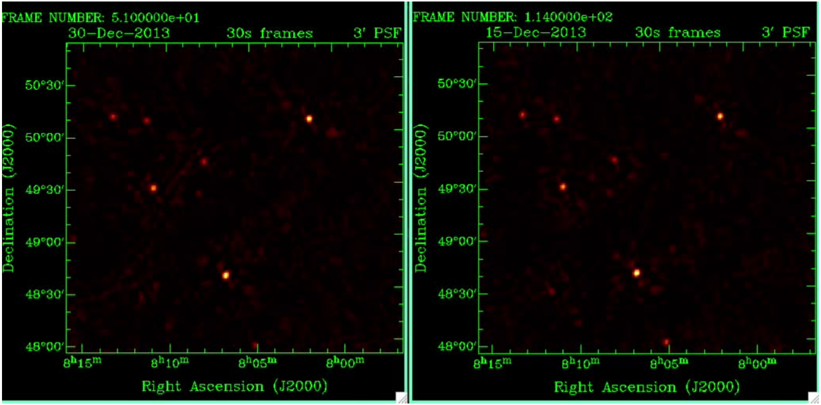


the Ionosphere: our main challenge

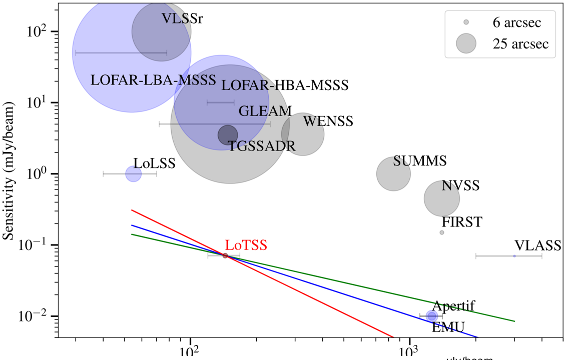
**reasonable** **good**




*video courtesy G. de Bruyn*

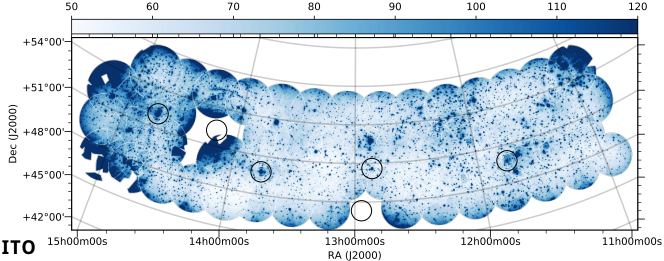
# LOFAR Two-metre Sky Survey

*Shimwell+**LM**+19*




Northern sky survey
Dutch LOFAR stations
120 - 168 MHz
5 arcsec
rms $\sim$ 70 $\mu$Jy bm$^{-1}$

Data Release 1, Feb 2019
424 deg$^2$
320,000+ sources



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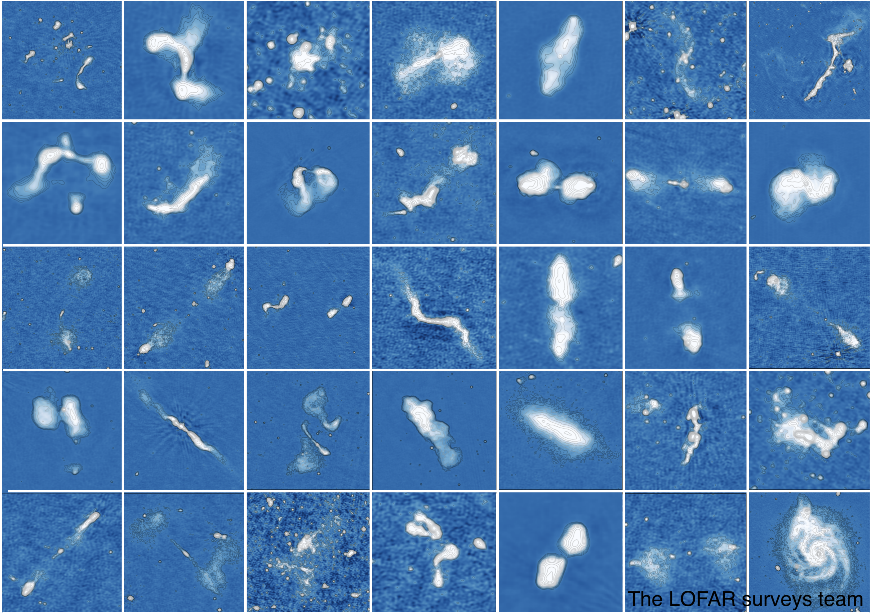

# LOFAR Two-metre Sky Survey

## Survey data calibration and description

The LOFAR Two-metre Sky Survey. II. First data release *Shimwell+**LM**+19*
The LOFAR Two-metre Sky Survey – III. Optical identifications and Value-added catalogue *Williams+**LM**+19*
The LOFAR Two-metre Sky Survey – IV. Photometric redshifts and rest-frame magnitudes *Duncan+**LM**+19*
Systematic effects in LOFAR data: a unified LOFAR-LBA and LOFAR-HBA calibration strategy *De Gasperin+**LM**+19*

## AGN and accretion processes

The origin of radio emission in broad absorption line quasars: results from the LOFAR Two-metre Sky Survey ***Morabito**+19* ● Radio-loud AGN in the first LoTSS data release: The lifetimes and environmental impact of jet-driven sources *Hardcastle+**LM**+19* ● LoTSS DR1: Double Double Radio Galaxies in the HETDEX Spring field *Mahatma+**LM**+19* ● Blazars in the LOFAR Two-Metre Sky Survey First Data Release *Mooney+**LM**+19* ● LoTSS/HETDEX: Optical quasars -I. Low-frequency radio properties of optically selected quasars *Gürkan+**LM**+19* ● The LoTSS view of radio-AGN in the local Universe. The most massive galaxies are always switched on *Sabater+**LM**+19* ● LOFAR first look at the giant radio galaxy 3C 236 *Shulevski* ● Disentangling star-formation and AGN activity in gravitationally-lensed radio-quiet quasars *Stacey+**LM**+19*

## Galaxy clusters

The spectacular cluster chain Abell 781 as observed with LOFAR, GMRT and XMM-Newton *Botteon +19* ● Ultra-steep spectrum emission in the merging galaxy cluster Abell 1914 *Mandal+19* ● Signatures from a merging galaxy cluster its AGN population: LOFAR observations of Abell 1682 *Clarke+19* ● The LOFAR view on the merging galaxy cluster Abell 2069 *Drabent+19* ● A double radio halo in Abell 1430 *Dumba+19* ● A LOFAR study of non-merging massive galaxy clusters *Savini+19* ● The evolutionary phases of merging clusters as seen by LOFAR *Wilber+19* ● Radio observations of the merging galaxy cluster Abell 520 *Hoang+19* ● Characterizing the radio emission from the binary galaxy cluster merger Abell 2146 *Hoang+19*

## Large scale structure

LOFAR Observations of the XMM-LSS field *Hale+**LM**+19* ● The intergalactic magnetic field probed by a giant radio galaxy *O'Sullivan+**LM**+19* ● The environments of radio-loud AGN from the LOFAR Two-Metre Sky Survey (LoTSS) *Croston+**LM**+19* ● The first detection of radio recombination lines at cosmological distances *Emig+19*

## Nearby galaxies (and Milky Way)

The low-frequency radio-SFR relation in nearby galaxies at 1-kpc scale with LOFAR *Heesen+19* ● Exploring the properties of low-frequency radio emission and magnetic fields of a sample of compact galaxy groups using the LOFAR Two-Metre Sky Survey *Nikiel-Wroczynski+19* ● CHANG-ES XII: A LOFAR and VLA view of the edge-on star-forming galaxy NGC 3556 *Miskolczi+19* ● A low-frequency view of mixed-morphology supernova remnant VRO 42.05.01, and its neighbourhood *Arias+19*

The LOFAR surveys team

# Radio AGN: open questions

**My research focuses on the following broad questions:**

1. What links galaxies and their AGN on the smallest scales?
   *What is the interplay between AGN activity and star formation?*
2. How and when were the most powerful AGN formed?
3. How do AGN evolve with redshift to shape the galaxies we see today?

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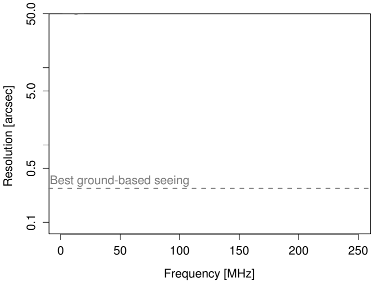
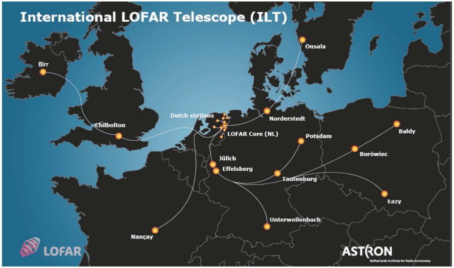
**To answer these questions requires:**

- High enough ***resolution*** to morphologically classify the radio emission and determine its source
- Samples ***large enough*** to break degeneracies amongst $P, \alpha, D, z$, and environment
- ***Multi-wavelength*** information to extract properties of the host galaxies

# High resolution imaging with LOFAR



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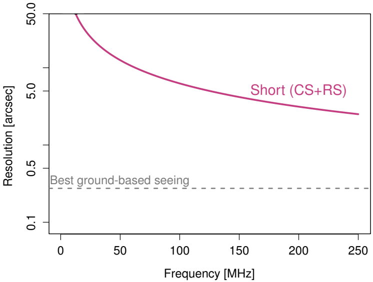


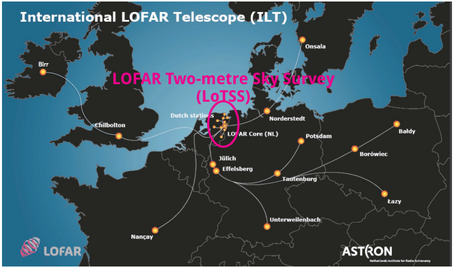

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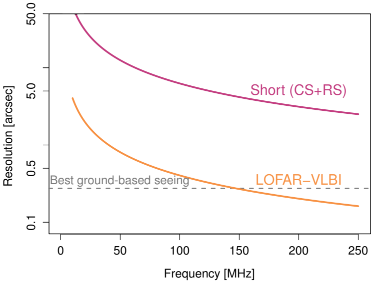


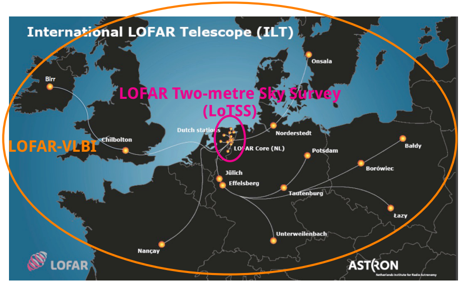

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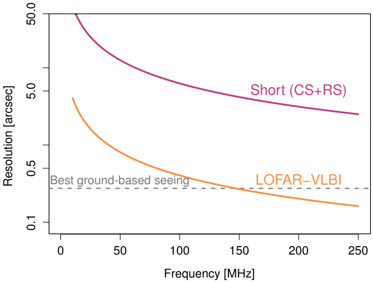


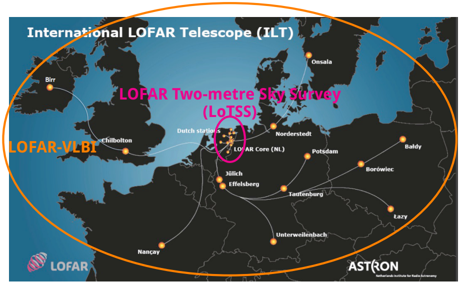


Combining signals from 25,000+ dipoles is very challenging

| | |
|---|---|
| **Data Volume** | typical observations are 4 - 20 TB |
| **Clocks** | independent station clocks have to be synchronized |
| **Correlator model** | baselines up to 2000 km mean lower tolerance for errors |
| **Ionopshere** | can be wildly varying with larger impact for longer baselines |
| **Calibrators** | need ‘Goldilocks’ calibrators: compact and bright enough |
| **Source structure** | *not everything is a point source ...* |

# High resolution imaging with LOFAR

I have helped develop a calibration strategy for high resolution imaging at $< 200$ MHz, incorporating some VLBI techniques.

***Morabito**+16, **Morabito**,Jackson+ in prep*

# High resolution imaging with LOFAR

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*Morabito+16, Morabito,Jackson+ in prep*

**fringe-fitting**, which estimates *delay* and *rate* in addition to phase errors:

$$\Delta\phi_{\nu,t} = \phi_0 + \left(\frac{\delta\phi}{\delta\nu}\Delta\nu + \frac{\delta\phi}{\delta t}\Delta t\right)$$

does not account for *dispersive* effects, which are dominant at low frequencies:

$$\Delta\phi_{\nu,t} \propto \nu^{-2}$$

and there are other direction-dependent effects ...

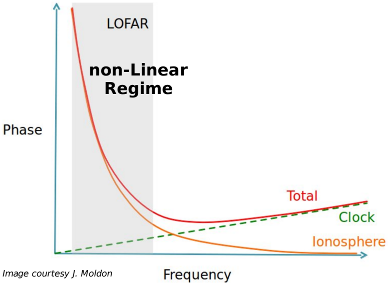
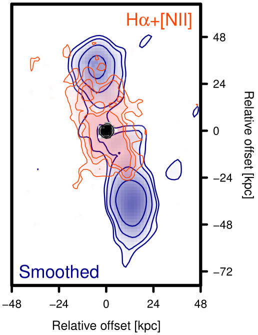



*Image courtesy J. Moldon*

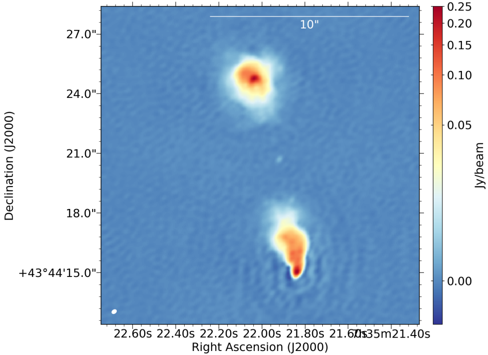
The Long Baseline Working Group is dedicated to building an automated pipeline for wide-field imaging at high resolution

# High resolution imaging with LOFAR

We have already built a pipeline for pointed observations of individual science targets




***Morabito**+16*
ionised gas from *Motohara+00*




*Sweijen+**LM**+ in prep*

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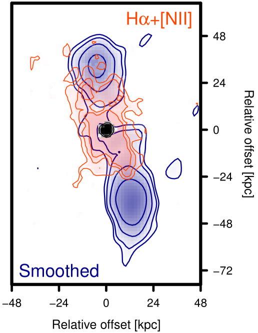


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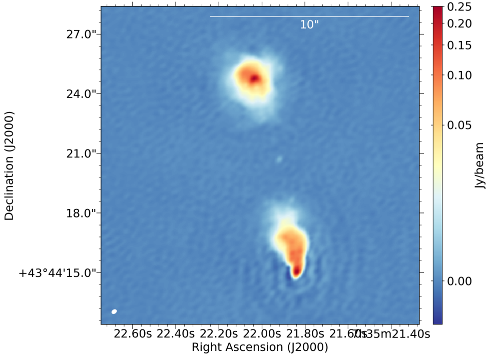
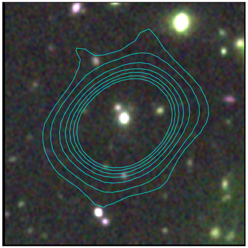


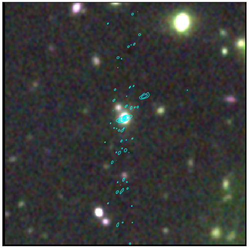

*Sweijen+**LM**+ in prep*

**we are now extending this to wide-field imaging and will achieve sub-arcsecond resolution across the entire 5 deg$^2$ field of view of a single LOFAR pointing**

# High resolution imaging with LOFAR



*VIDEO J,H,$K_S$ • LOFAR contours*



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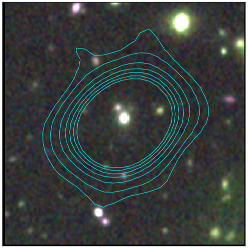

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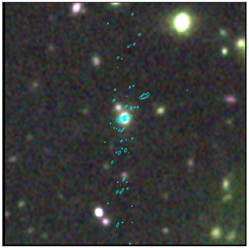
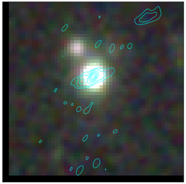
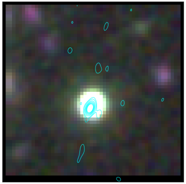


*VIDEO J,H,$K_S$ • LOFAR contours*

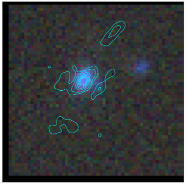
examples from XMM-LSS



*VIDEO J,H,$K_S$*



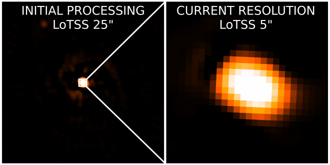
*VIDEO J,H,$K_S$*

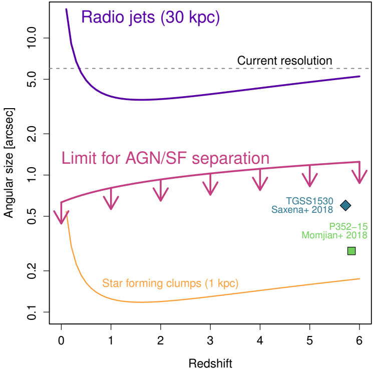


*Subaru g,r,i*

# High resolution imaging with LOFAR

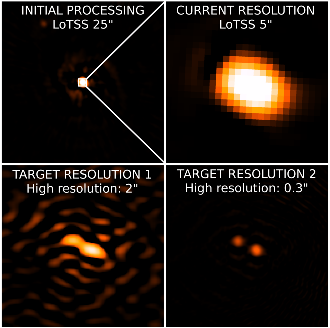
***This is precisely what is needed to achieve science goals***

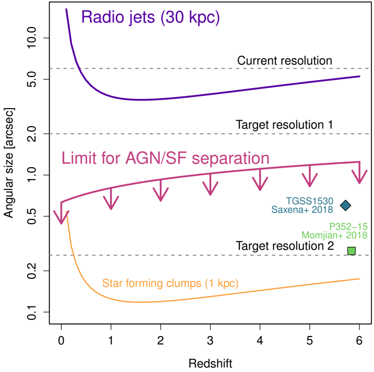


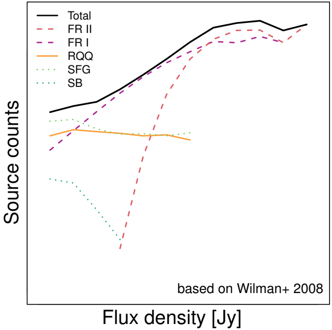
# High resolution imaging with LOFAR

## *This is precisely what is needed to achieve science goals*



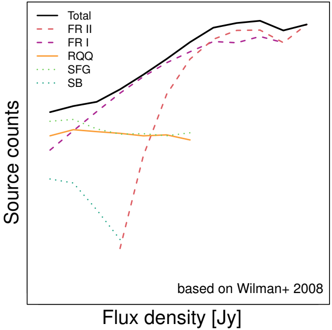



# A new type of radio survey observed

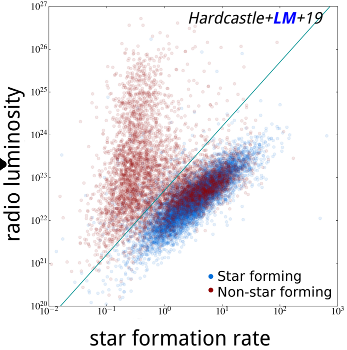


# A new type of radio survey

## observed

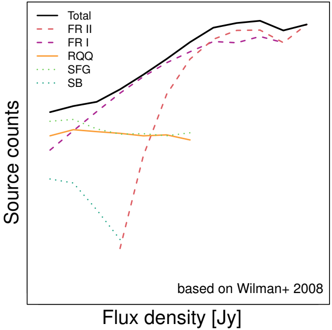



## physical properties

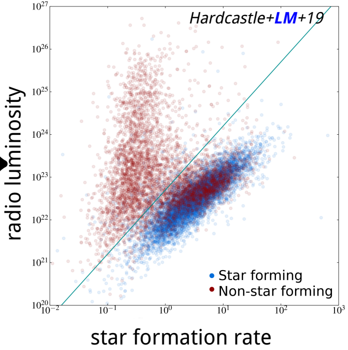


# A new type of radio survey

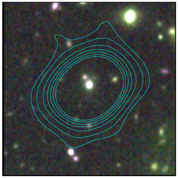
## observed

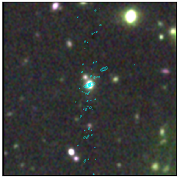



## physical properties



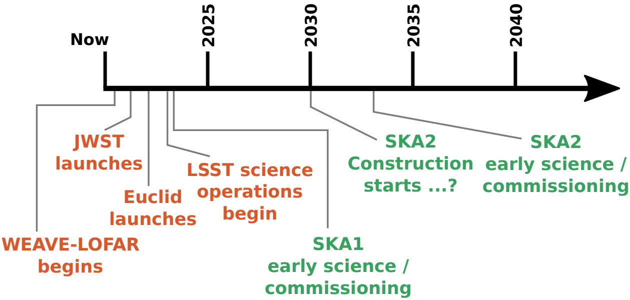

## multi-wavelength data



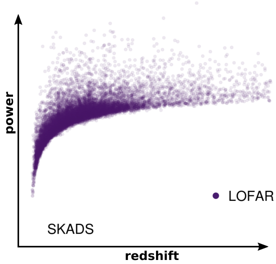


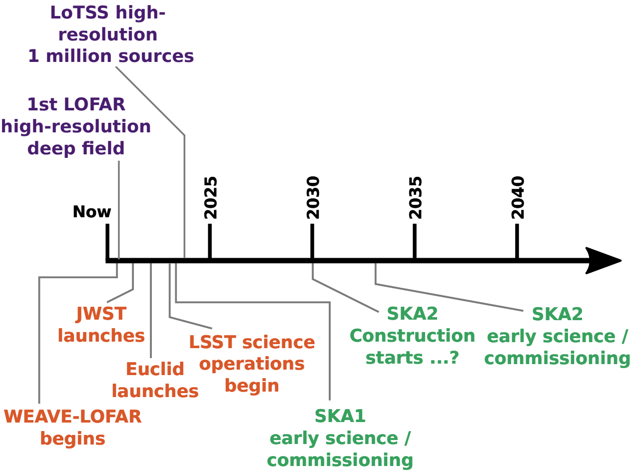
Precise cross-matching
enables accurate science

# Looking to the future

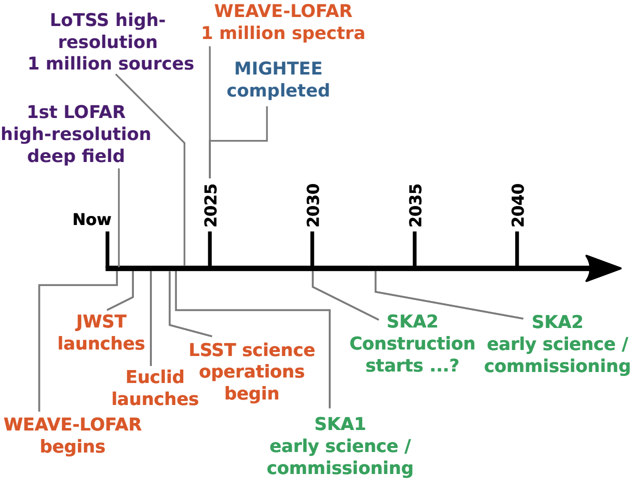


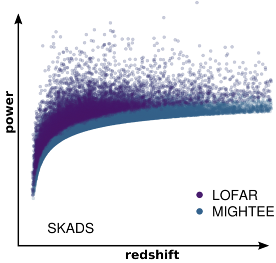
# Looking to the future



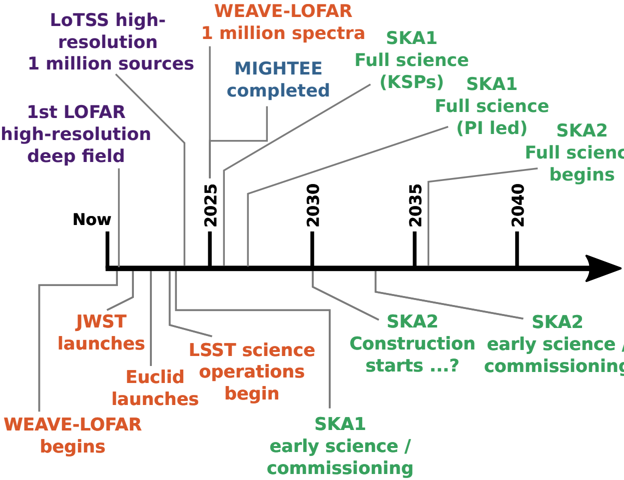



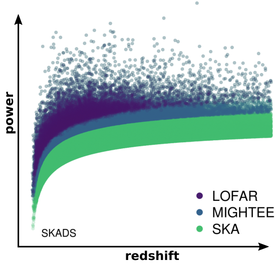
# Looking to the future



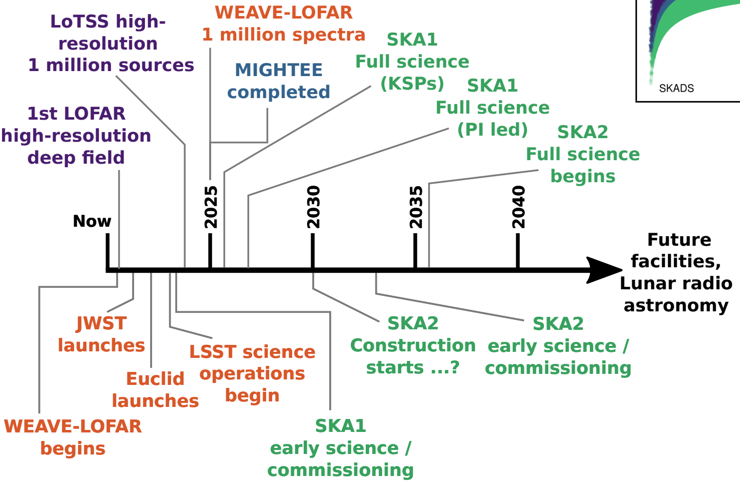



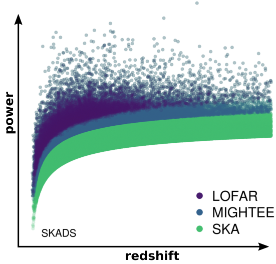
# Looking to the future



# Looking to the future



**The advent of new radio telescopes with unprecedented capabilities provides a unique opportunity to drive forward our understanding of radio AGN in the coming years.**

*Many thanks to my collaborators:*
*Neal Jackson, Martin Hardcastle, Yarin Gal (CS), Philip Best, Judith Croston, Beatriz Mingo, Tim Shimwell, Wendy Williams, Ken Duncan, James Matthews, Dan Smith, Jeremy Harwood, Matt Jarvis, Rogier Windhorst, Reinout van Weeren, Jose Sabater, Gulay Gürkan, Isabella Prandoni, Sean Mooney, John Quinn, James Allison, Ian Heywood, Catherine Hale, Francesco Shankar, Cyril Tasse, Etienne Bonnasieux, Alexander Drabent, Huub Röttgering, Kristina Nyland, John McKean, Eskil Varenius, Javier Moldon, George Miley, Magdalena Kunert-Bajraszewski, Huib Intema, George Heald, Adam Deller, Raymond Oonk*

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