Cosmology from Radio Continuum Surveys

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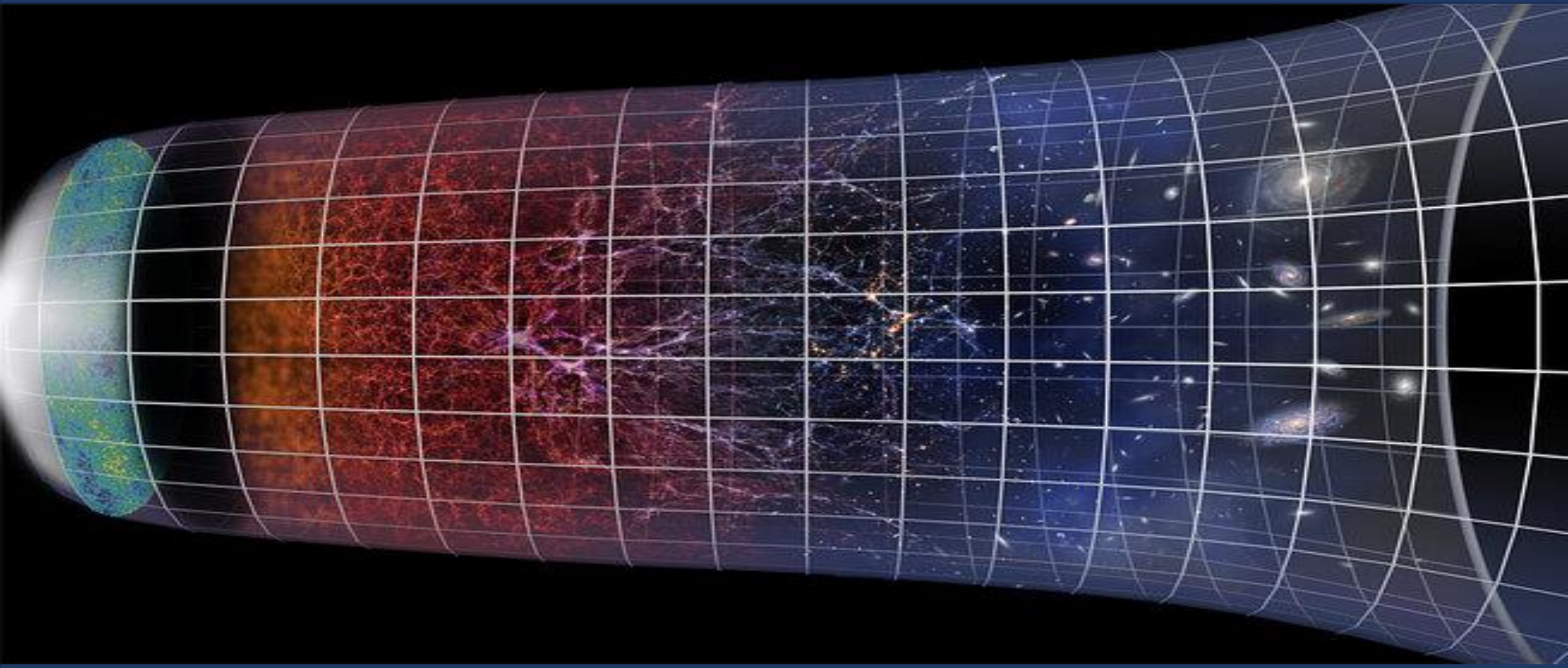
University of Oxford

Talk Overview

Credit: SKAO

- Radio emission in galaxy surveys
- Advantages/Challenges in Radio Astronomy
- Current Extragalactic radio survey with SKAO Precursor/Pathfinders
- Cosmology with current surveys
- Cosmology with the SKAO

Large-Scale Structure of the Universe

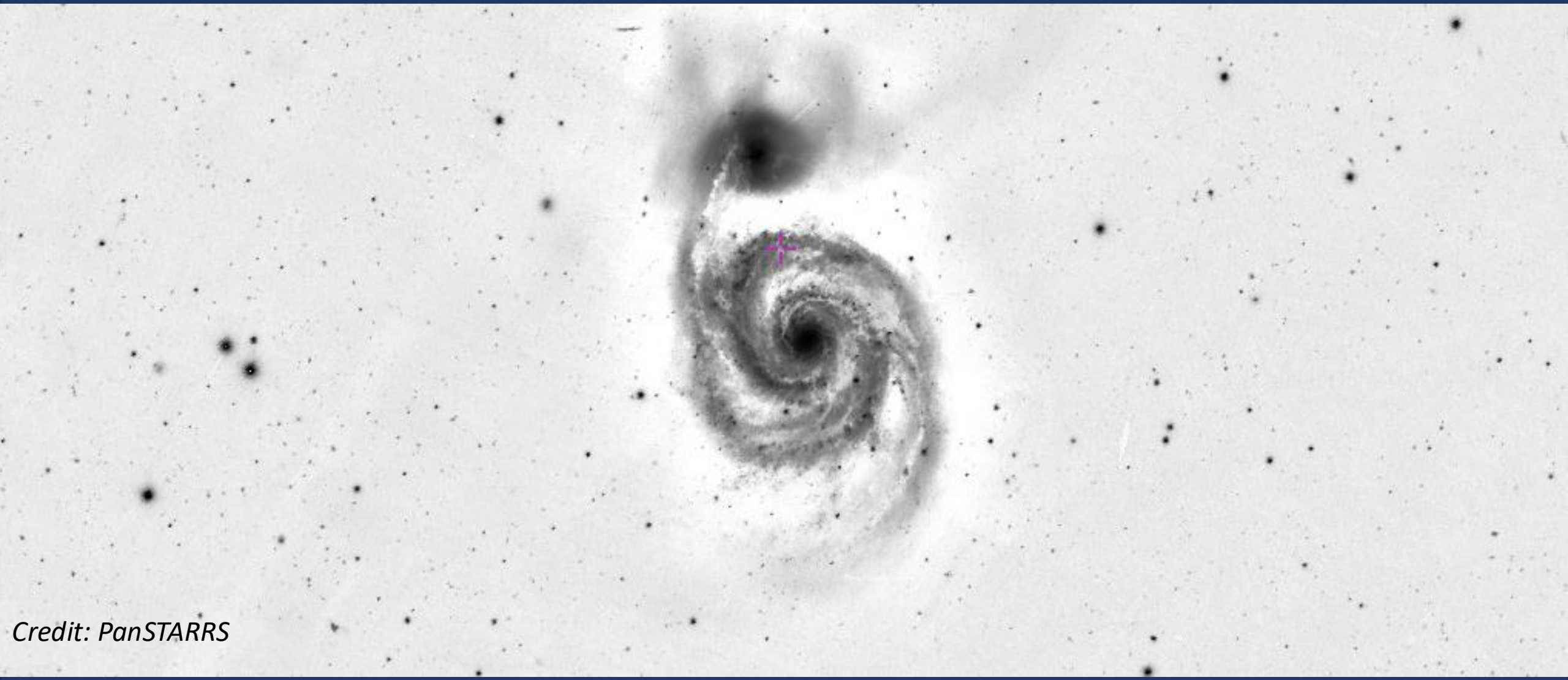


Credit: ESO/M. Kornmesser

Large-Scale Structure of the Universe

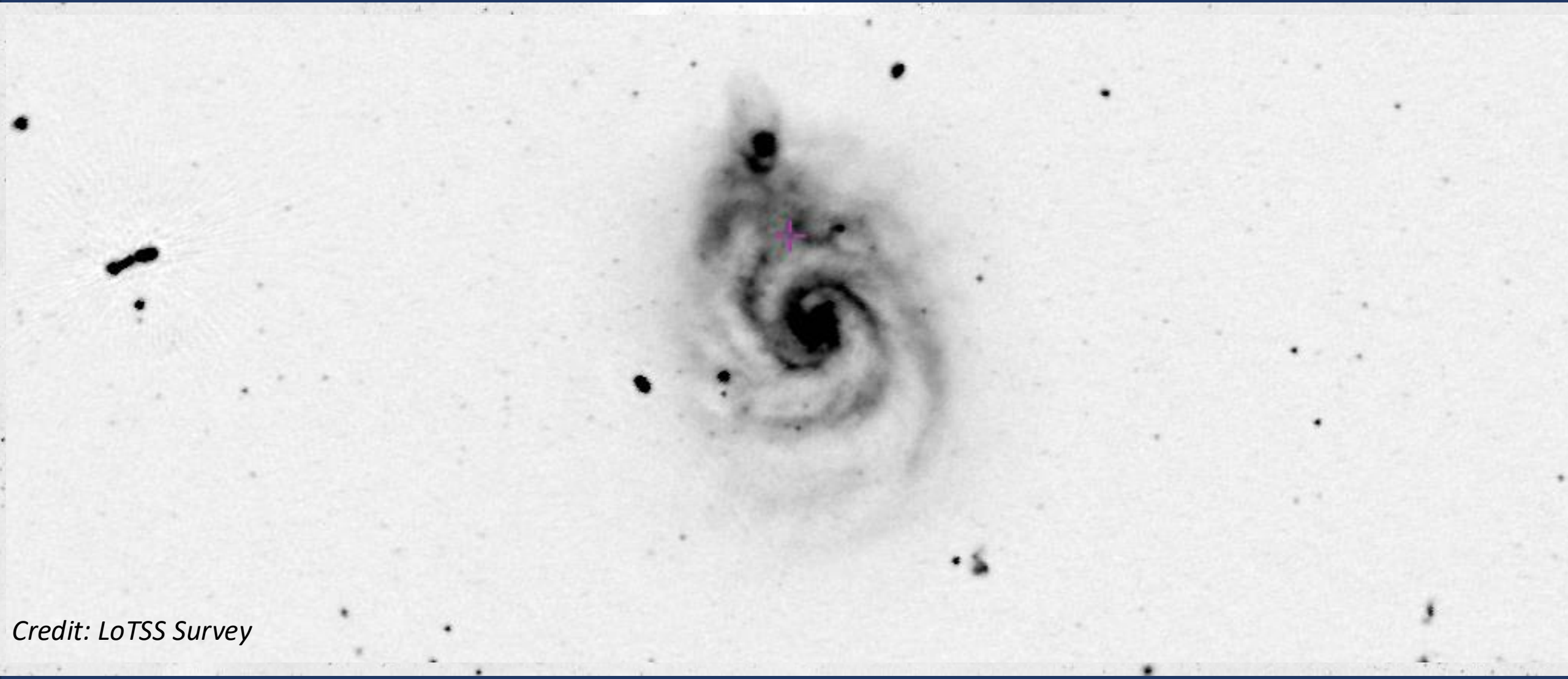
Credit: ESA/Euclid/Euclid Consortium/NASA
Image processing by M. Walmsley, M. Huertas-Company, J.-C. Cuillandre

Radio Emission from Extragalactic Sources



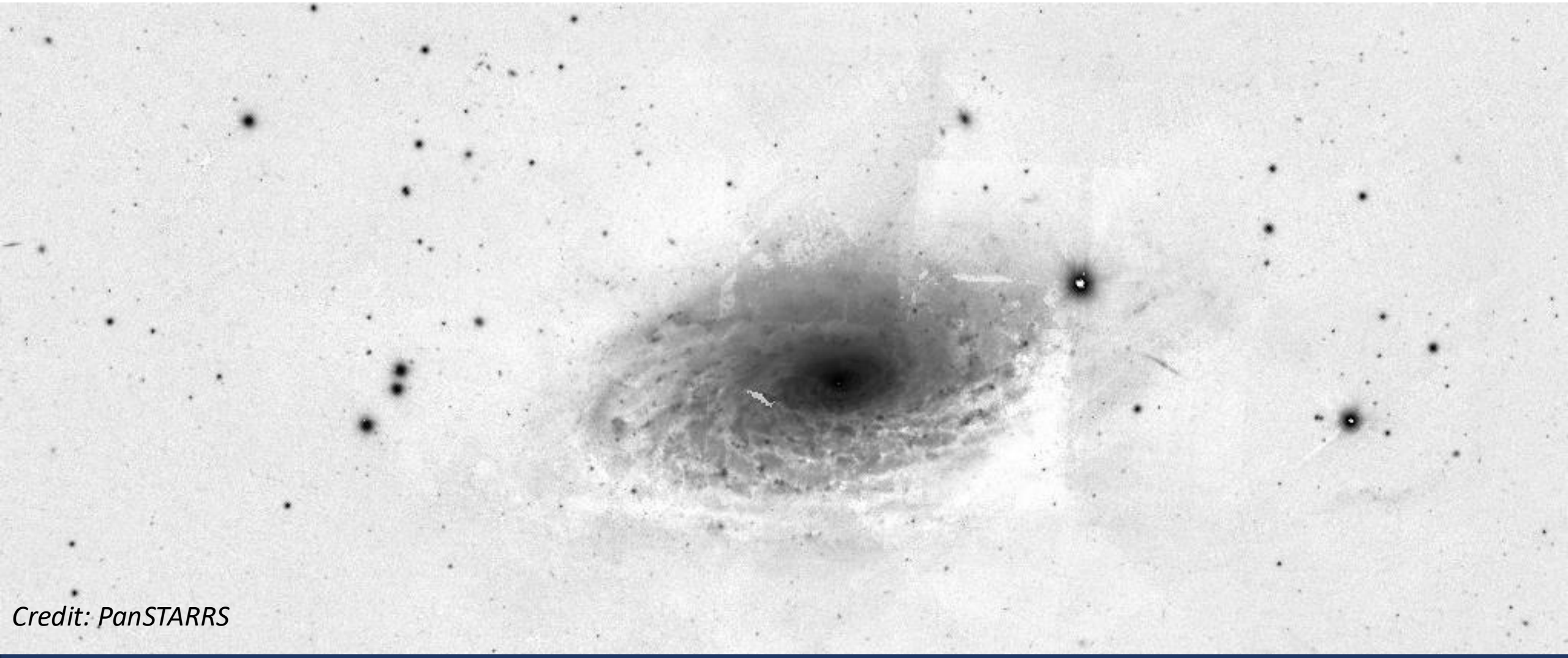
Credit: PanSTARRS

Radio Emission from Extragalactic Sources



Credit: LoTSS Survey

Radio Emission from Extragalactic Sources



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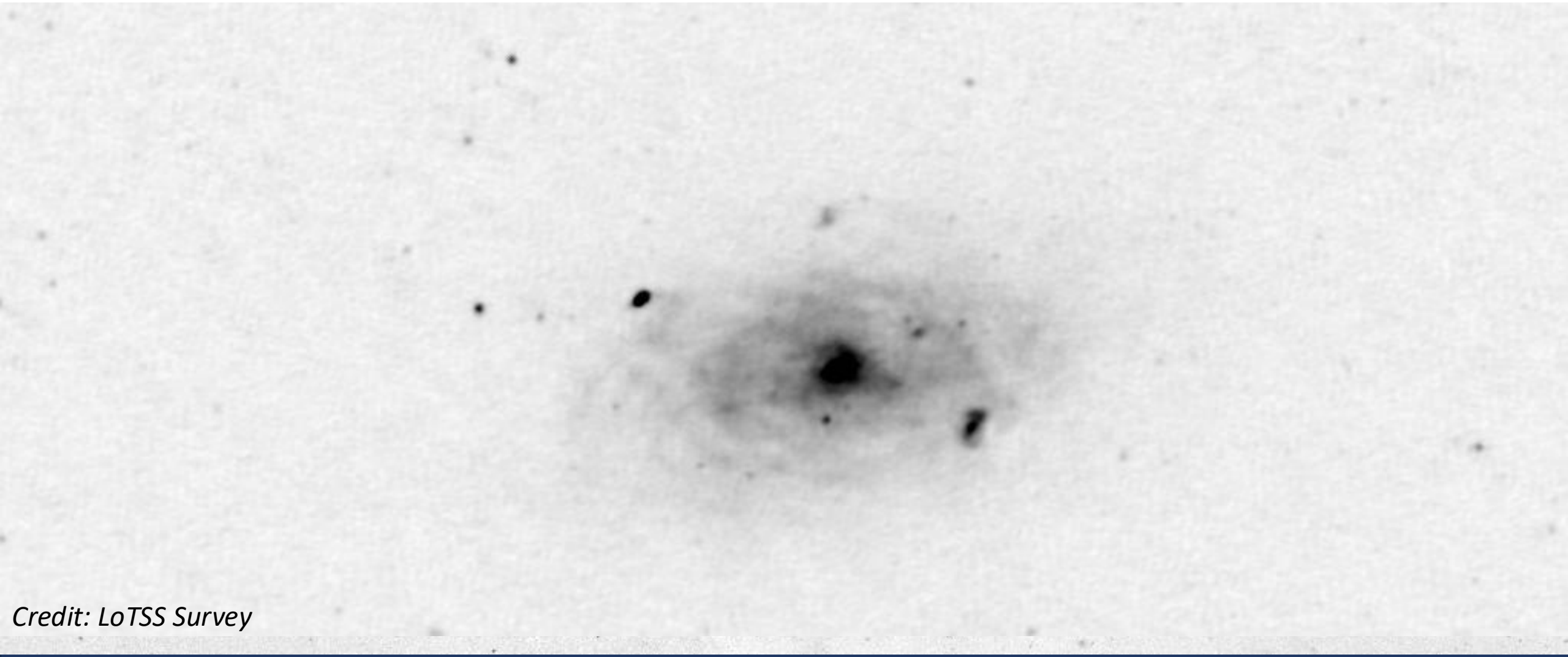

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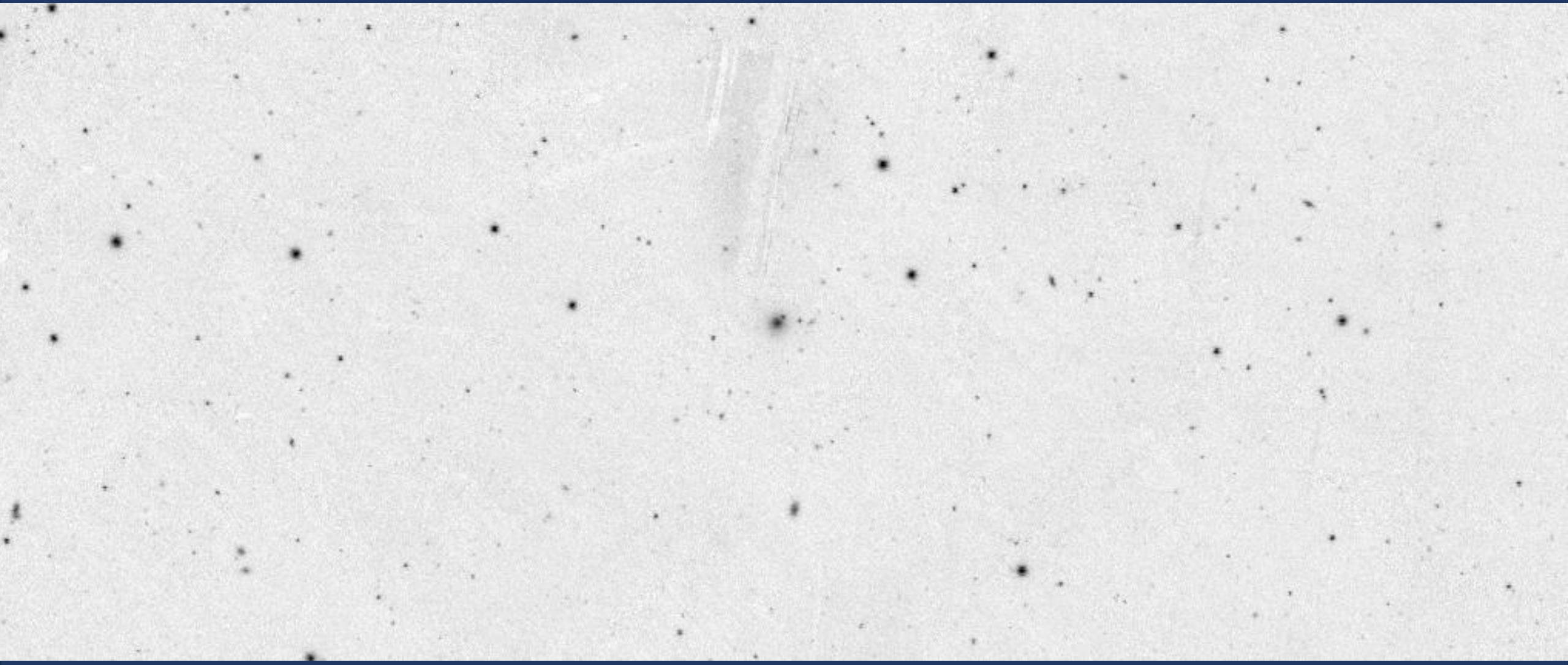
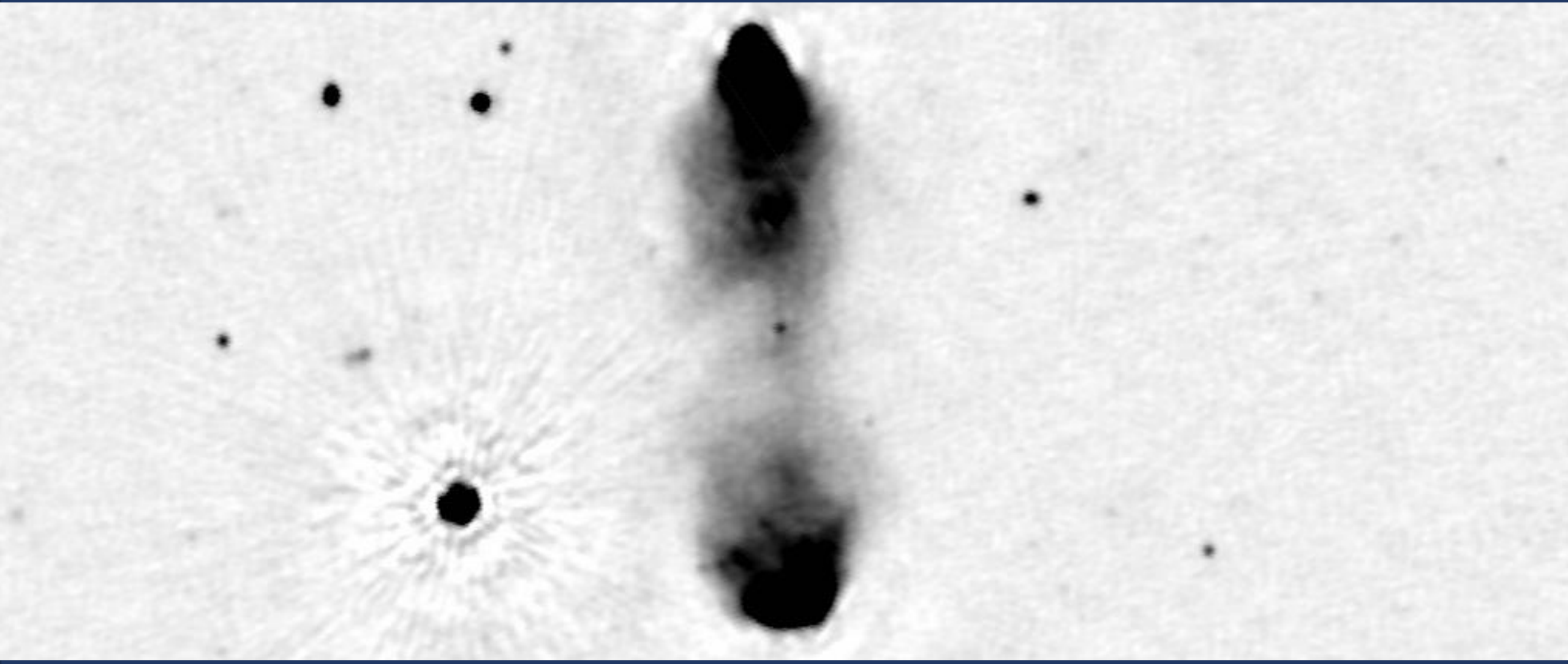
Radio Emission from Extragalactic Sources



Radio Emission from Extragalactic Sources



Radio Skies

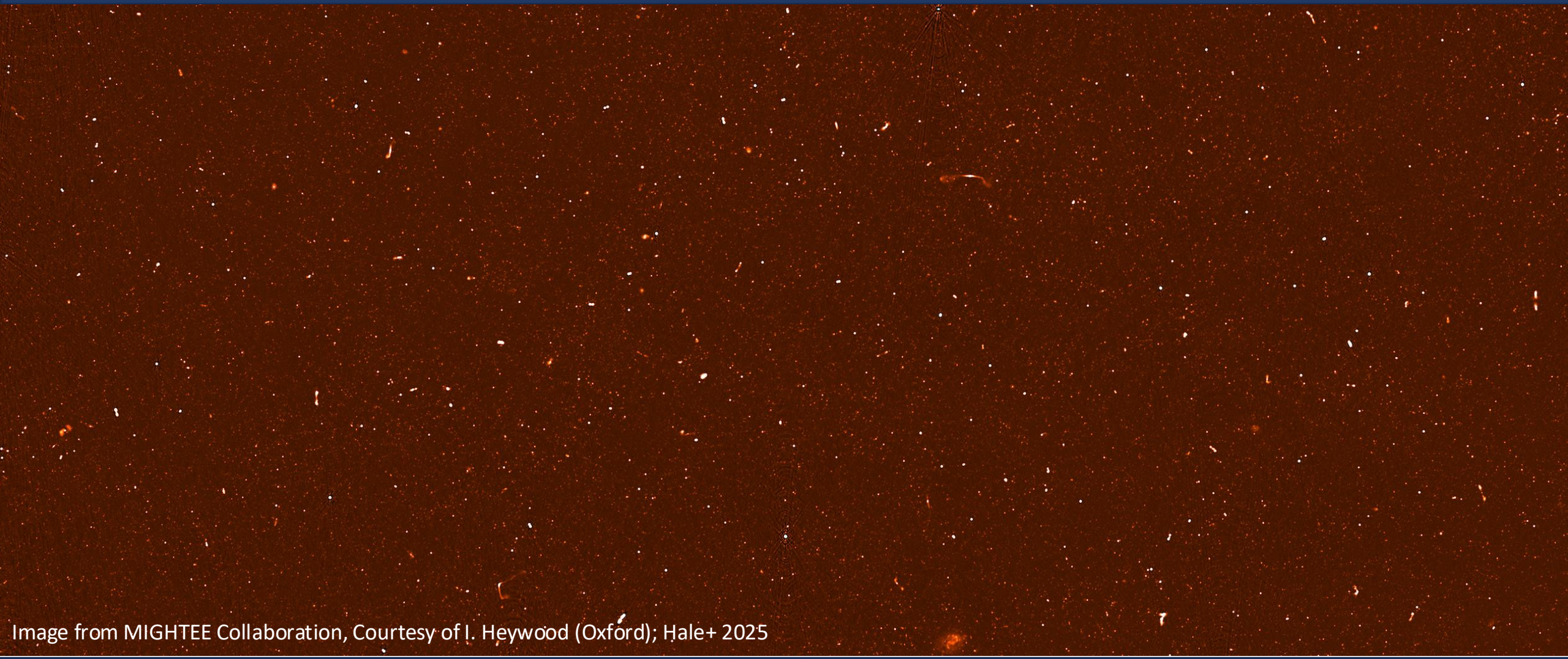
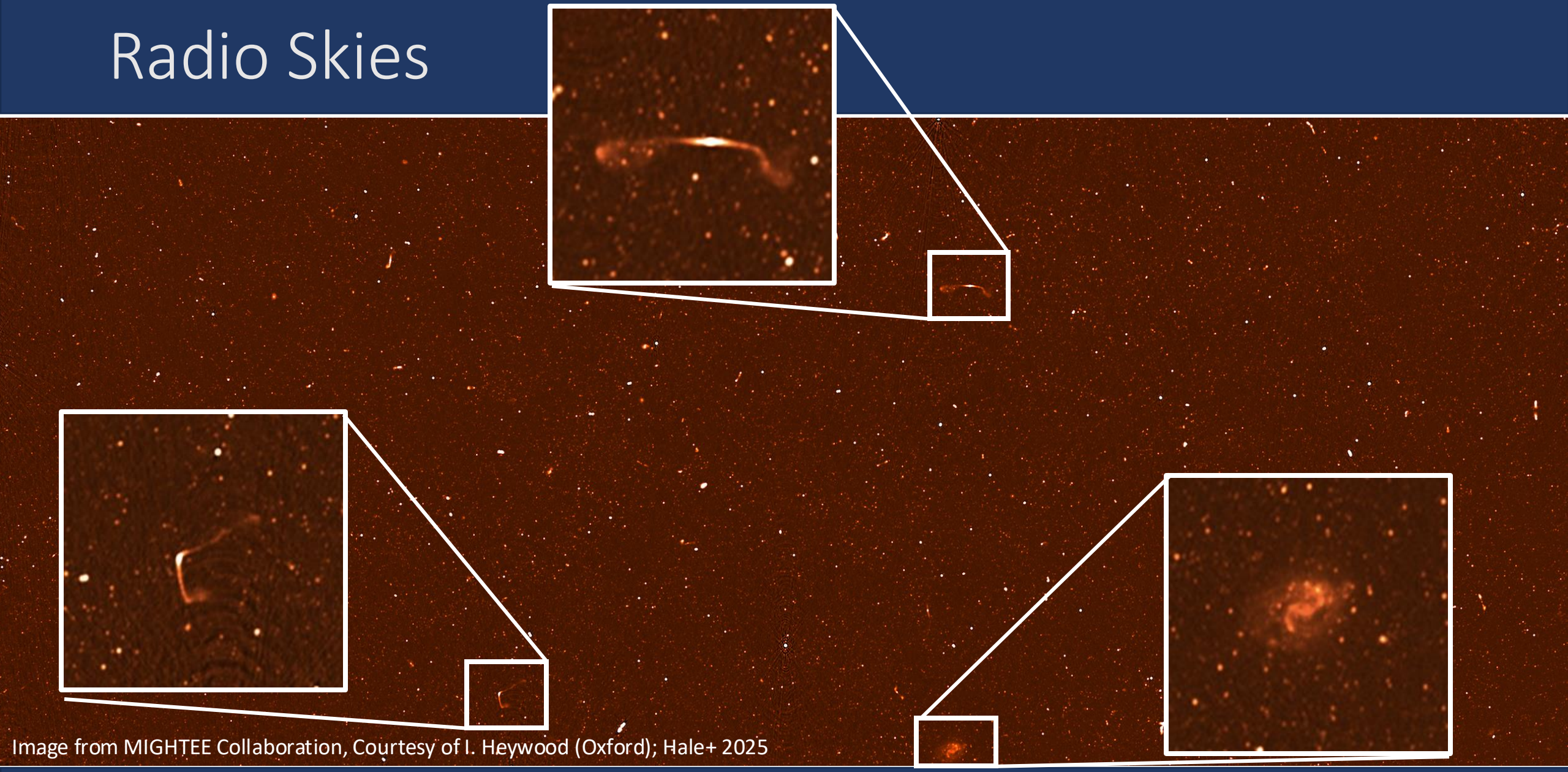


Image from MIGHTEE Collaboration, Courtesy of I. Heywood (Oxford); Hale+ 2025

Radio Skies



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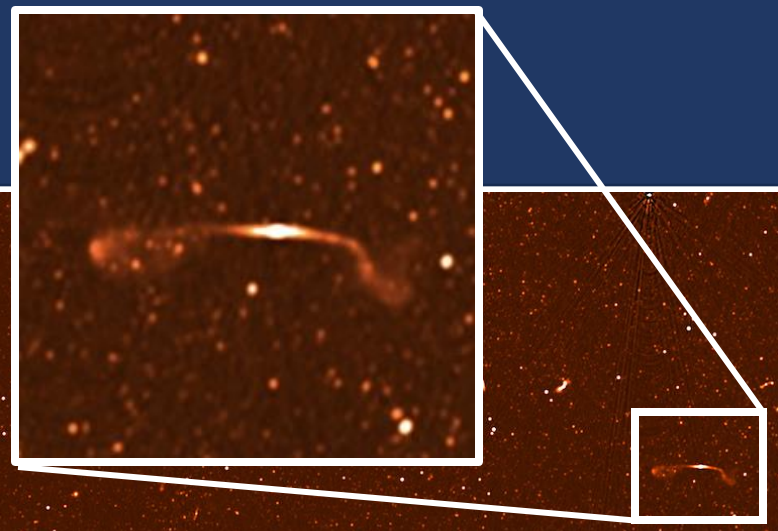
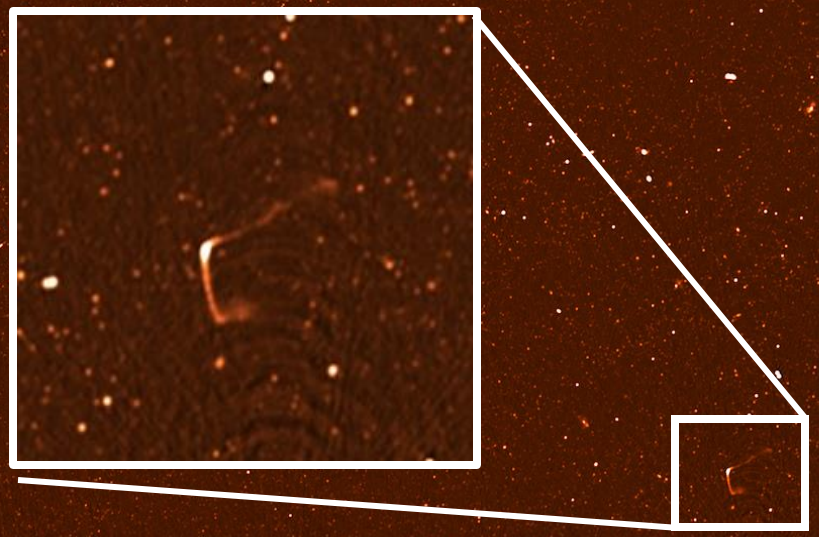


Unbiased tracer of star formation which can be used to probe SFR of star forming galaxies (e.g. Bell+ 2003, Garn+ 2009, Davies+ 2017, Smith+ 2021).

Star Forming Galaxies



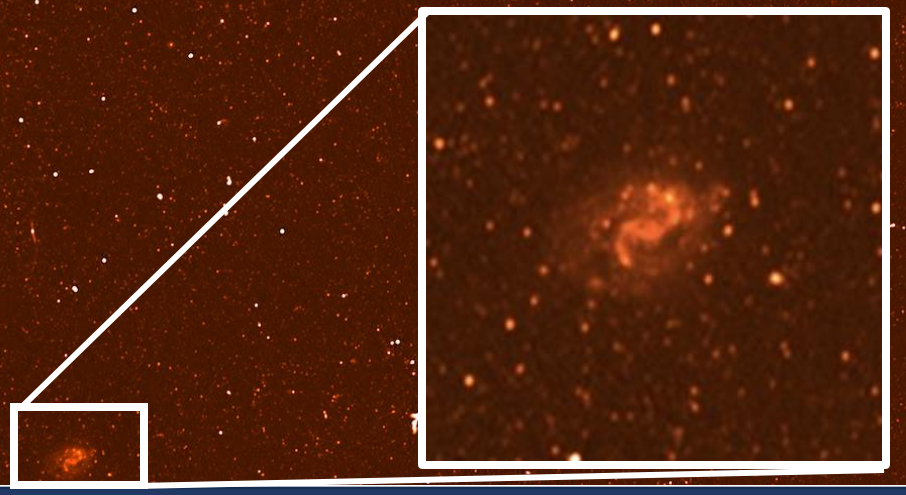
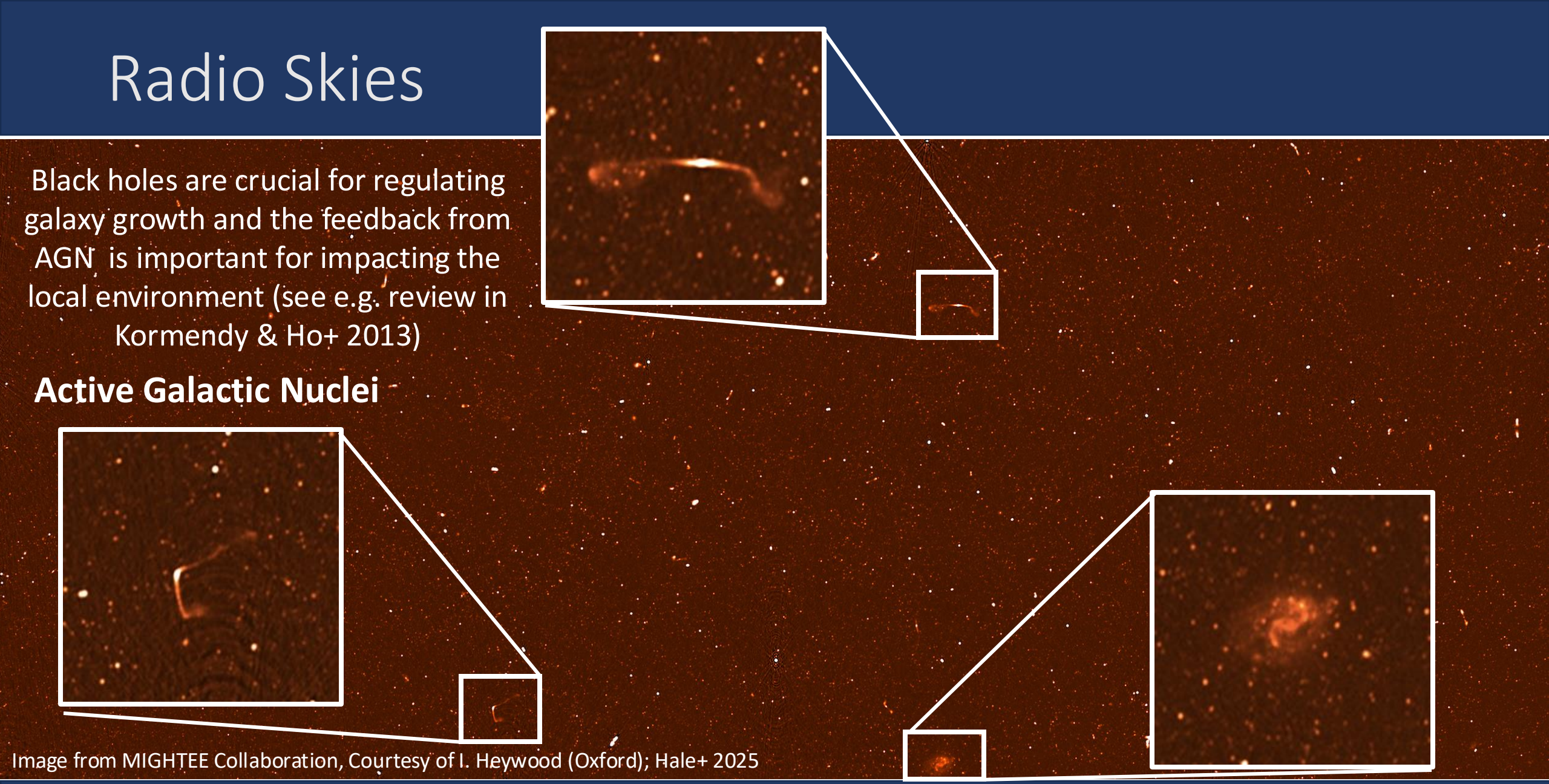


Image from MIGHTEE Collaboration, Courtesy of I. Heywood (Oxford); Hale+ 2025

Radio Skies

Black holes are crucial for regulating galaxy growth and the feedback from AGN is important for impacting the local environment (see e.g. review in Kormendy & Ho+ 2013)

Active Galactic Nuclei



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Radio Skies

+ Many unresolved galaxies and reaching survey confusion

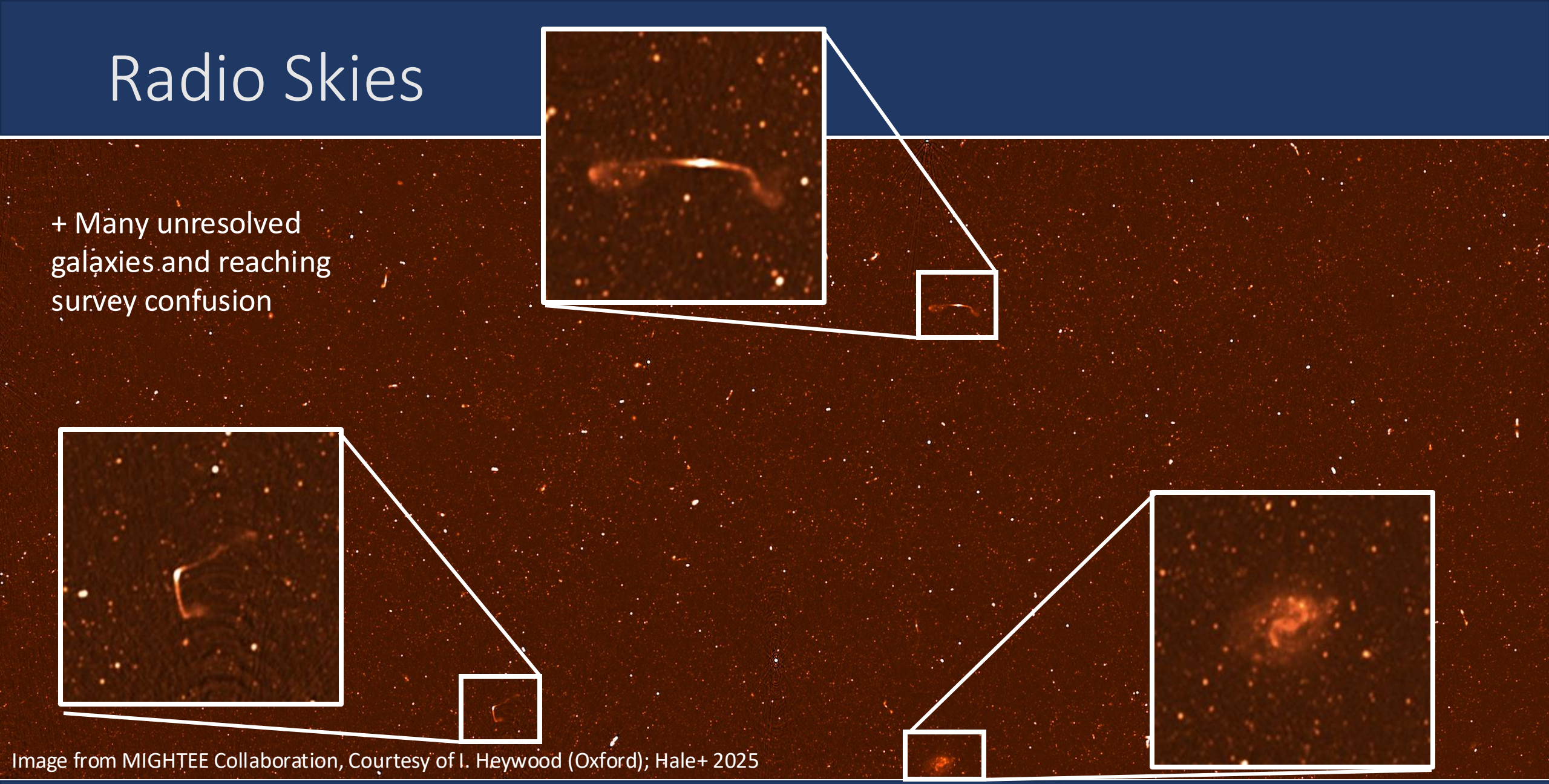


Image from MIGHTEE Collaboration, Courtesy of I. Heywood (Oxford); Hale+ 2025

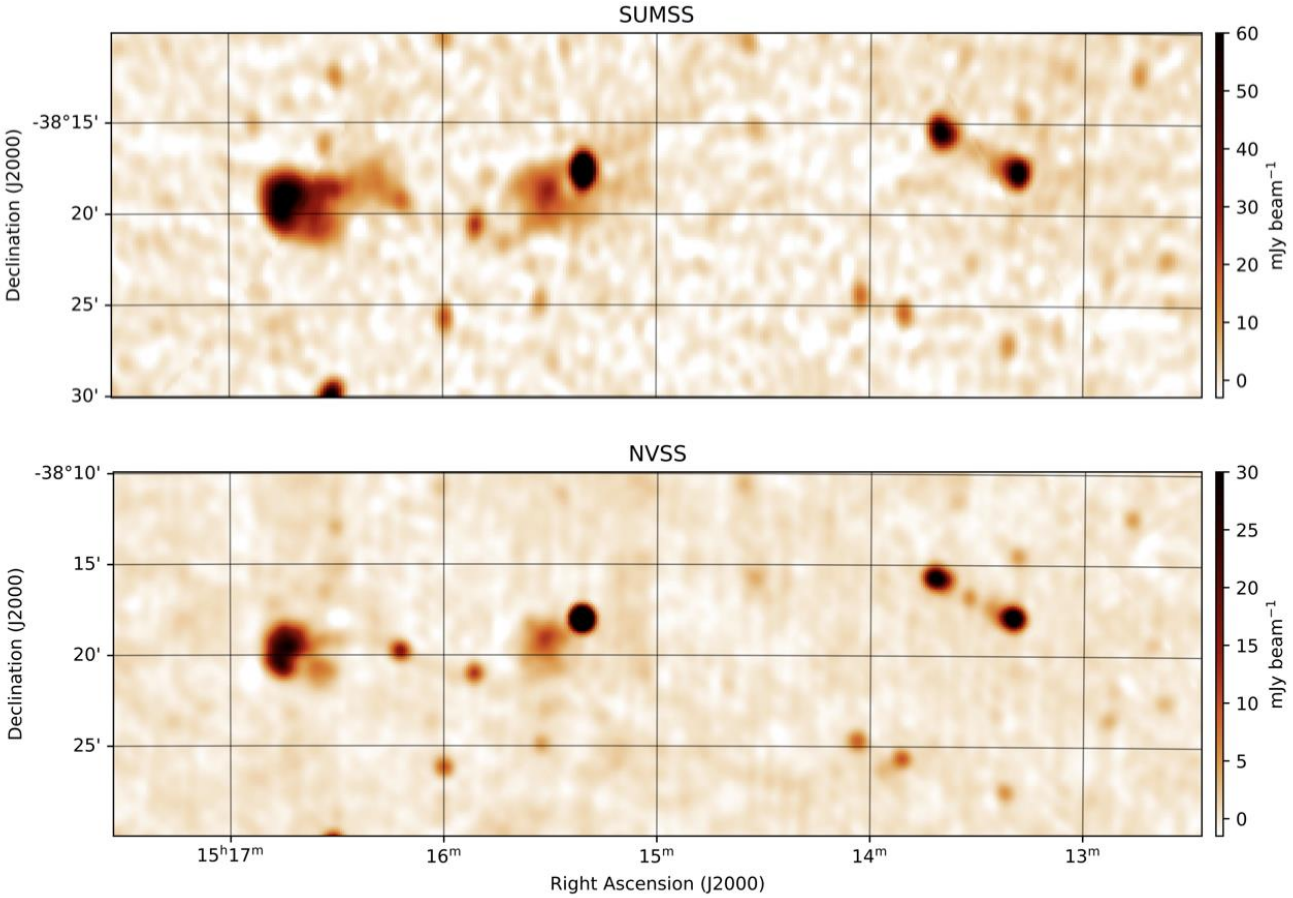
Challenges in Radio Astronomy

1) Massive data volumes
2) Complex data reduction pipelines
3) Imaging Artefacts and systematics
4) Lower source density
5) No redshift information

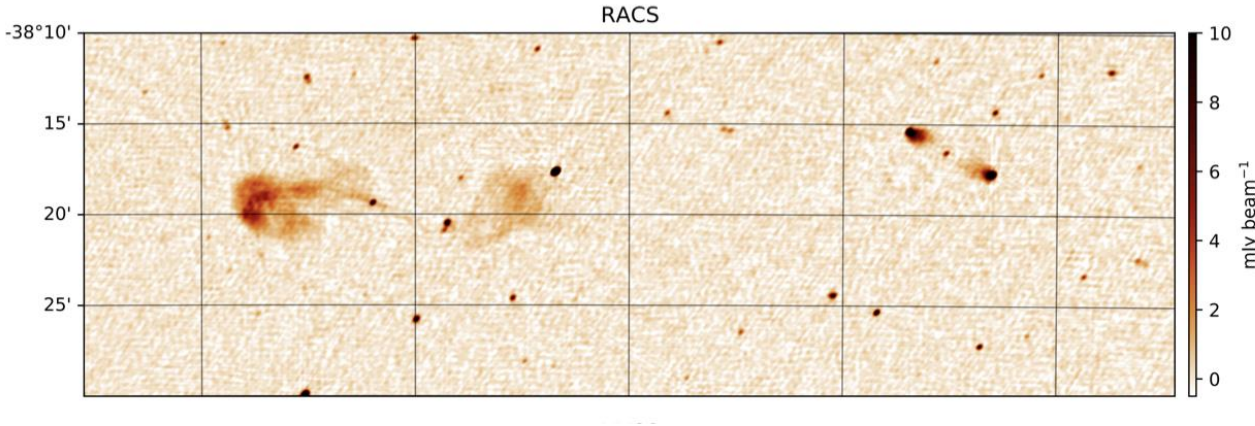
Advantages of Radio Astronomy

1) Observe Large Areas of Sky easily
2) Simple spectrum – easy to obtain intrinsic luminosities
3) Observable to large distances
4) No dust obscuration effects

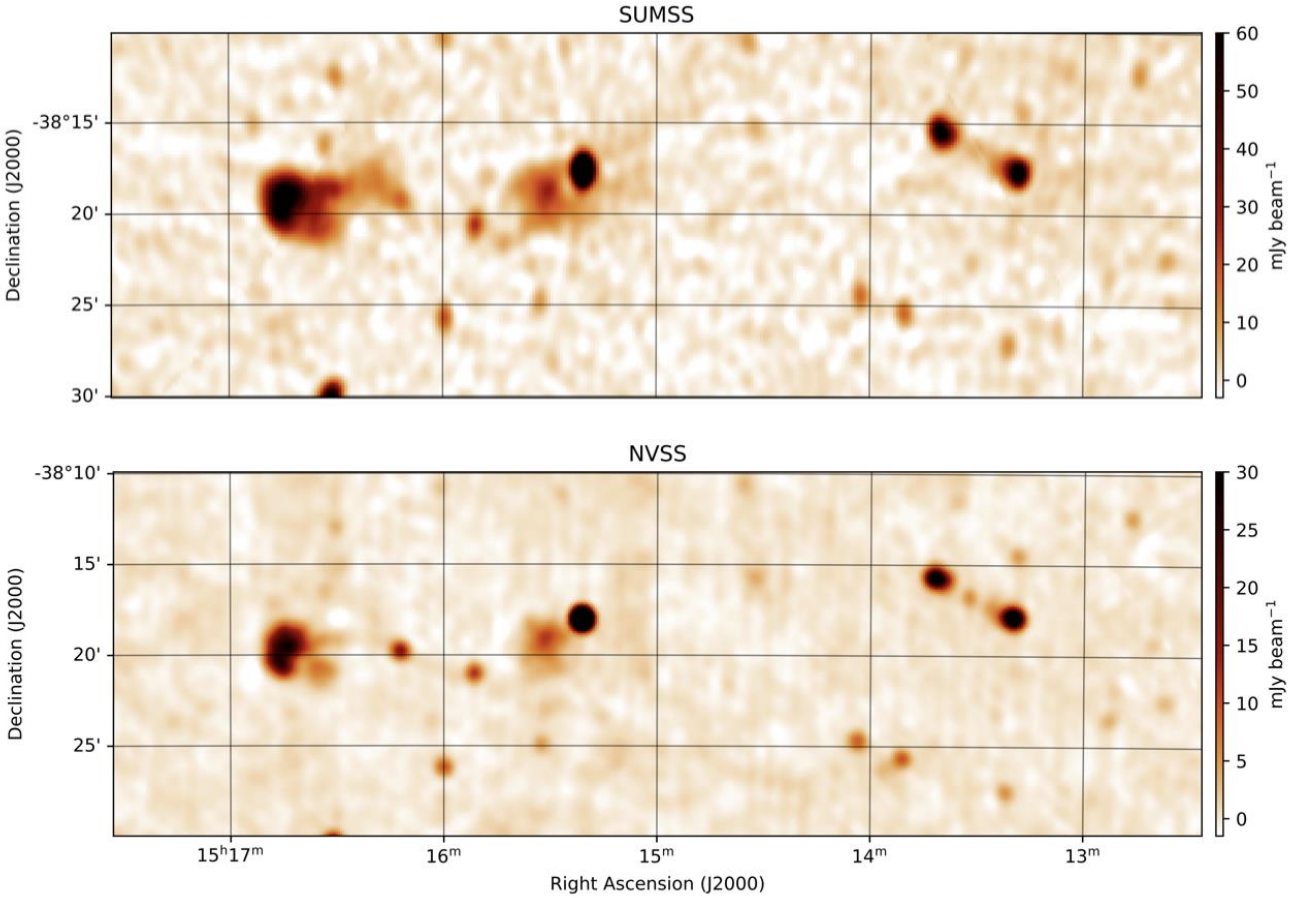
Rapid Survey Speed



Rapid ASKAP Continuum Survey
(McConnell, Hale+2020)



Rapid Survey Speed



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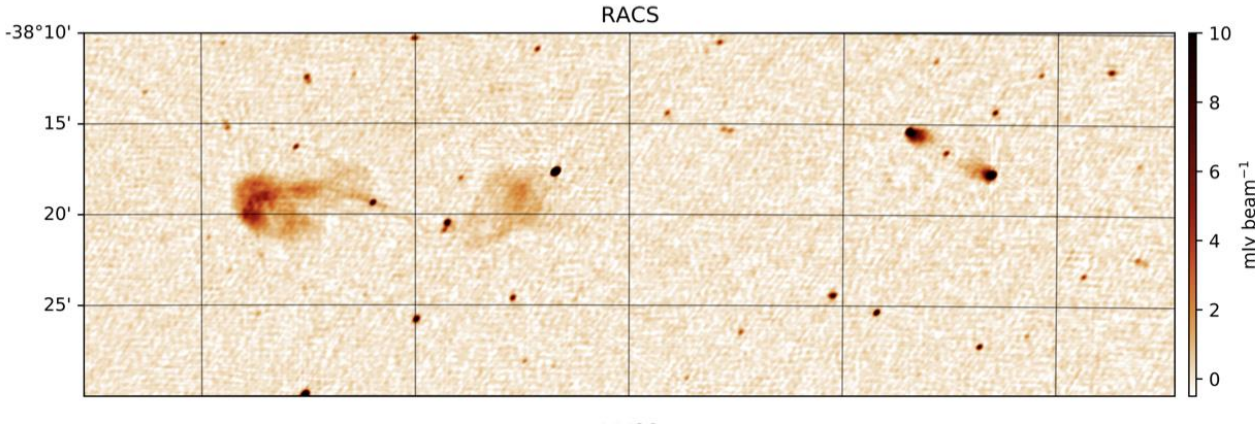
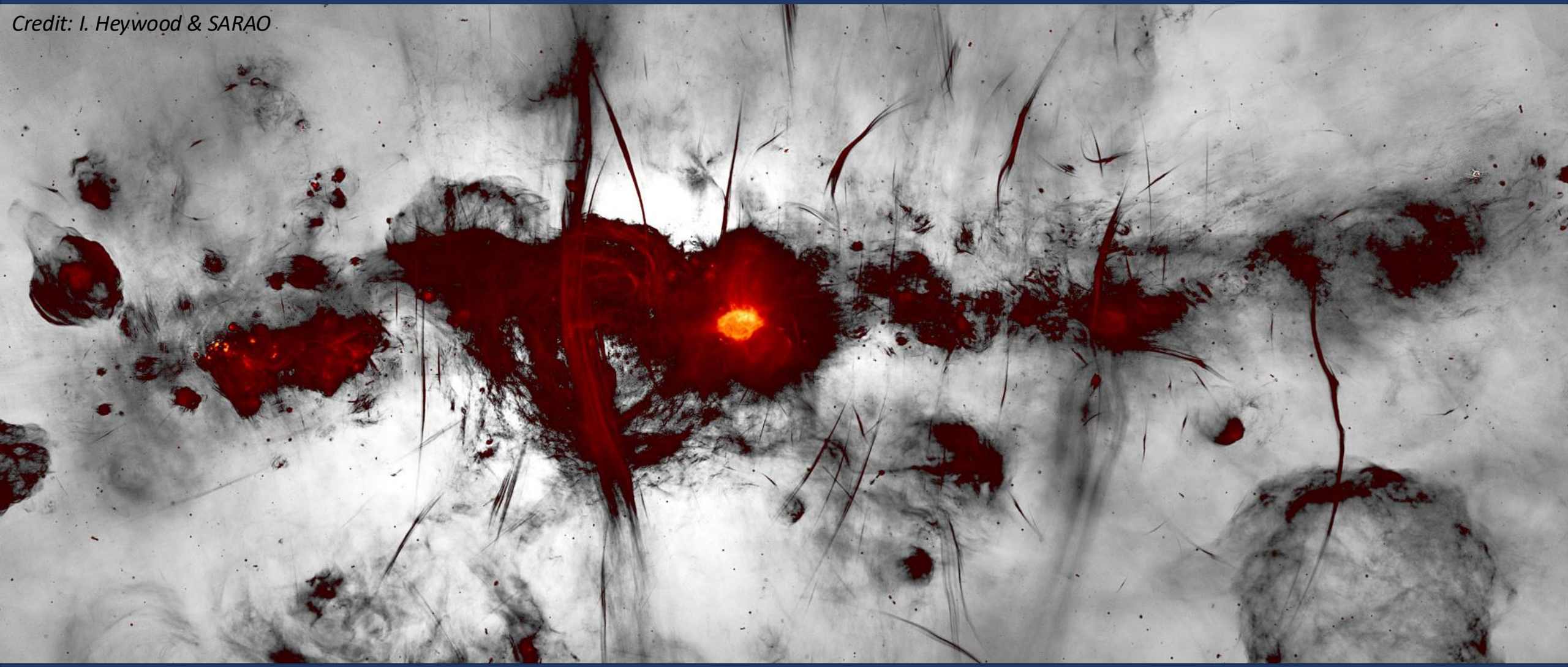


15 minute snapshot imaging over ~900 tiles

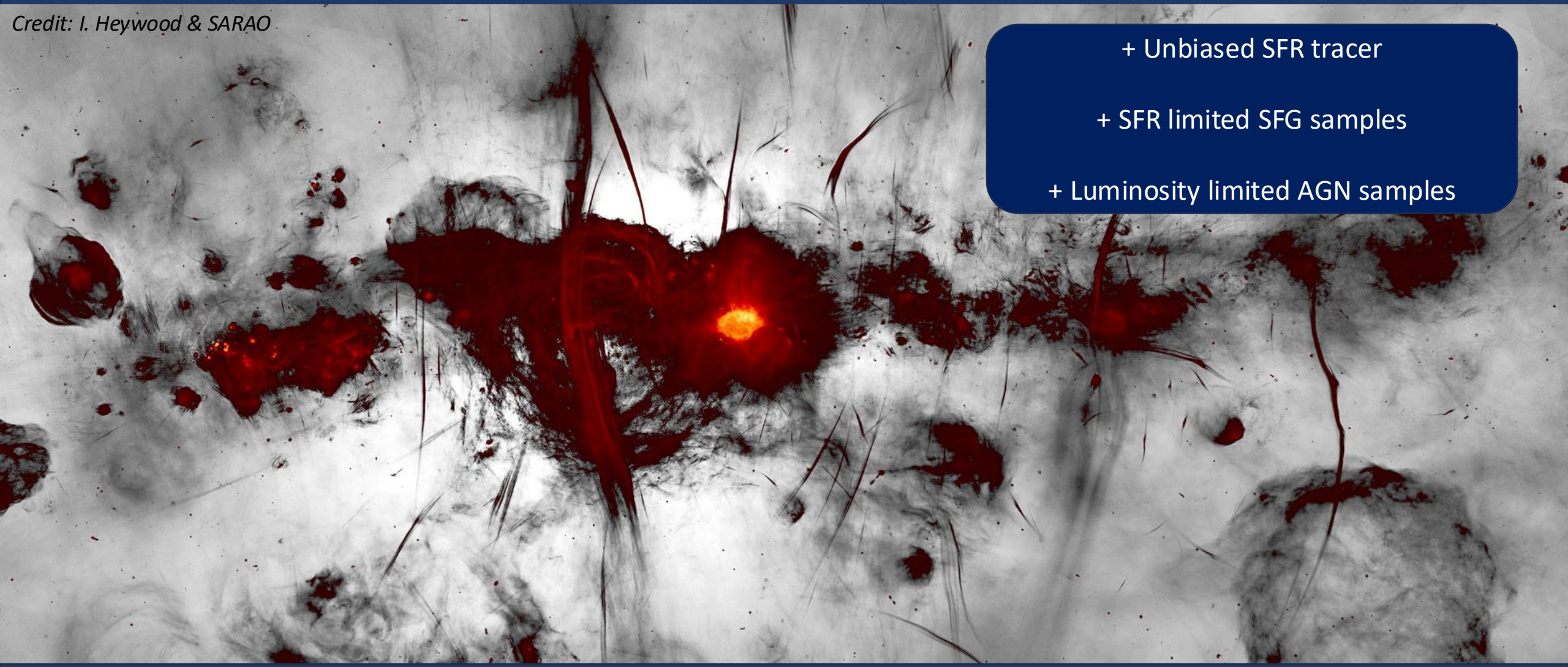
~9 days on source

Advantages of Radio Astronomy



Credit: I. Heywood & SARAO

Advantages of Radio Astronomy



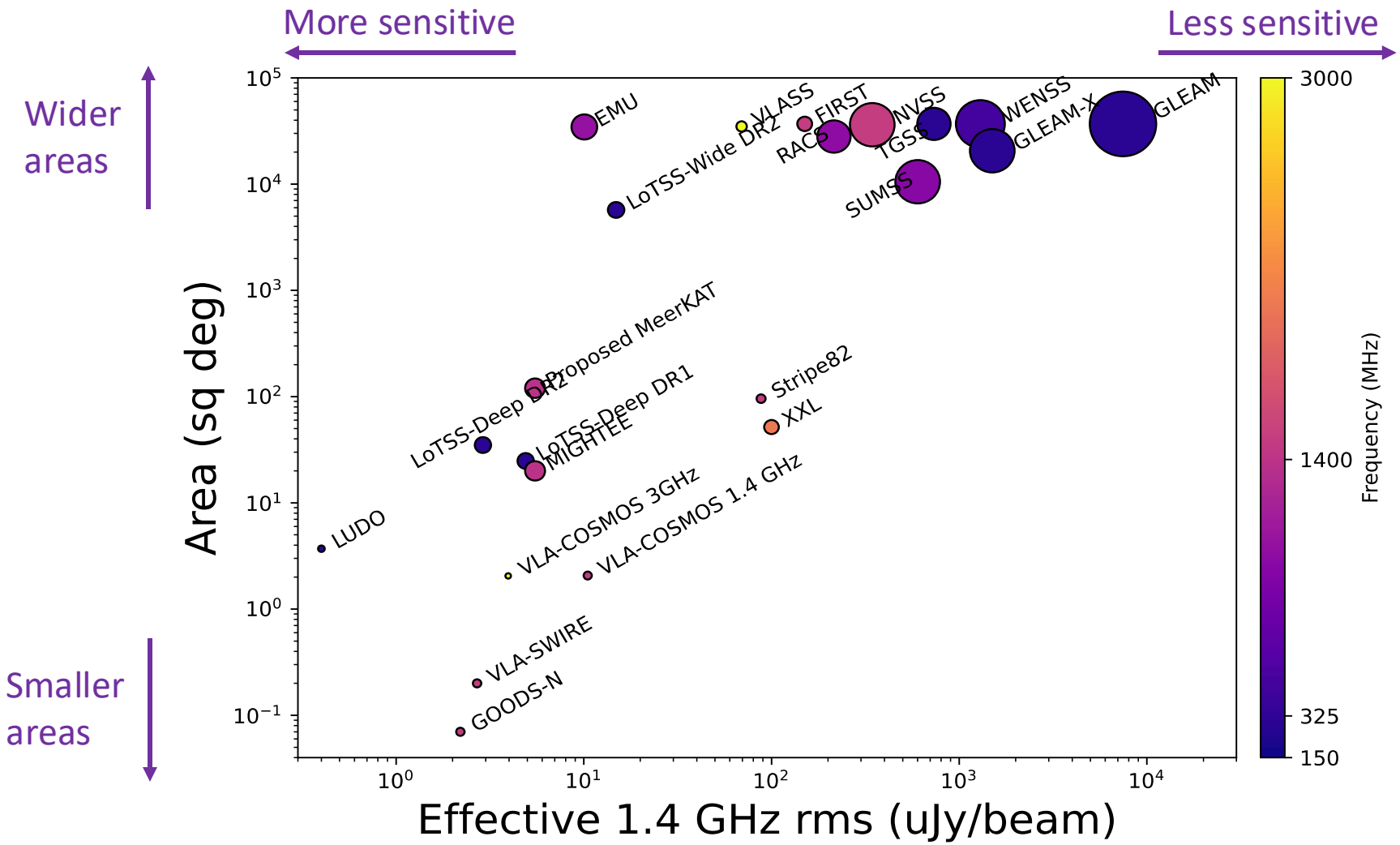
Credit: I. Heywood & SARAO

+ Unbiased SFR tracer

+ SFR limited SFG samples

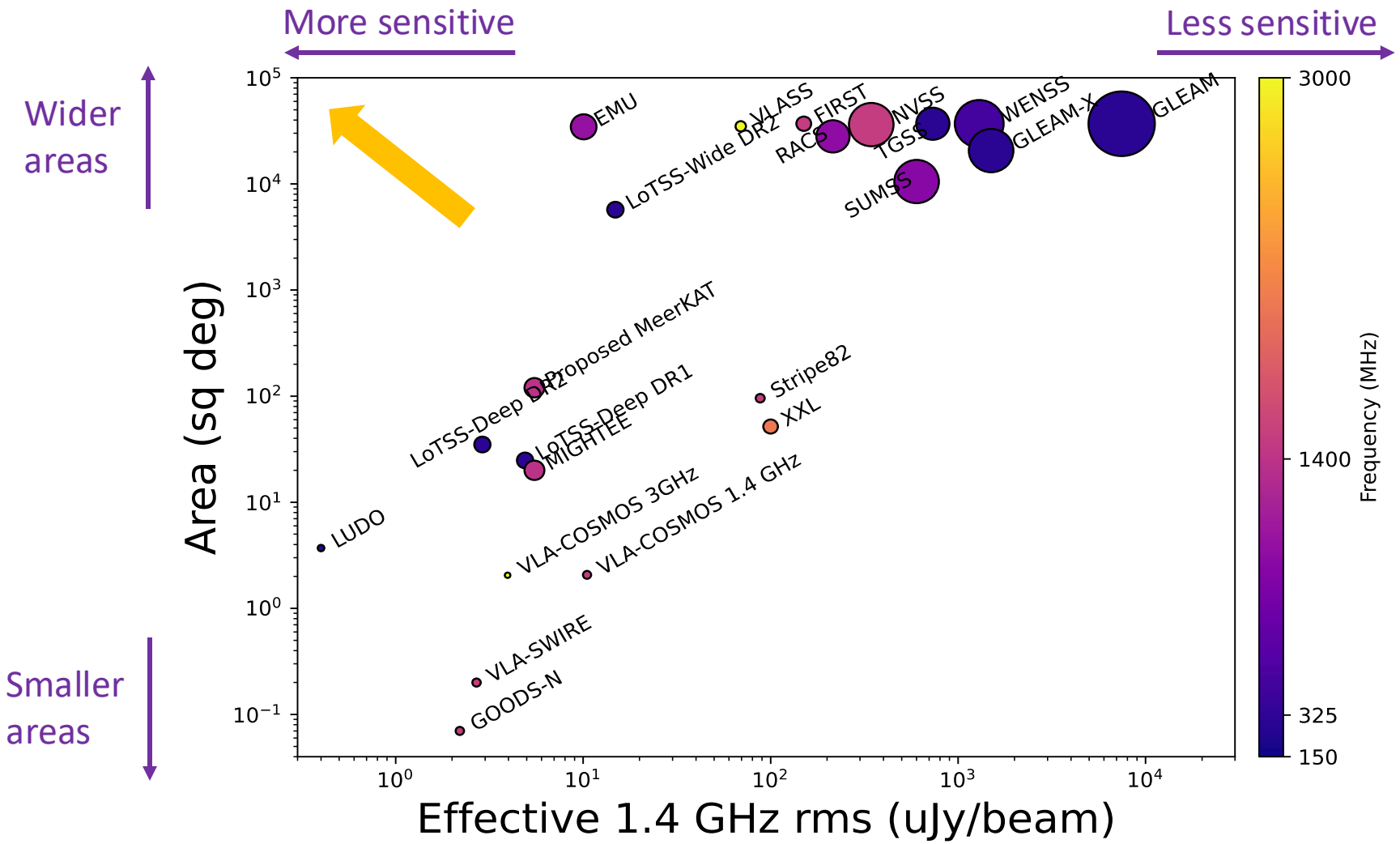
+ Luminosity limited AGN samples

Radio Surveys



(marker size indicates angular resolution)

Radio Surveys



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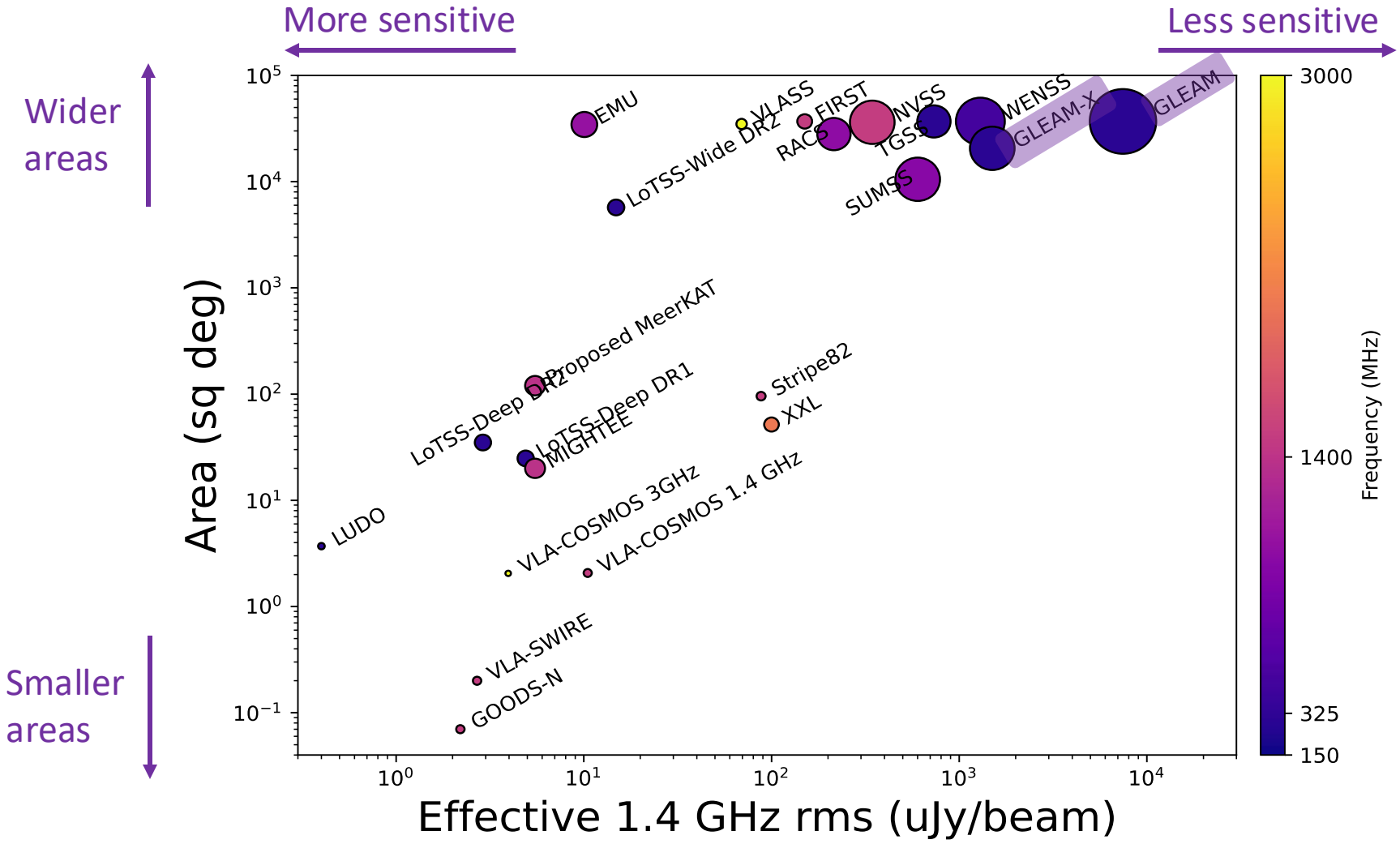
Radio Surveys – SKAO Precursor/Pathfinders

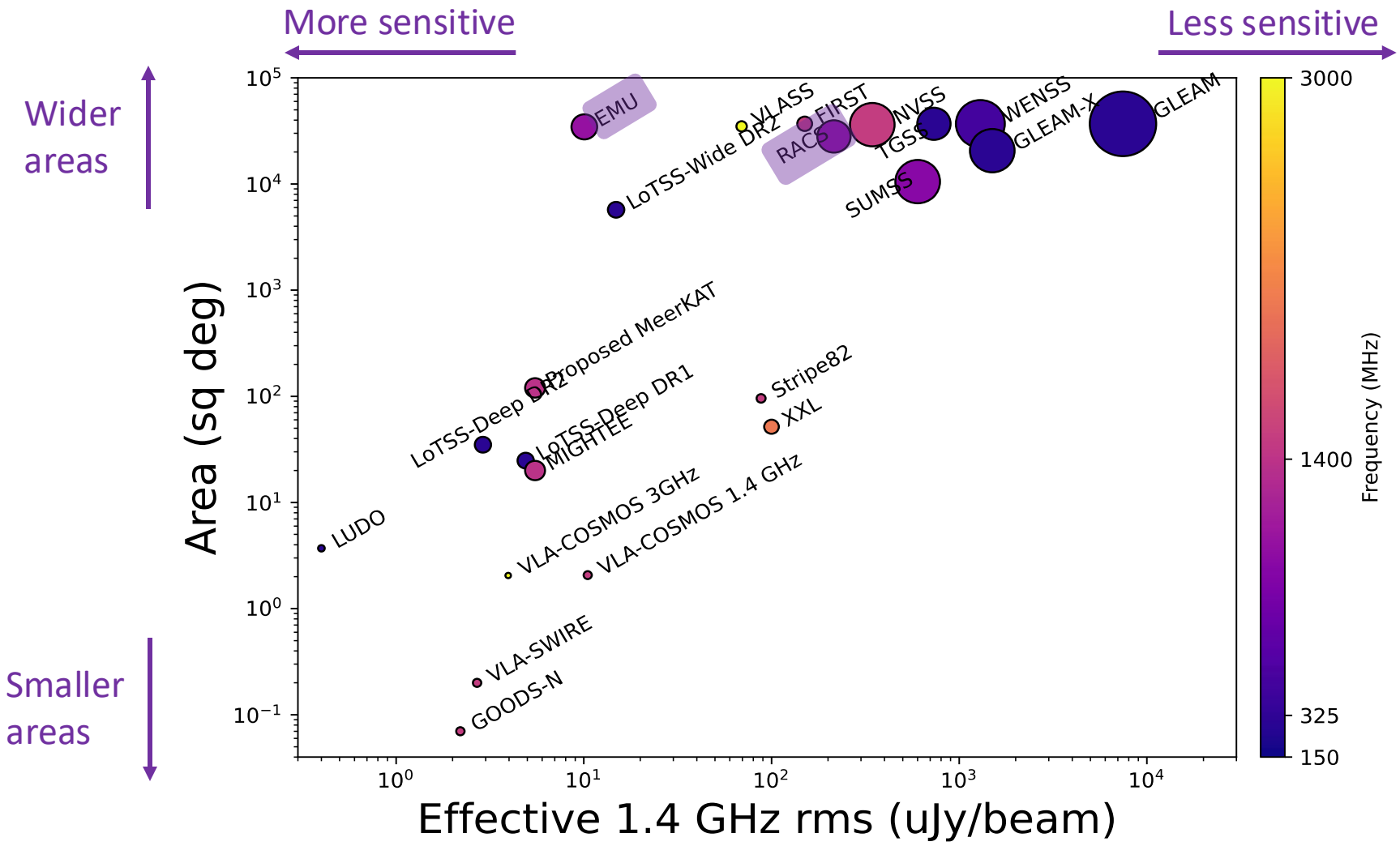


Murchinson Widefield Array (MWA)

Credit: Marianne Annereau, 2015

(marker size indicates angular resolution)

Radio Surveys – SKAO Precursor/Pathfinders

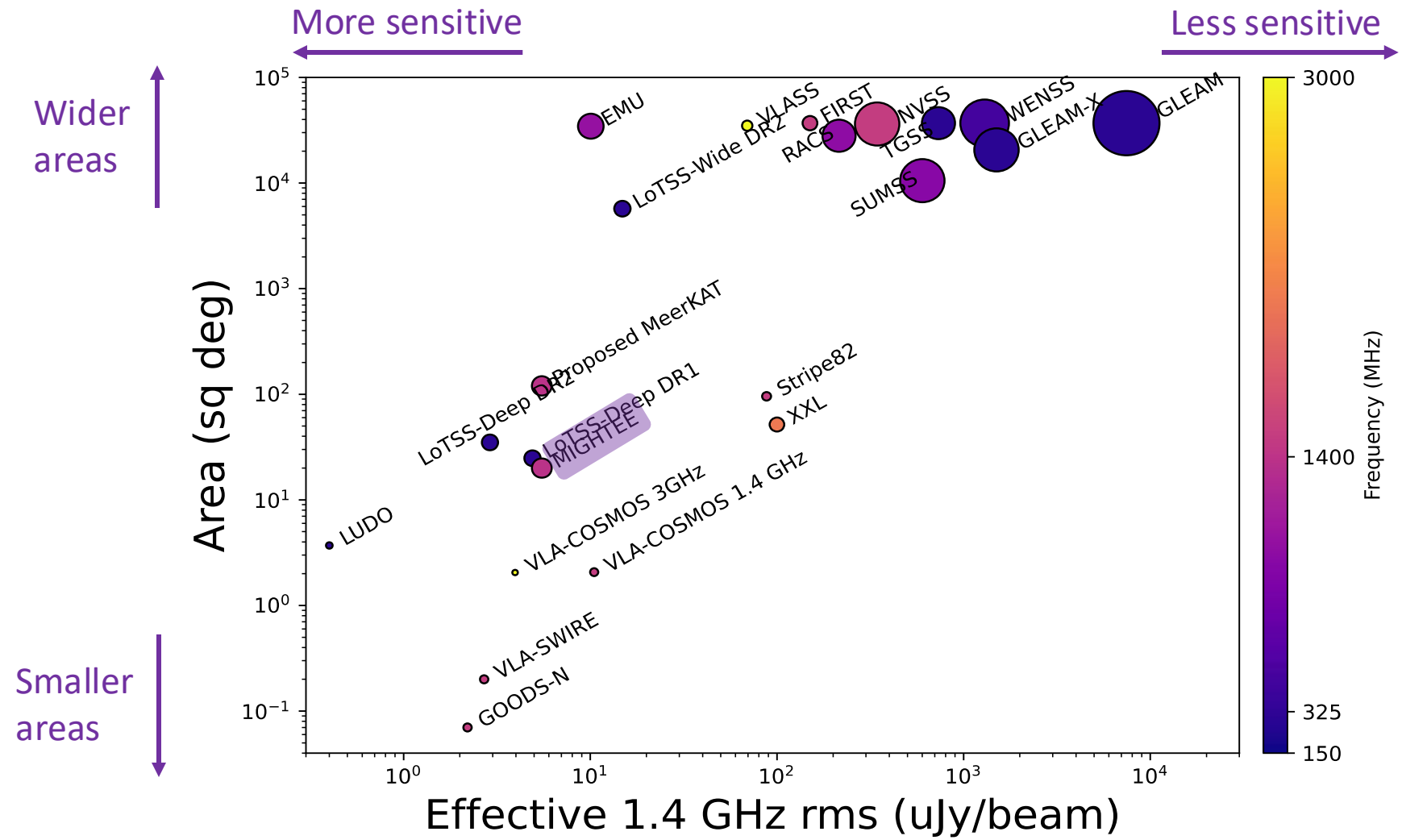


Australian Square Kilometre Array Pathfinder (ASKAP)

Credit: CSIRO/A. Cherney

(marker size indicates angular resolution)

Radio Surveys – SKAO Precursor/Pathfinders

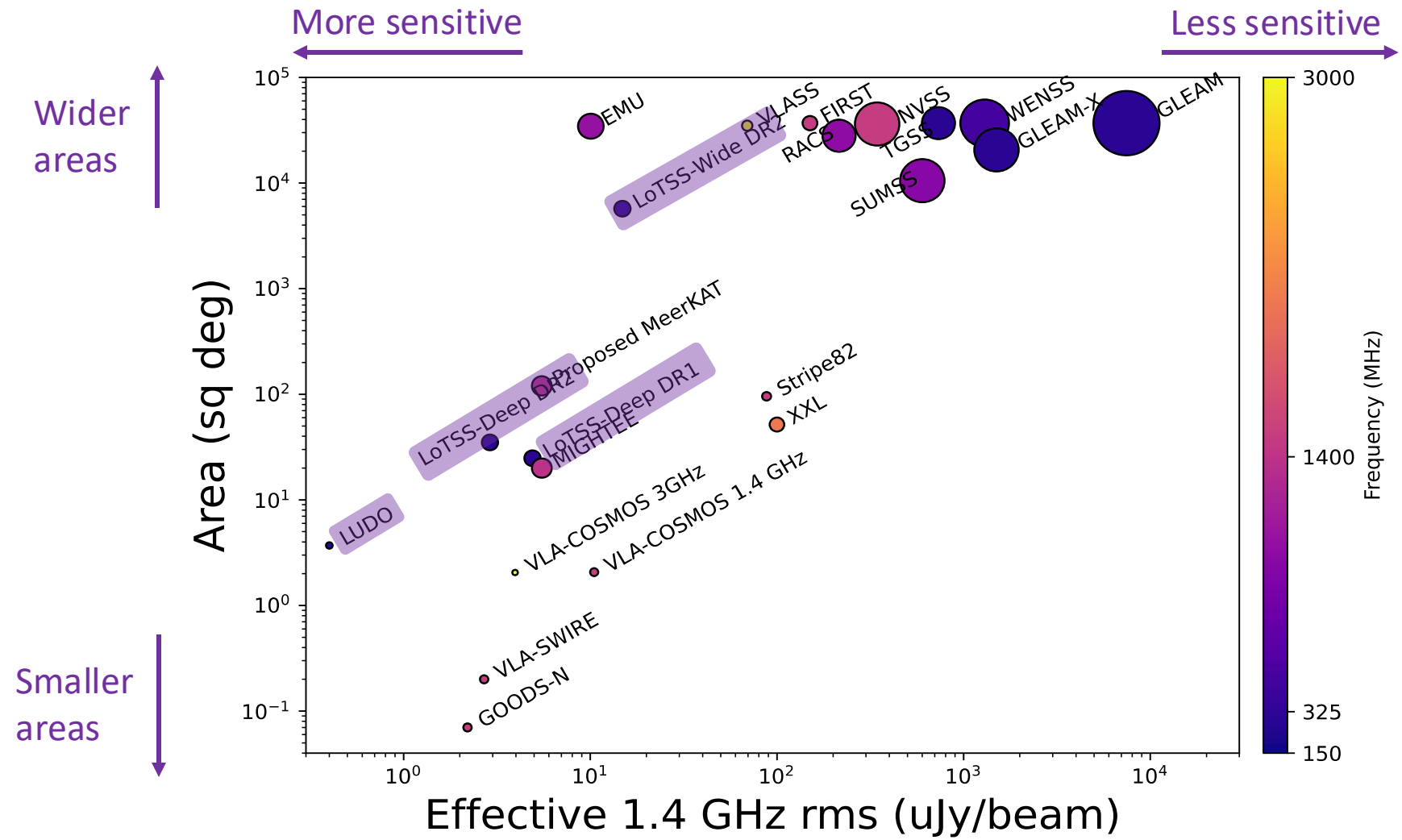


MeerKAT

Credit: SARAO

(marker size indicates angular resolution)

Radio Surveys – SKAO Precursor/Pathfinders

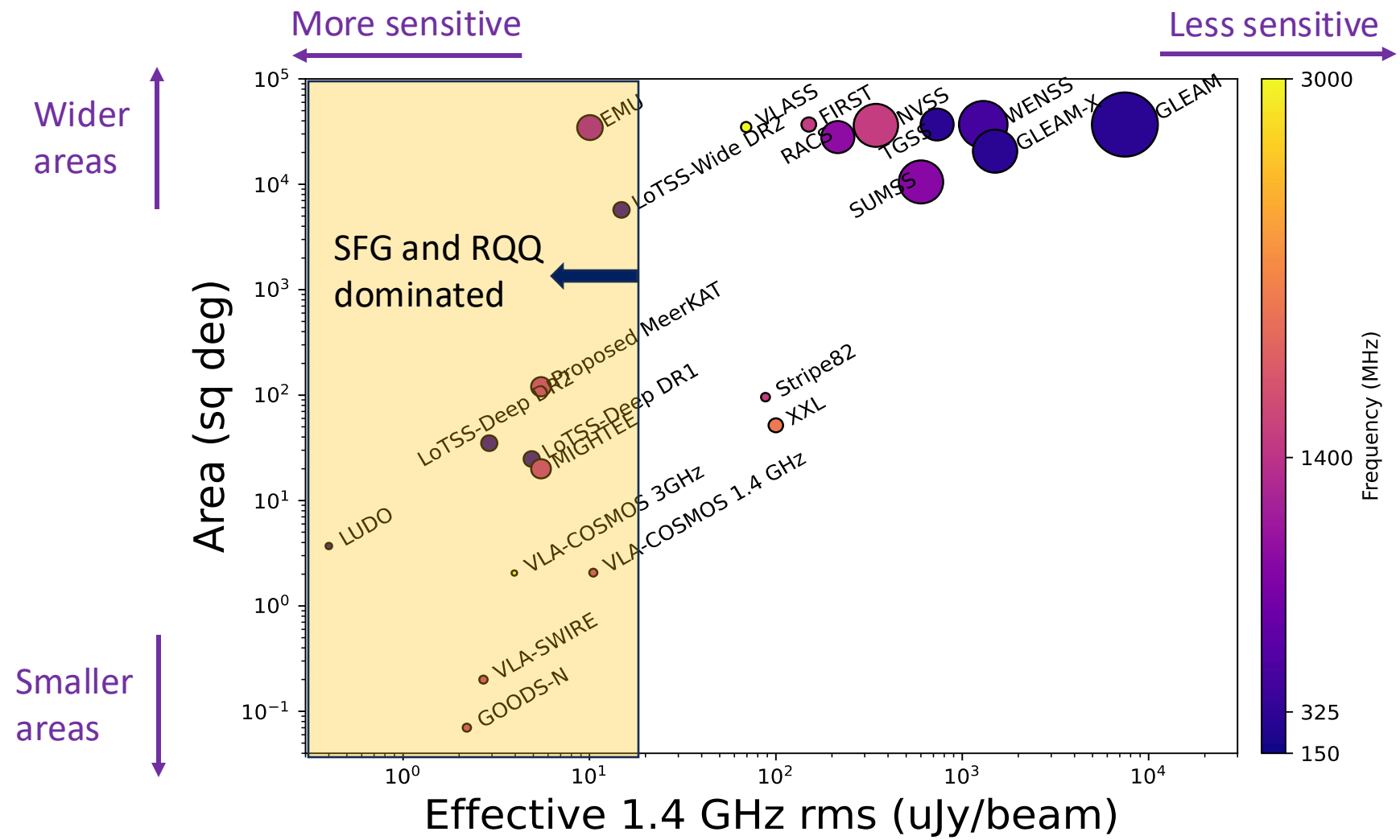


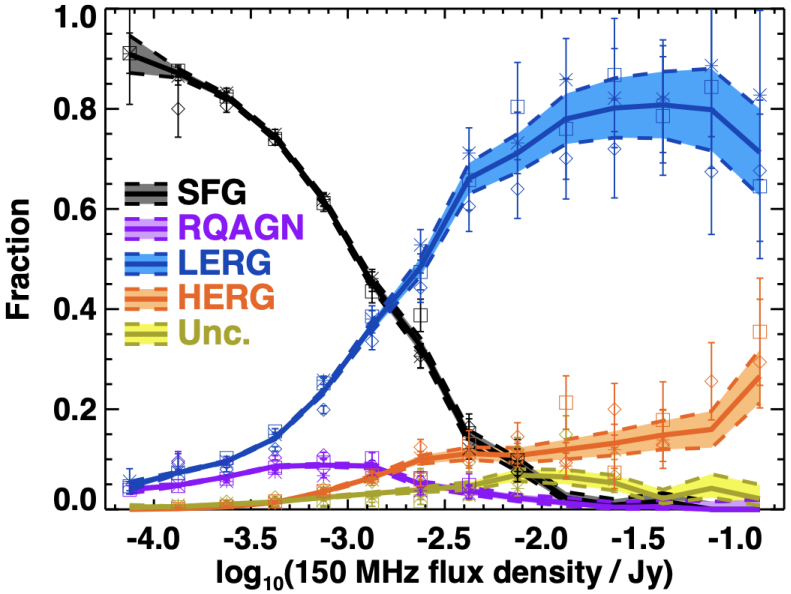
Low Frequency Array (LOFAR)

Credit: ASTRON

(marker size indicates angular resolution)

Radio Surveys

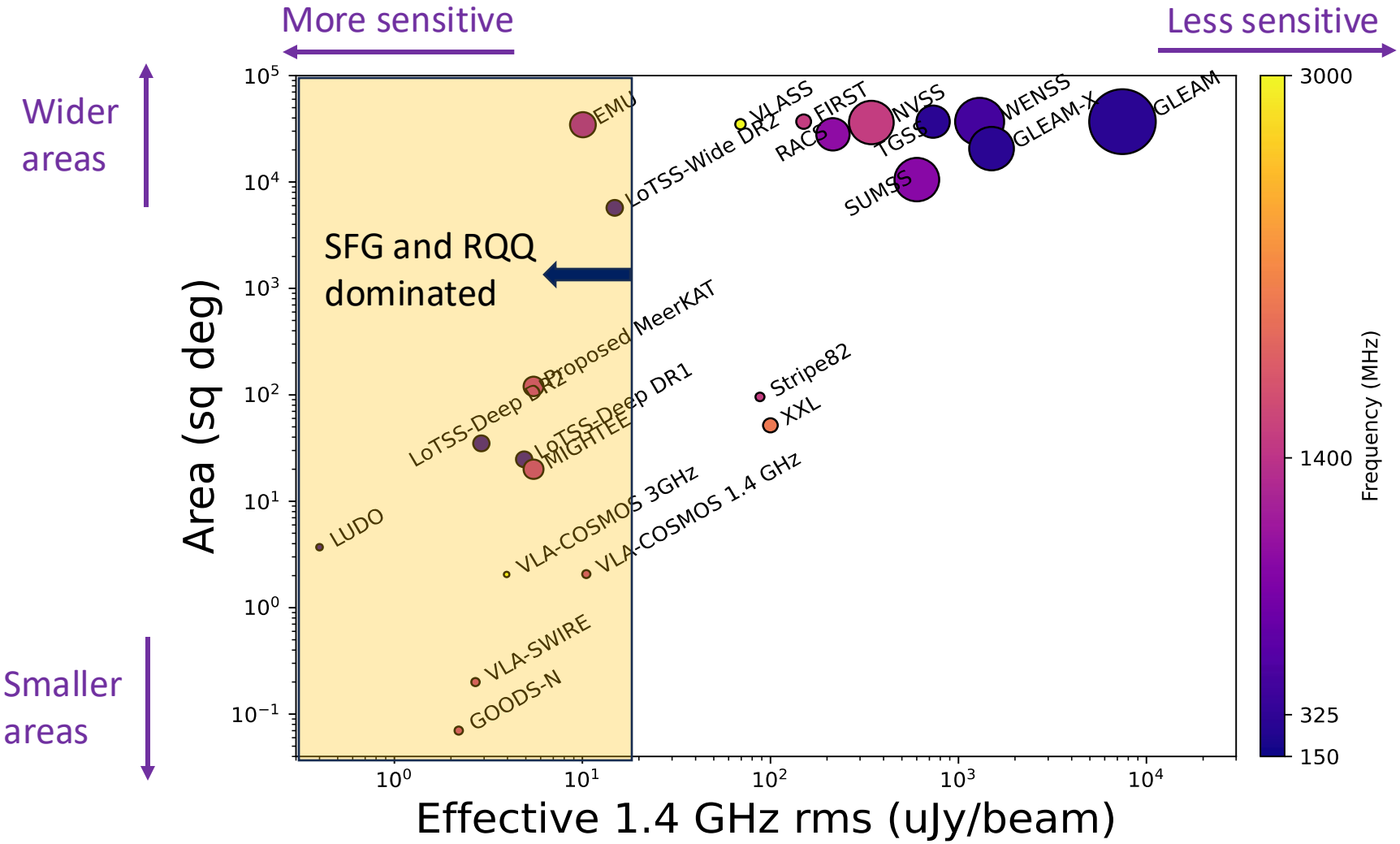




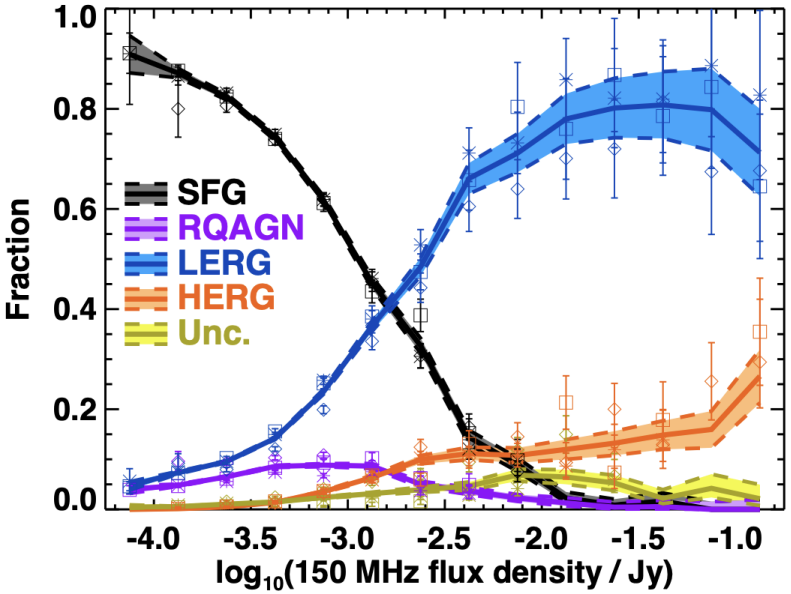
Best+ 2023

(marker size indicates angular resolution)

Radio Surveys



LERG/HERG are RLAGN which are thought to have different accretion mechanisms



Best+ 2023

(marker size indicates angular resolution)

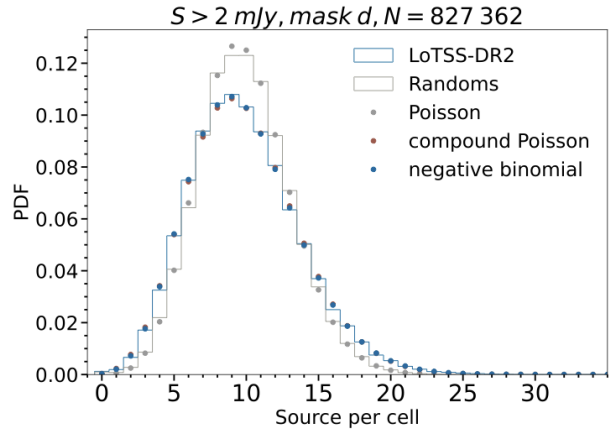
Cosmology with Radio Continuum Surveys

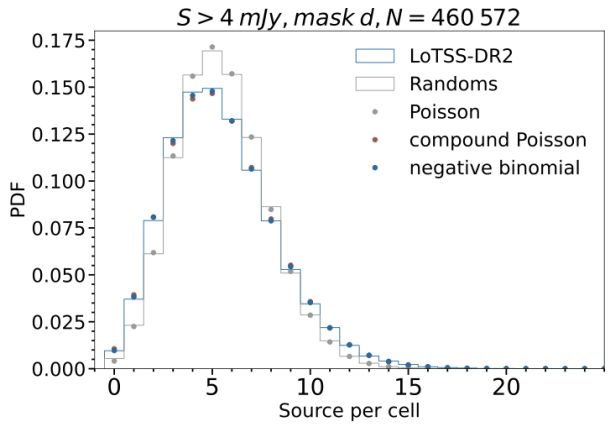
As radio continuum surveys cannot provide redshifts, if used alone then we probe projected angular clustering of the large-scale structure

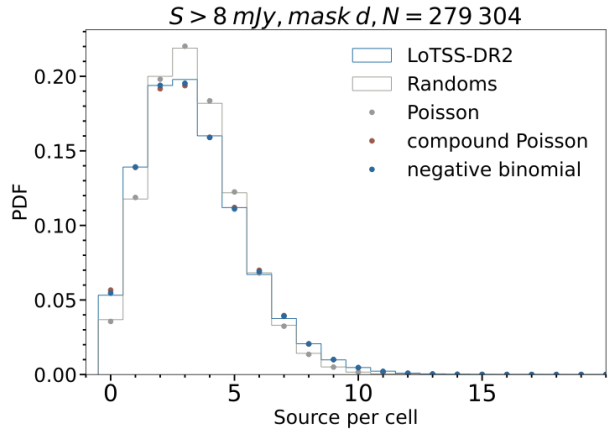
Cosmology with Radio Continuum Surveys

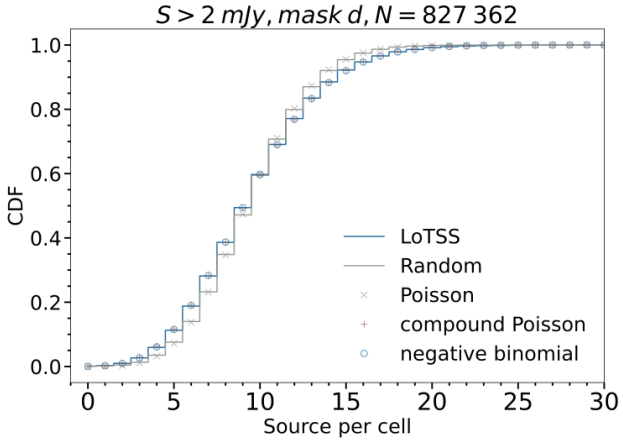
Results with Current Radio Surveys

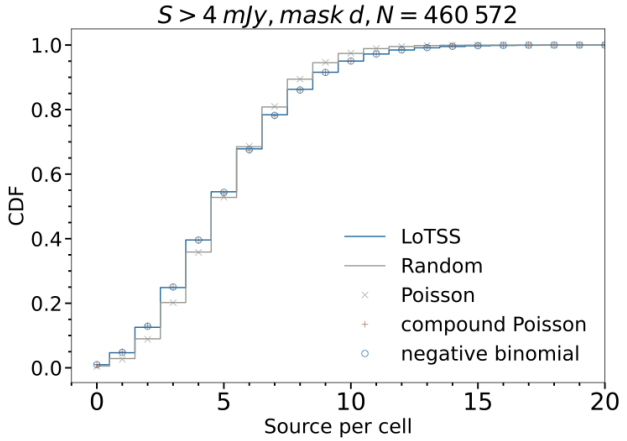
1-Point Statistics

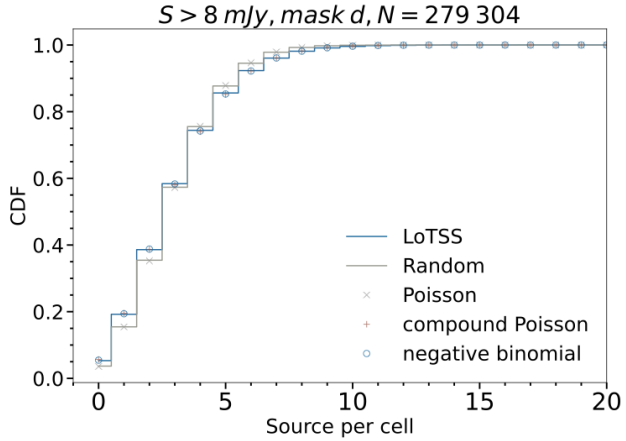








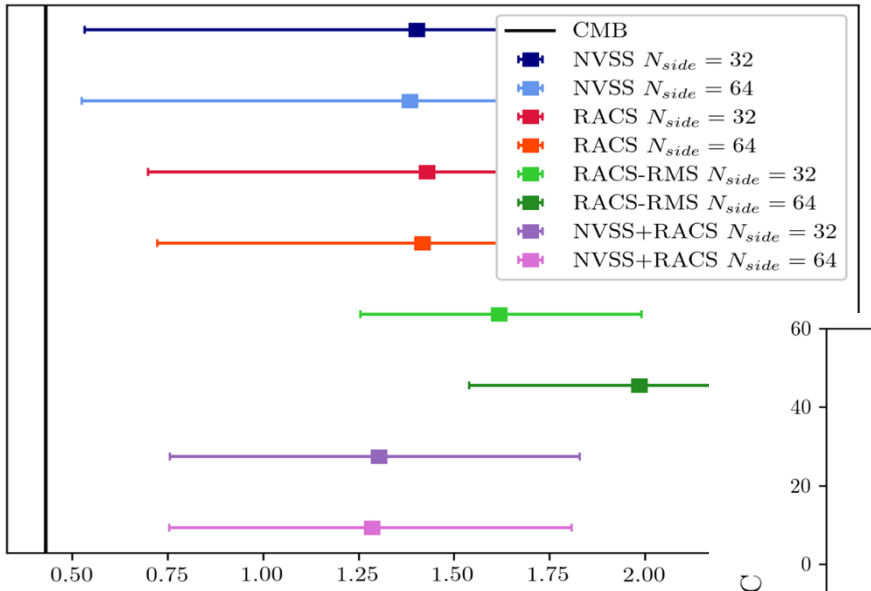




[Pashapour-Ahmadabadi + 2025]

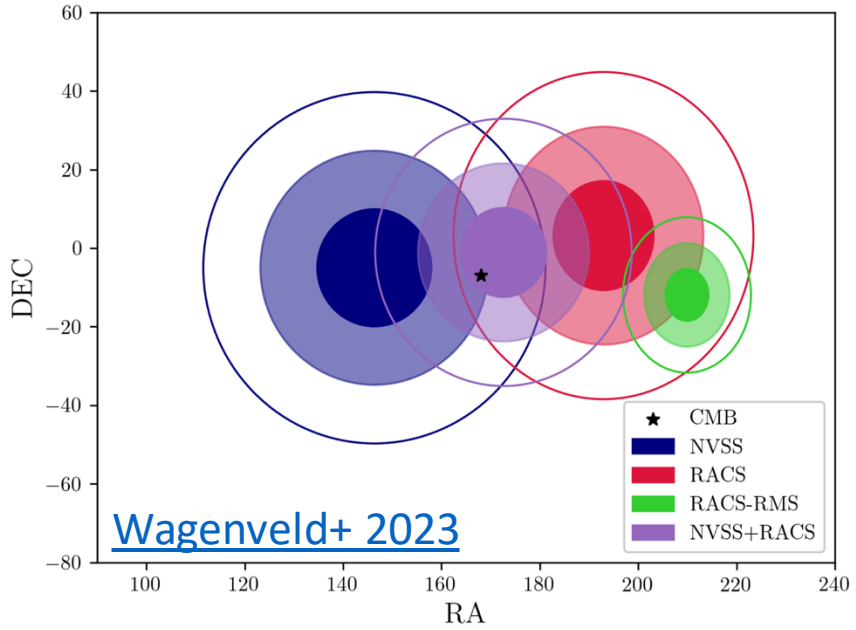
Using: LOFAR (LoTSS DR2, Shimwell+ 2021)

Dipole Studies



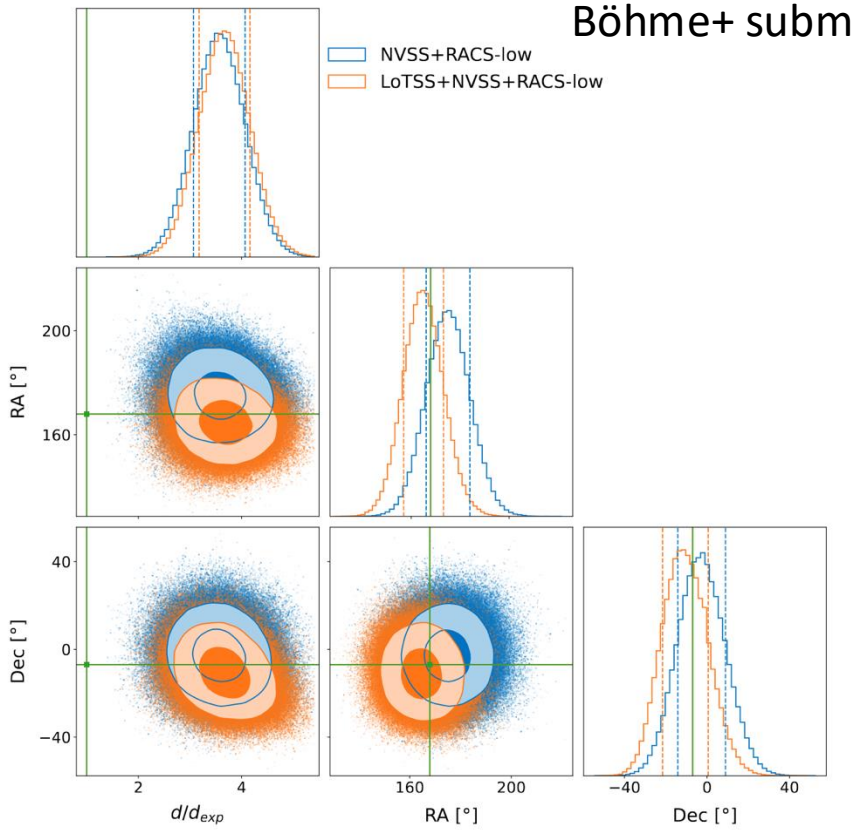
Wagenveld+ 2023

Using: RACS = ASKAP large area survey (Hale+2021, Duchense+ 2023, 2025) and NVSS = VLA sky survey (Condon+ 1998)



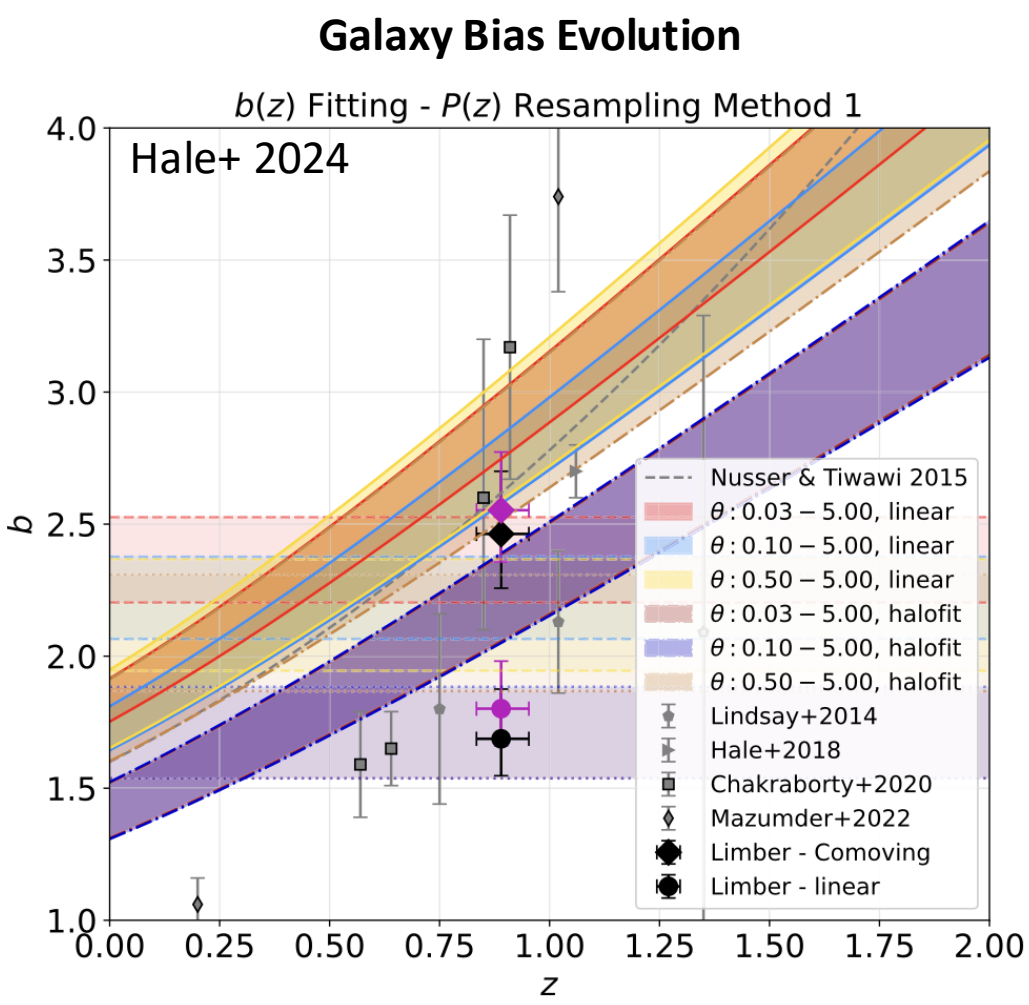
Wagenveld+ 2023

Böhme+ subm.



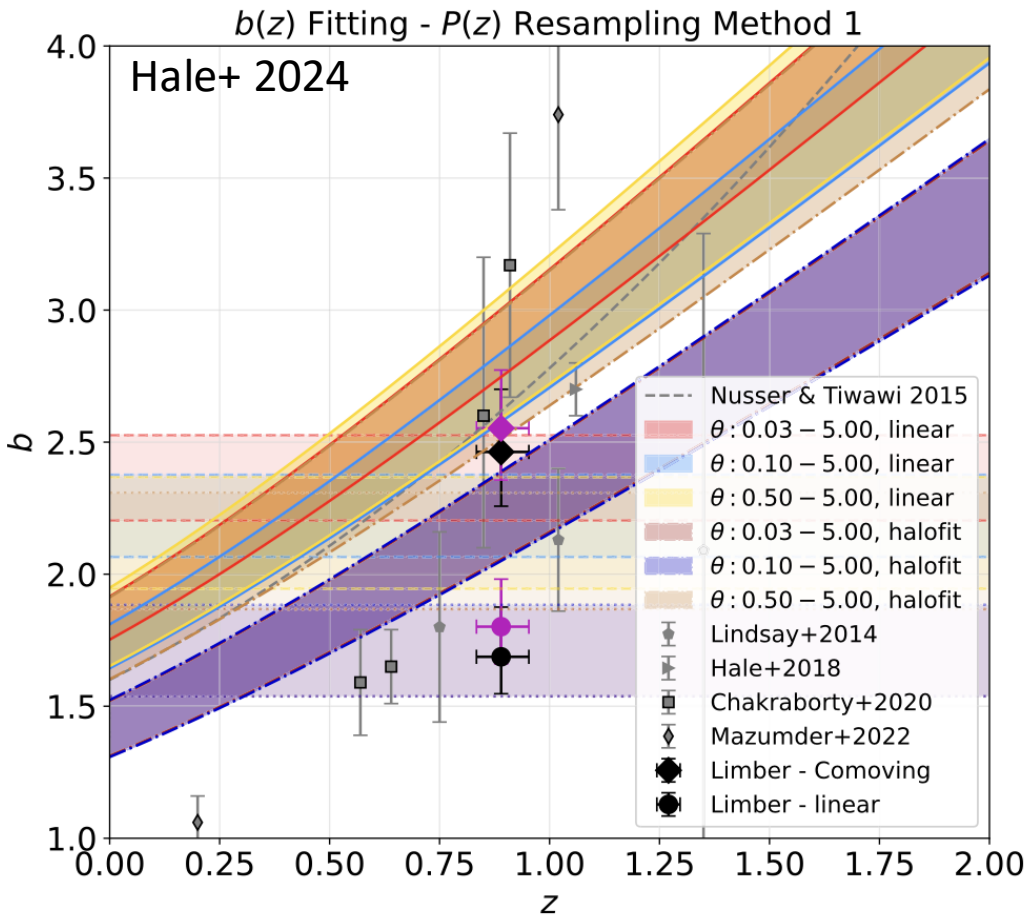
Using: LOFAR (LoTSS DR2, Shimwell+ 2021), NVSS and RACS

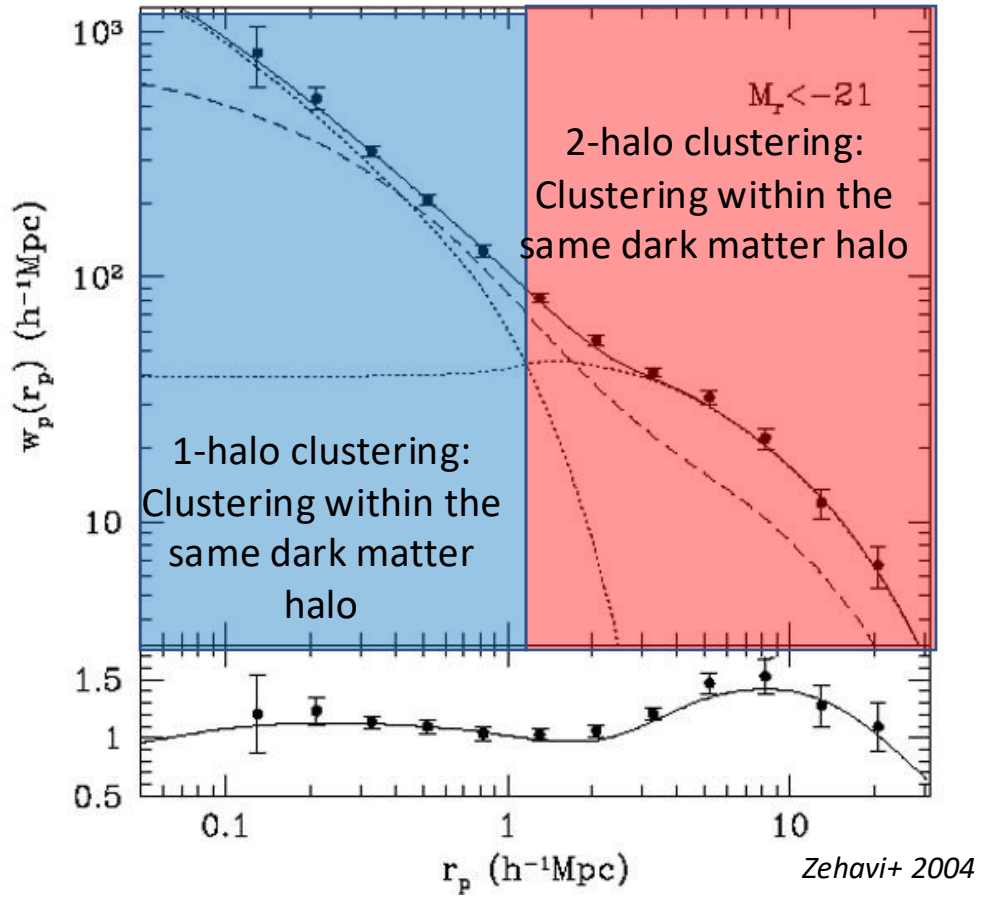
Angular Auto-Correlation



Angular Auto-Correlation

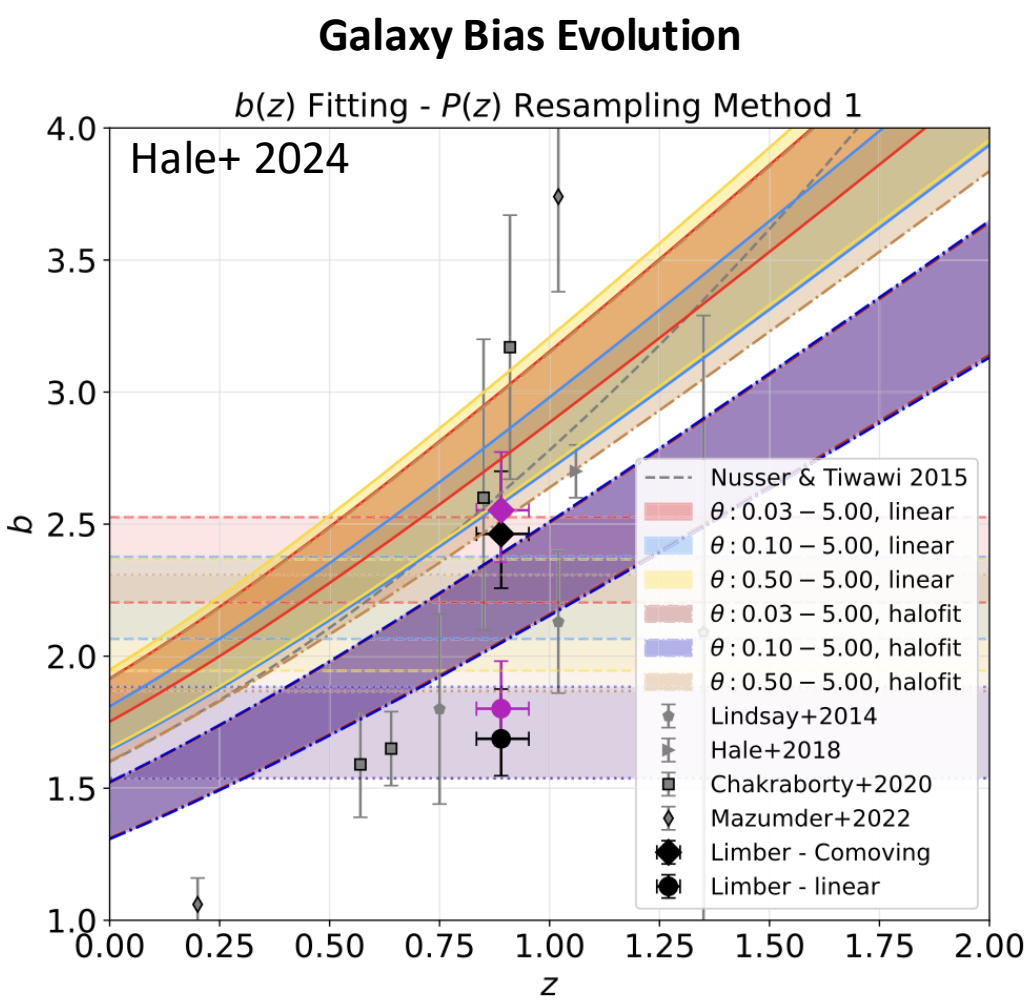
Galaxy Bias Evolution

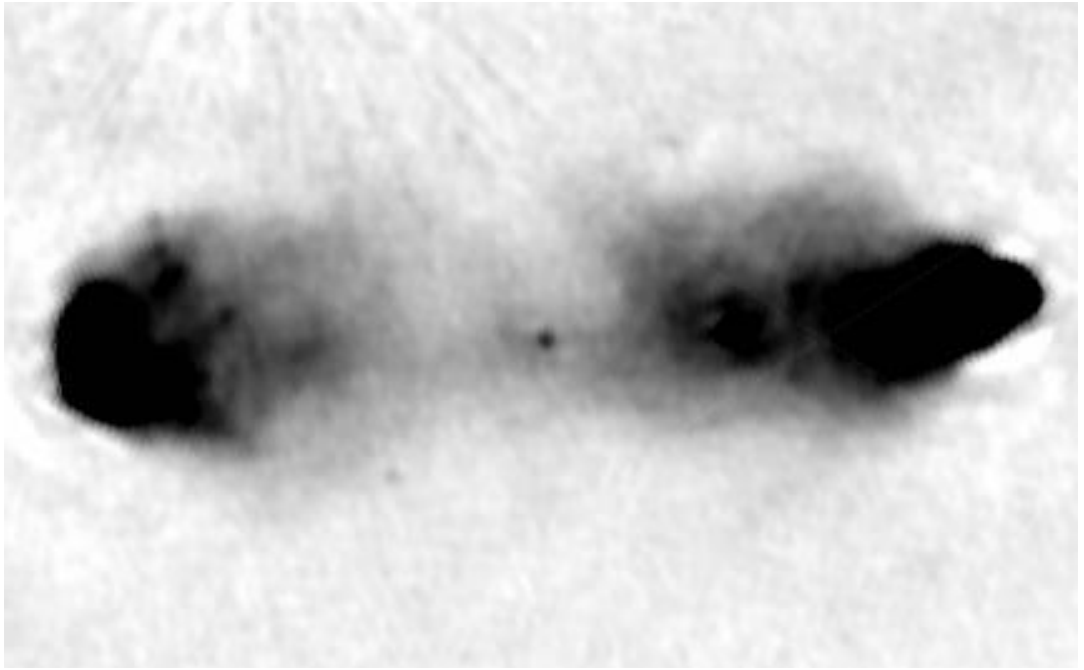




Zehavi+ 2004

Angular Auto-Correlation





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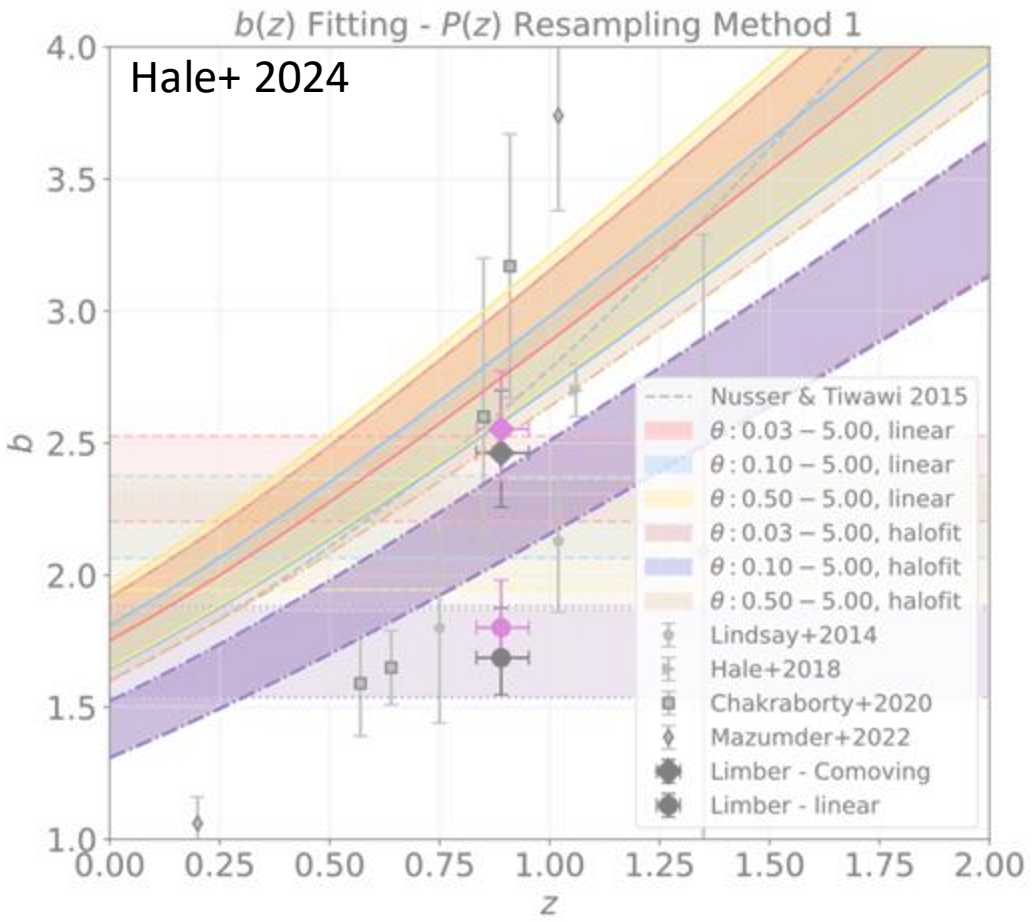

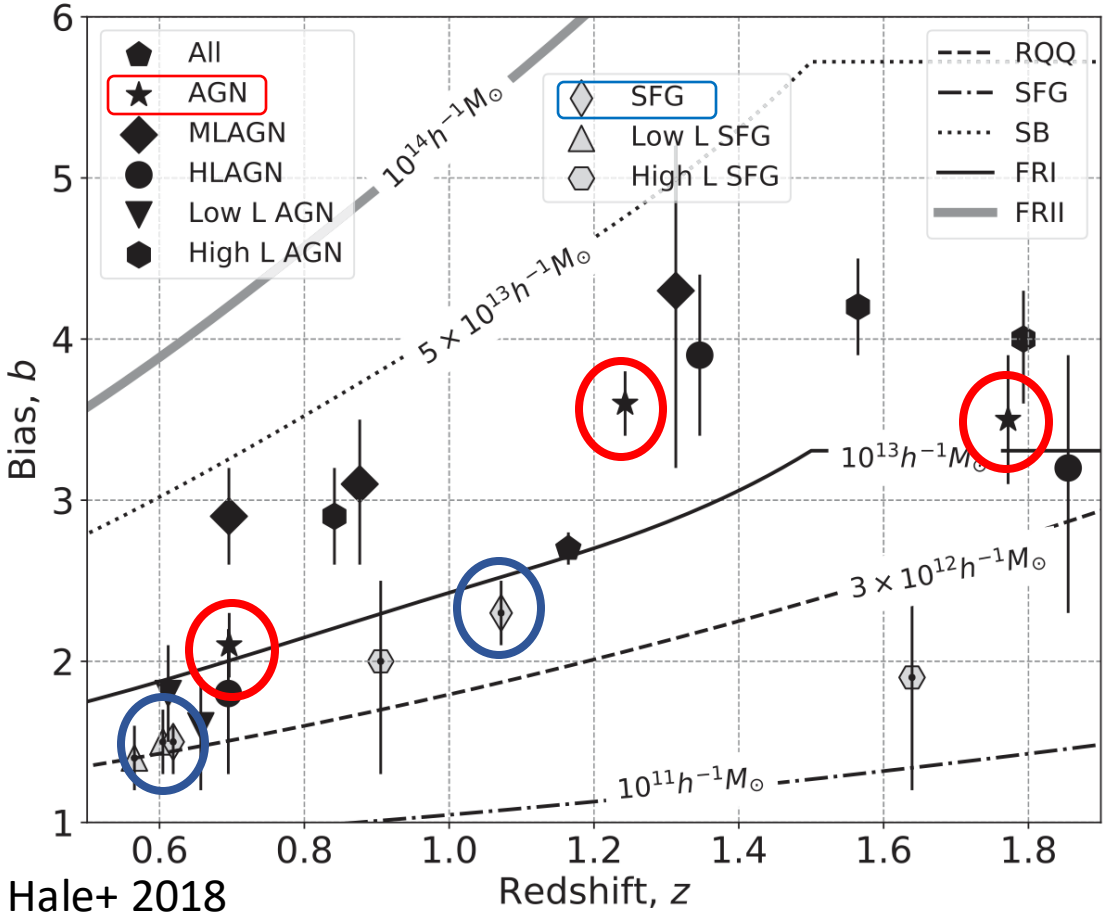

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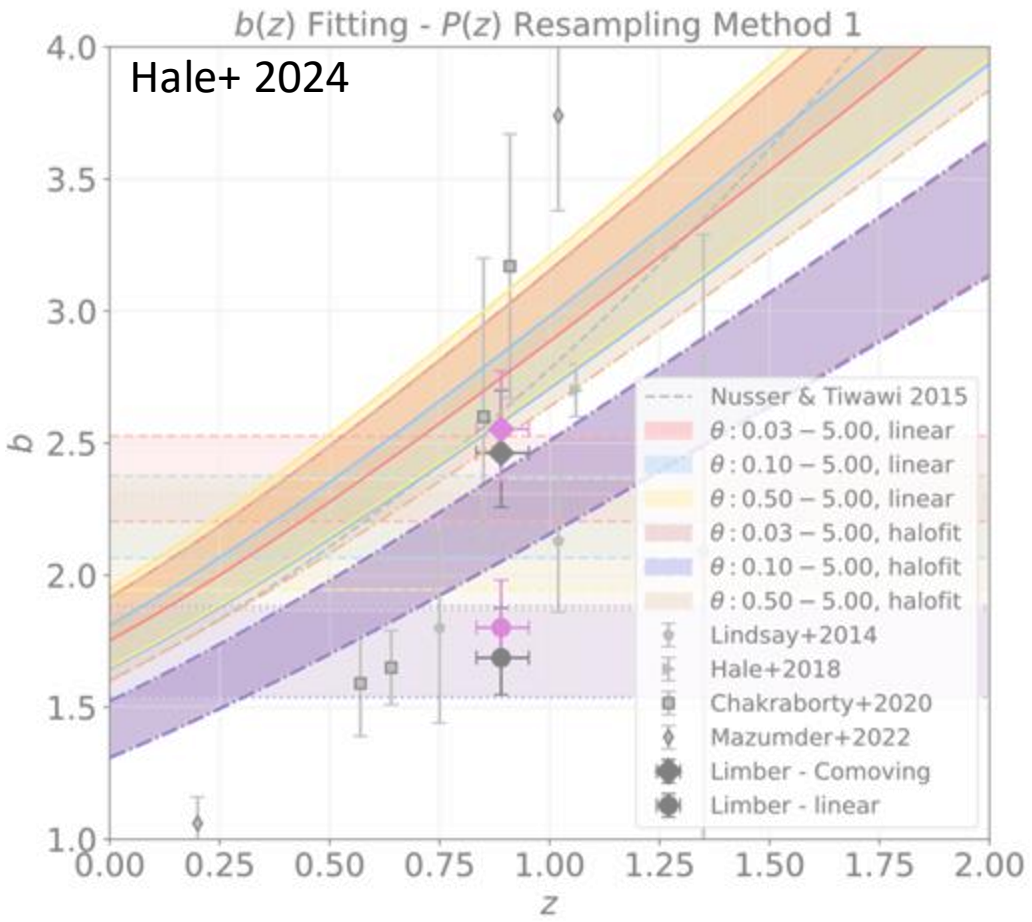
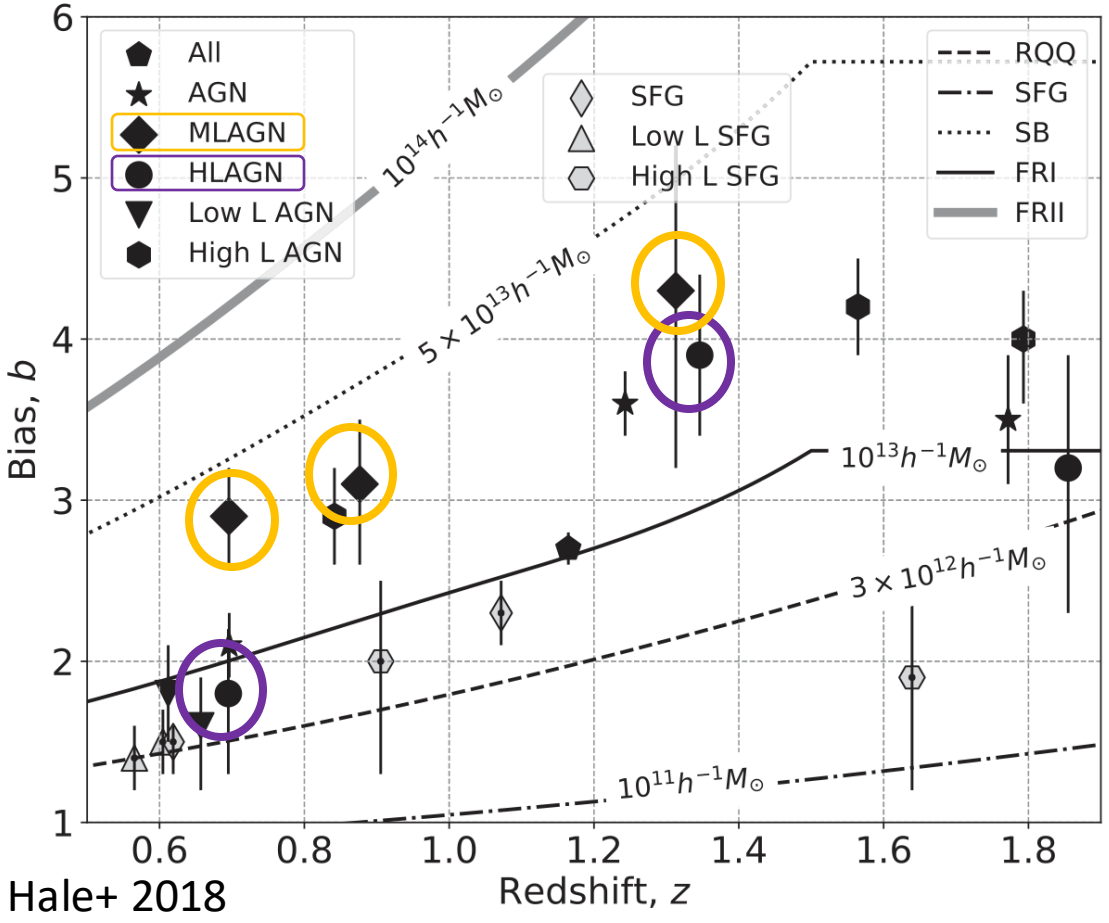
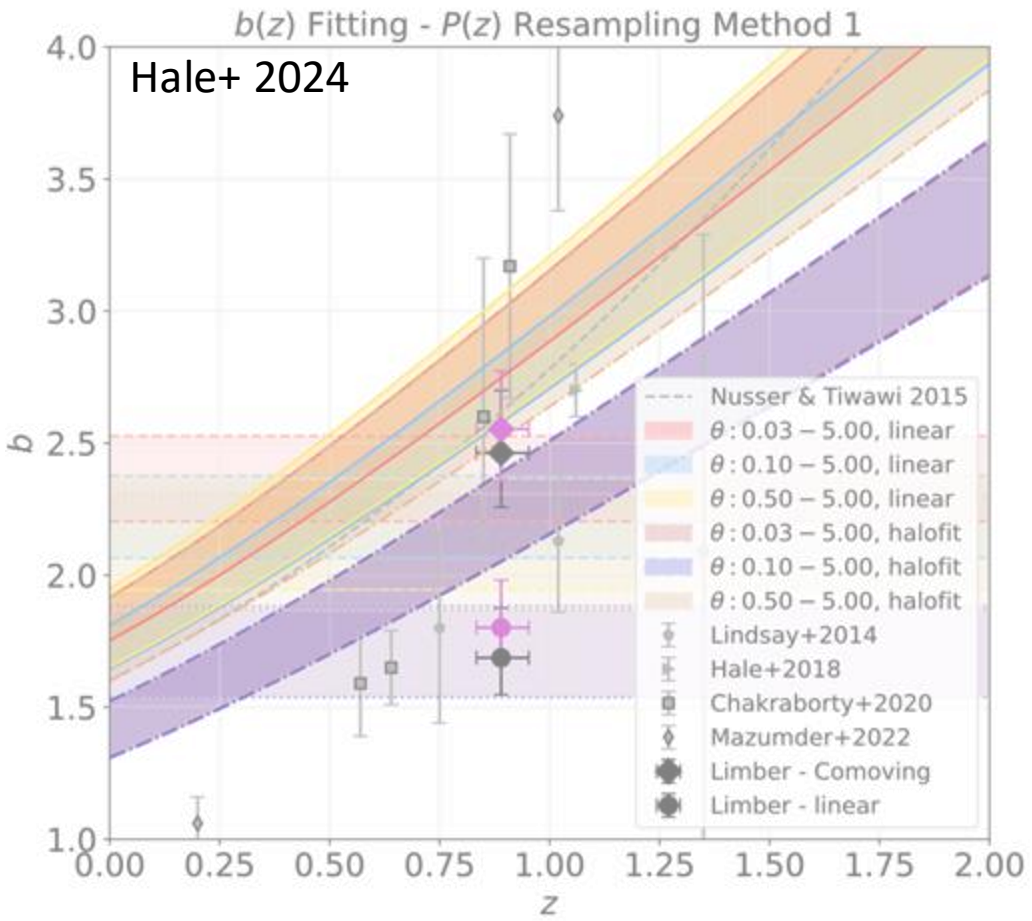
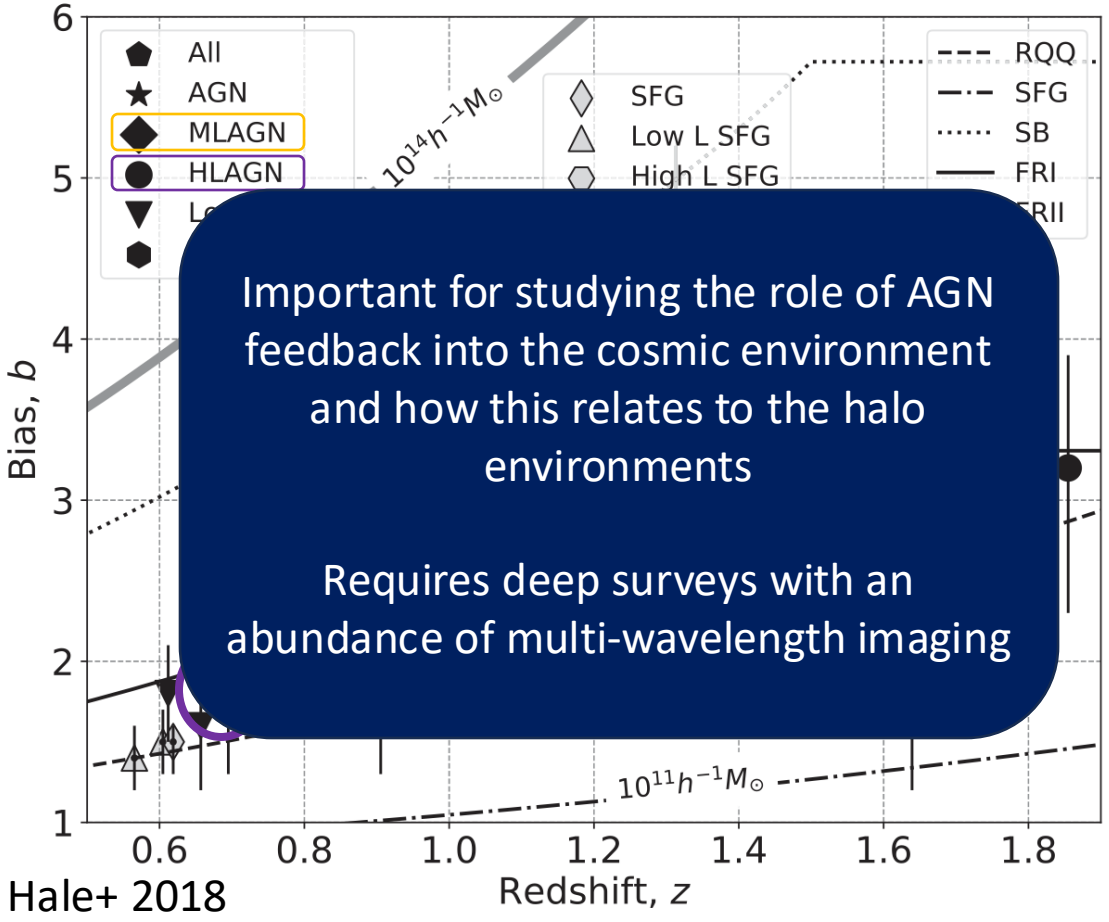




Angular Auto-Correlation

Galaxy Bias Evolution

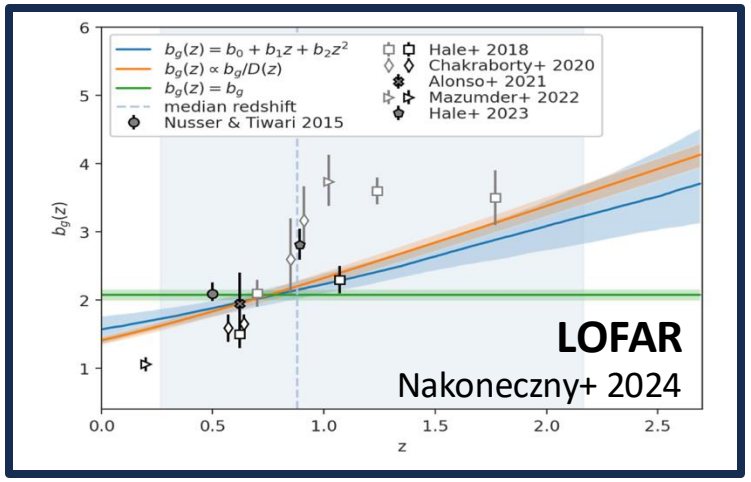


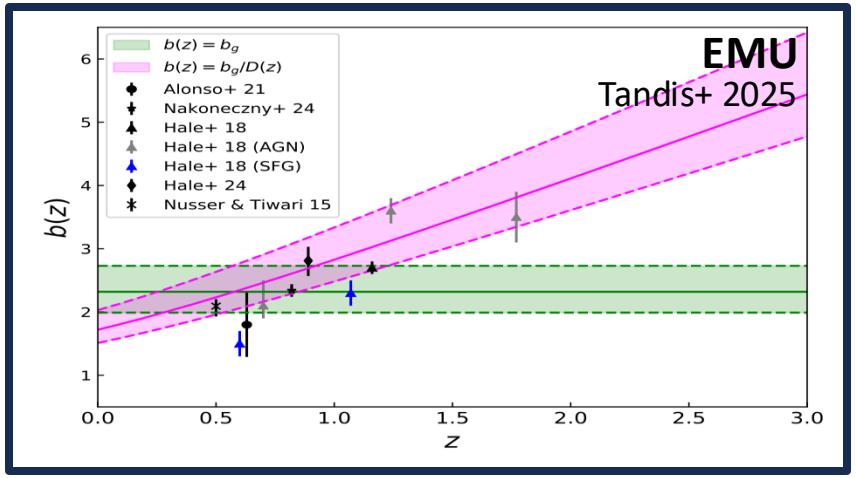


Important for studying the role of AGN feedback into the cosmic environment and how this relates to the halo environments

Requires deep surveys with an abundance of multi-wavelength imaging

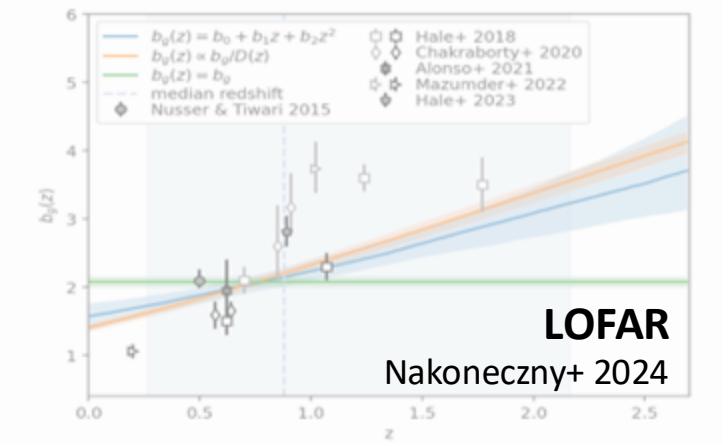
Angular Cross-Correlation with CMB

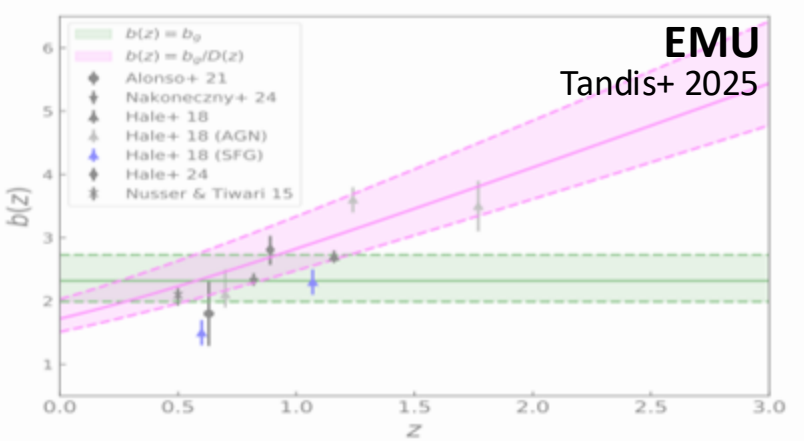


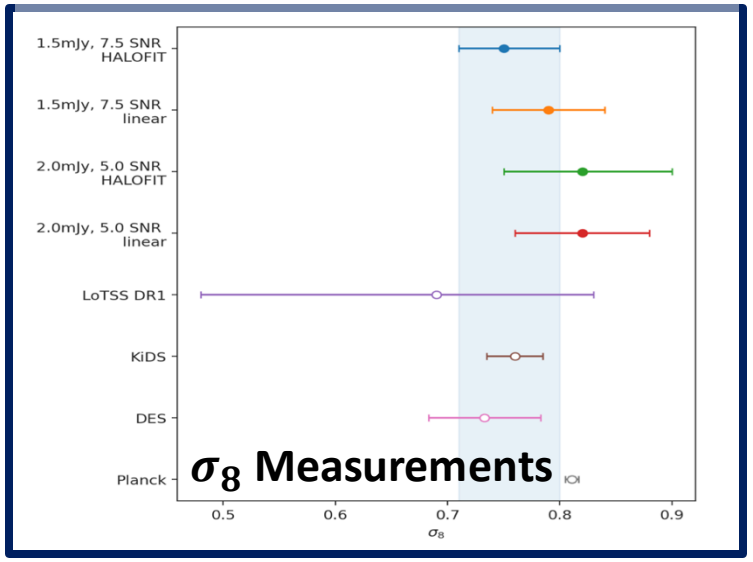


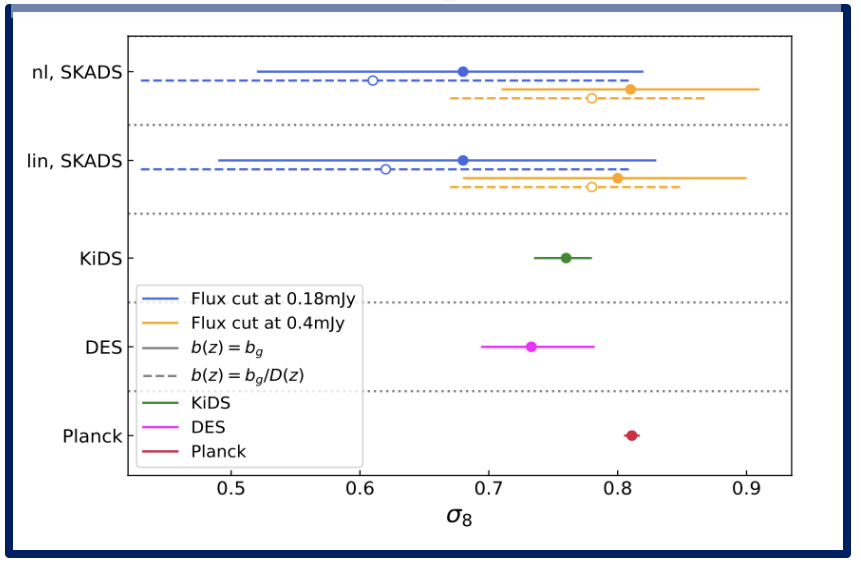
Galaxy Bias Evolution

Angular Cross-Correlation with CMB









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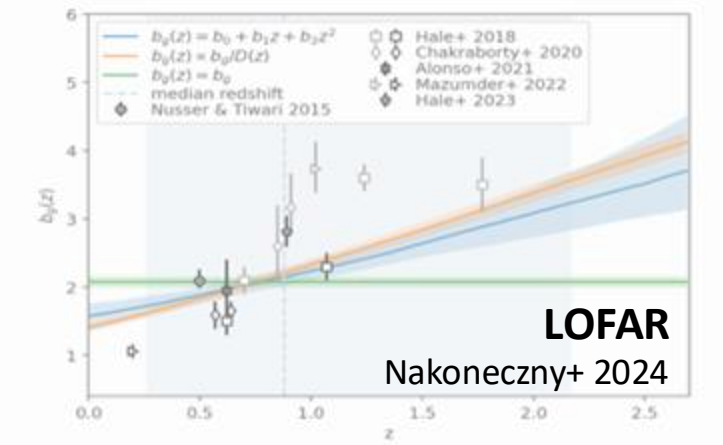
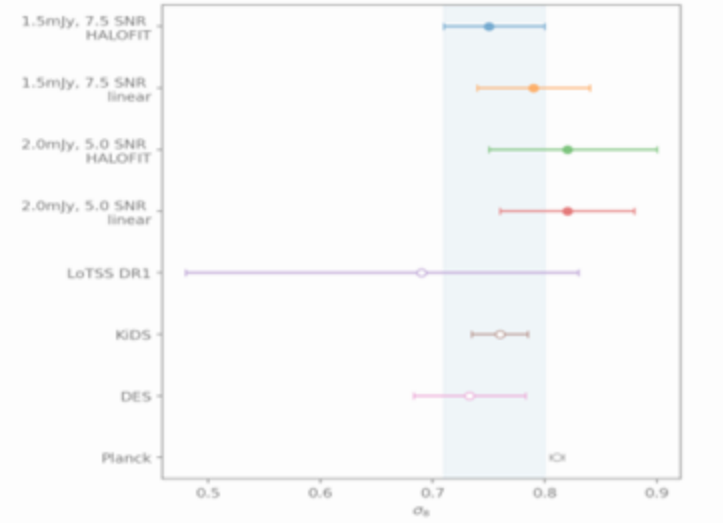
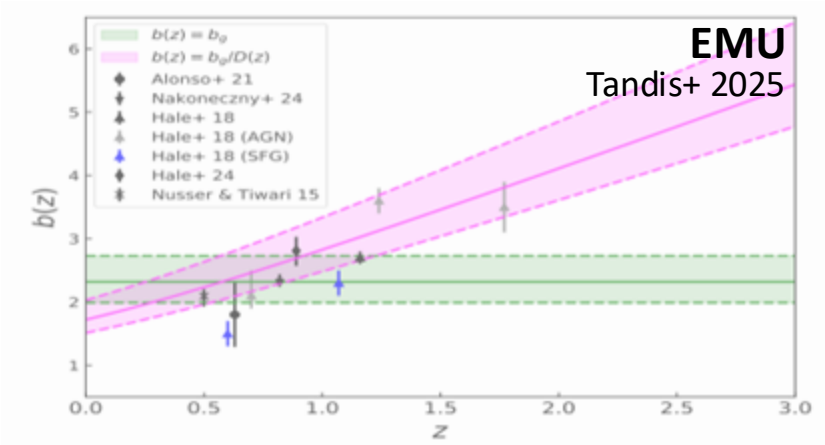
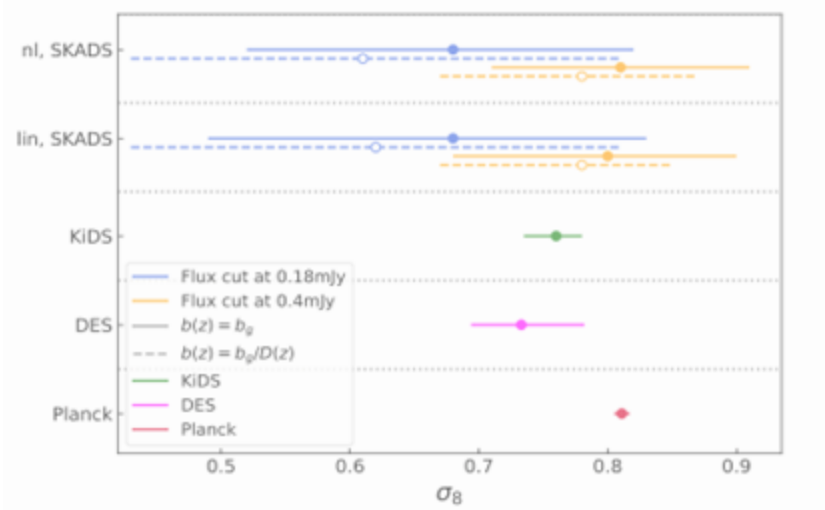
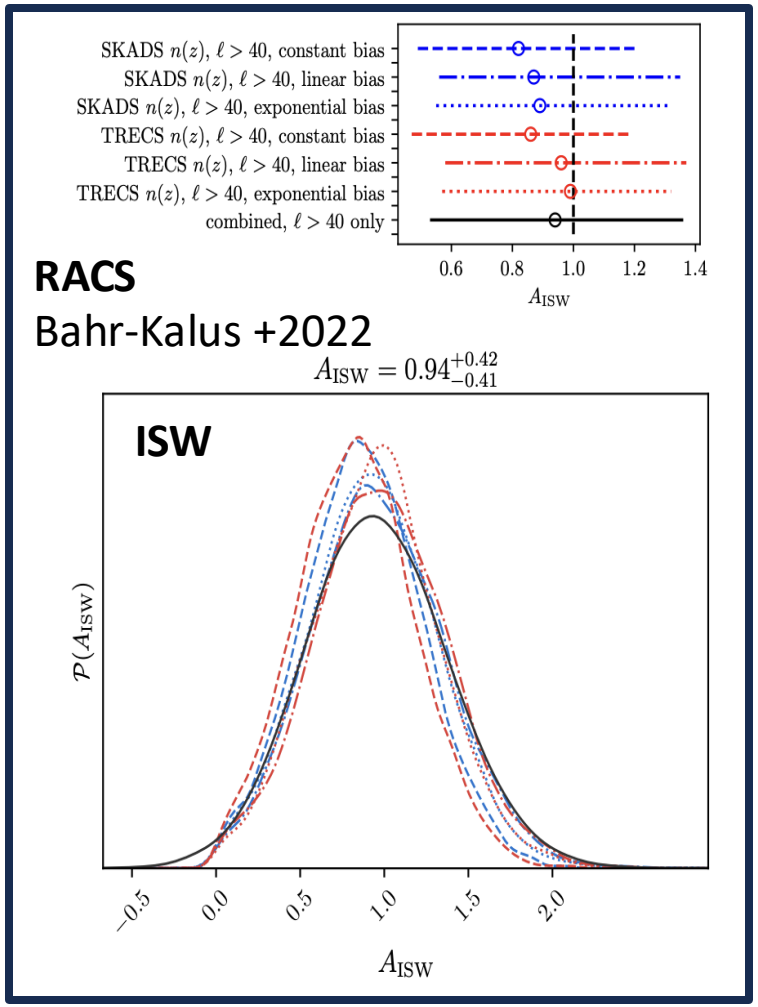


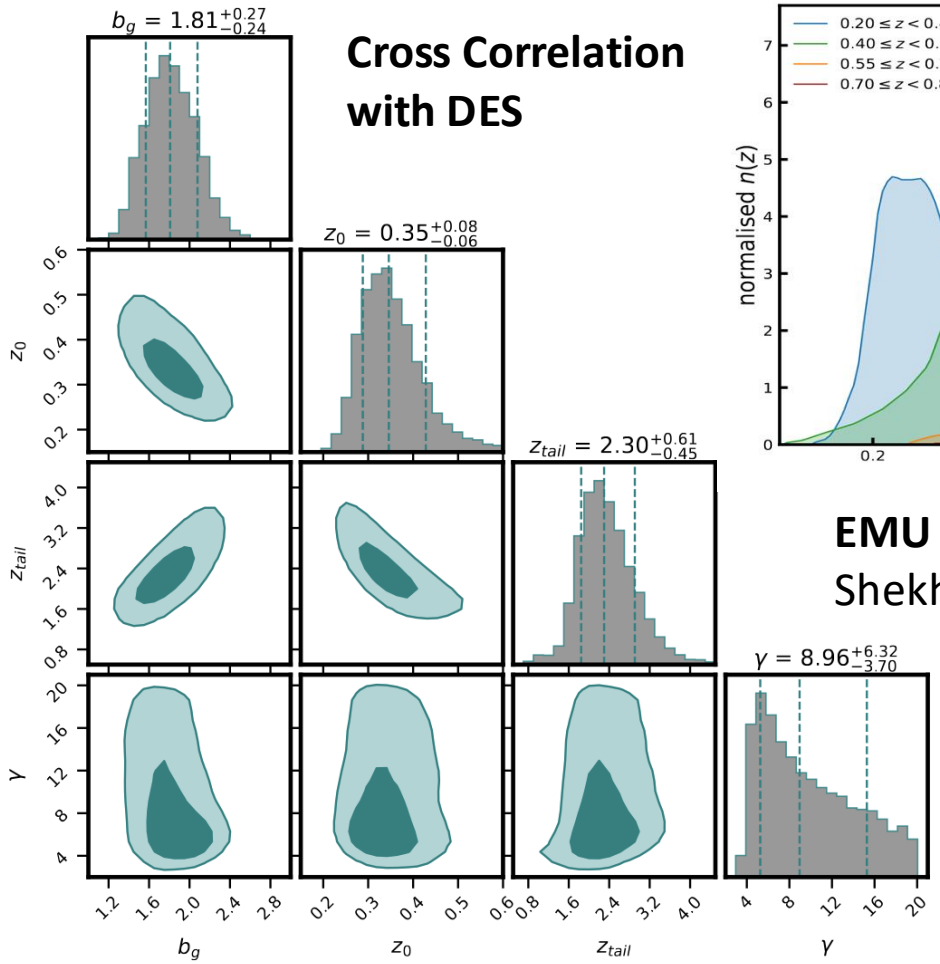




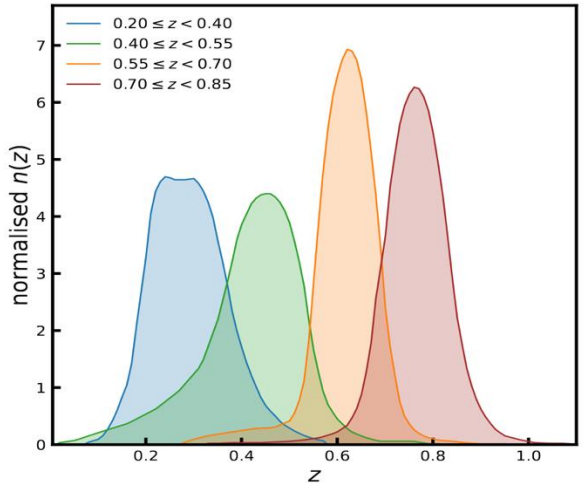




Angular Cross-Correlation with Galaxy Surveys



Cross Correlation with DES

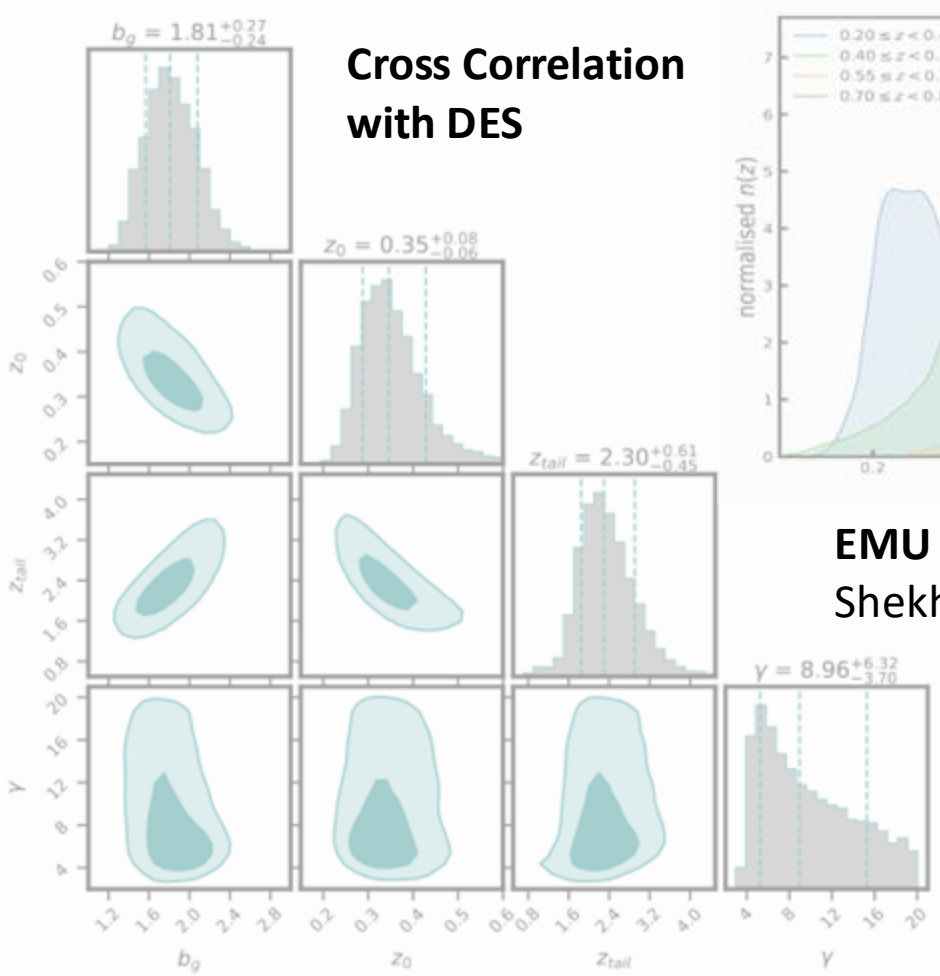


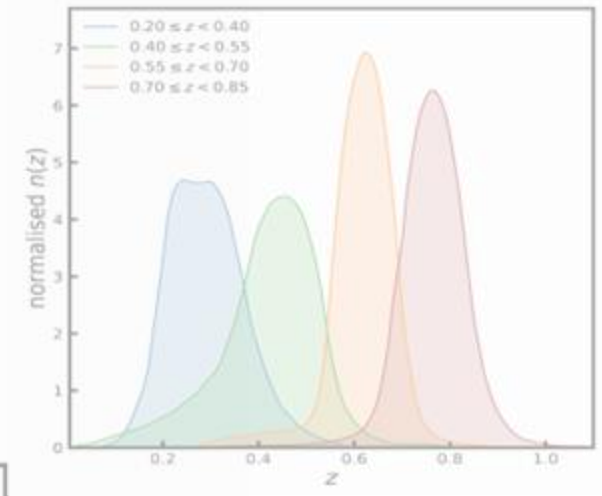
EMU

Shekhar Saraf+ subm.

Angular Cross-Correlation with Galaxy Surveys

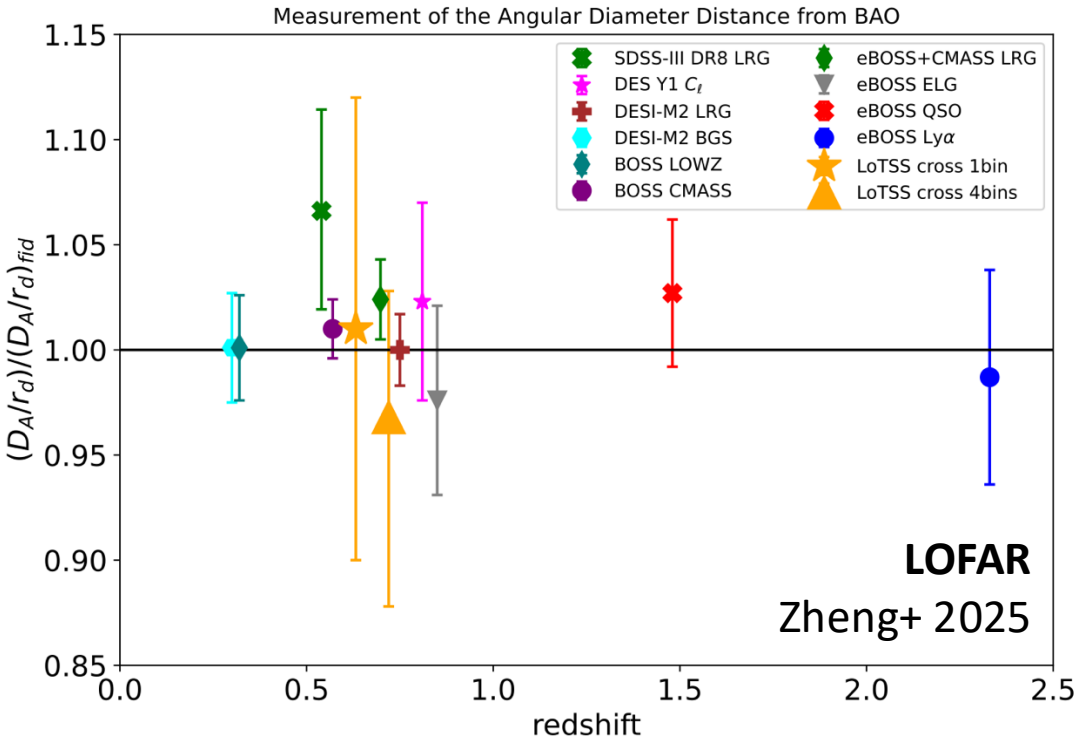
Cross Correlation with DES





EMU
Shekhar Saraf+ subm.

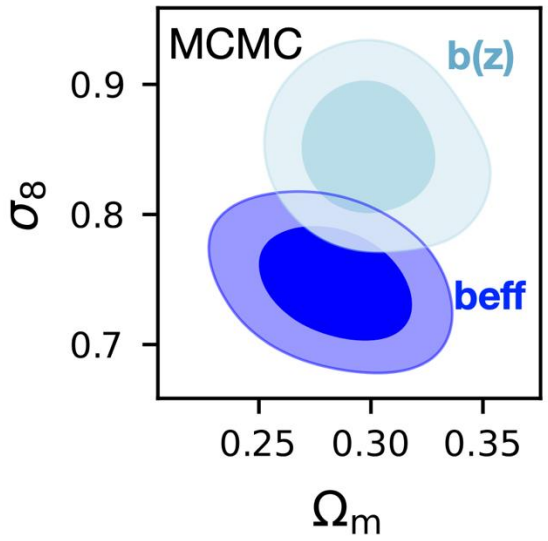
Cross Correlation with eBOSS LRGs



LOFAR
Zheng+ 2025

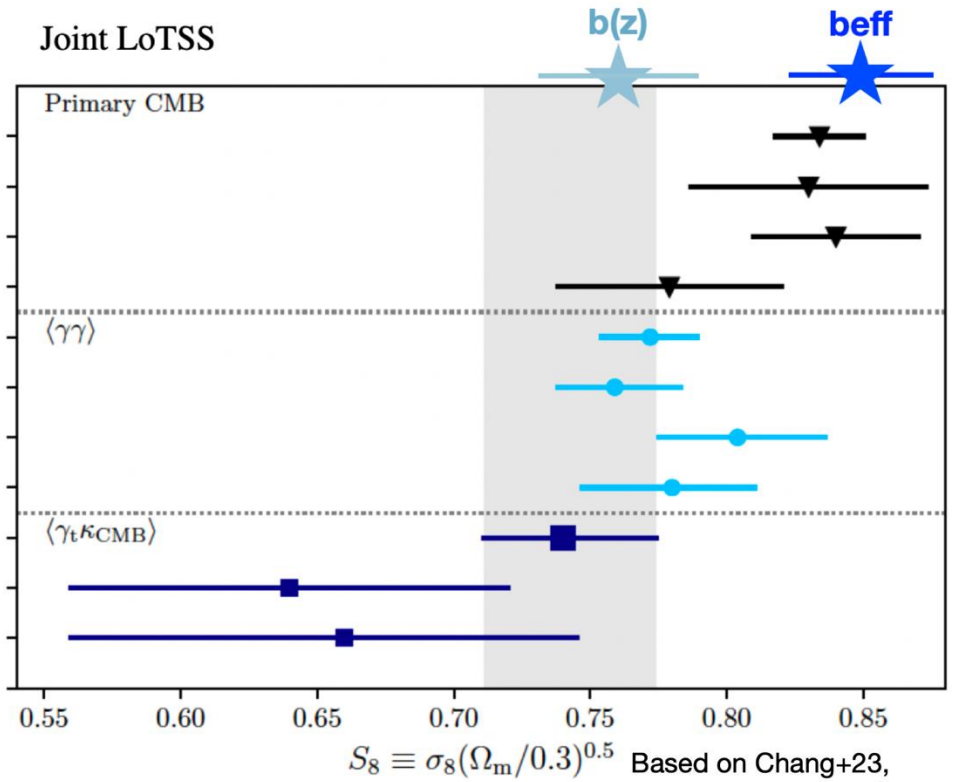
Combined Cosmology Joint Constraints

LOFAR Joint Constraints from multiple probes



Heneka+, The LOFAR cosmology team, Joint cosmological constraints LoTSS DR2, in prep. 2025

Joint: Radio auto-, radio x eBOSS cross- & radio x CMB lensing convergence cross-correlations



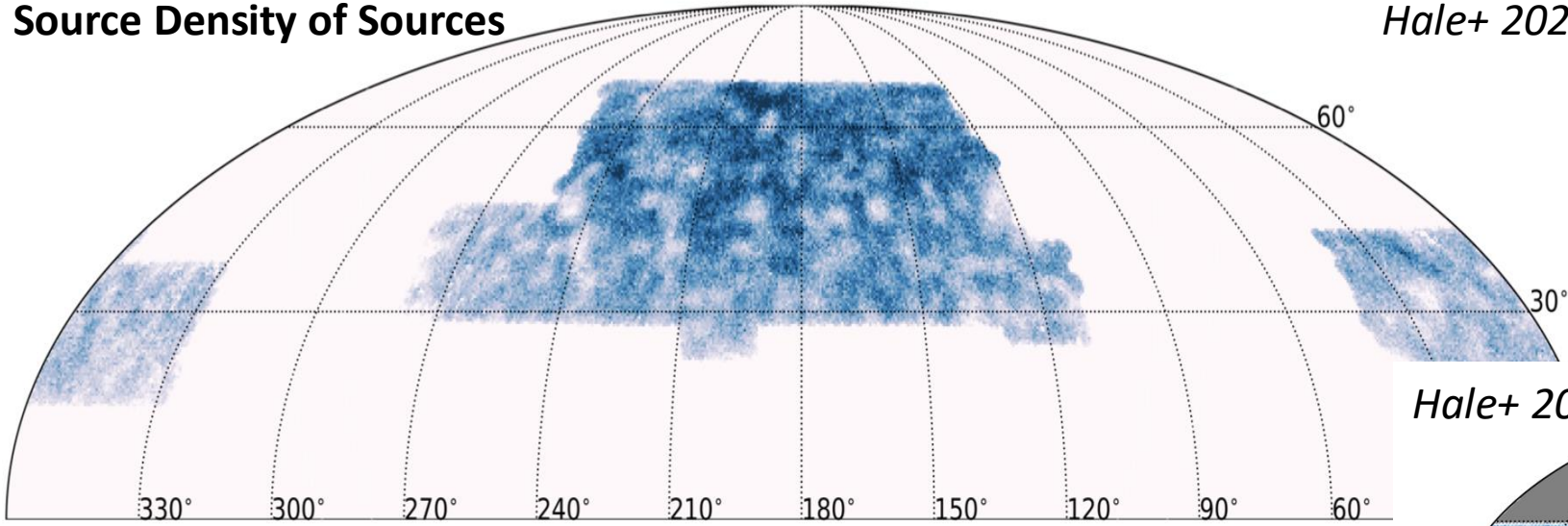
Based on Chang+23, Joint analysis of DES Year 3 data and CMB lensing from SPT and Planck II

Heneka+ in prep

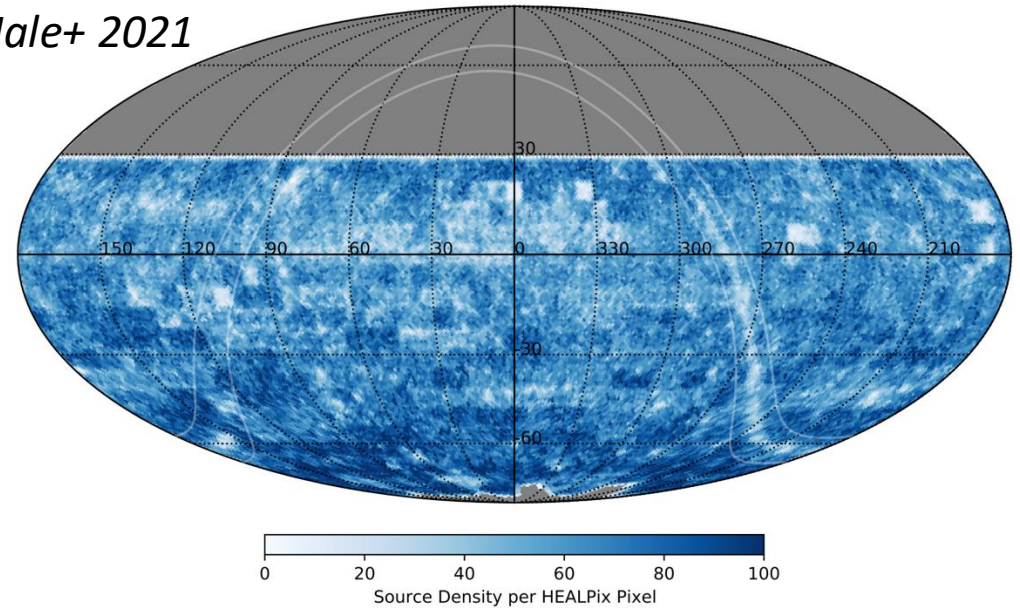
Challenges

Source Density of Sources

Hale+ 2024



Hale+ 2021



Distribution of sources are very non-Uniform due to a combination of observational factors
e.g. loss of sensitivity with elevation, bright sources, mosaicking effects, resolution variations

Need to account for such observational biases in the generation of random catalogues

SKAO – Square Kilometre Array Observatory

Credit: SKAO

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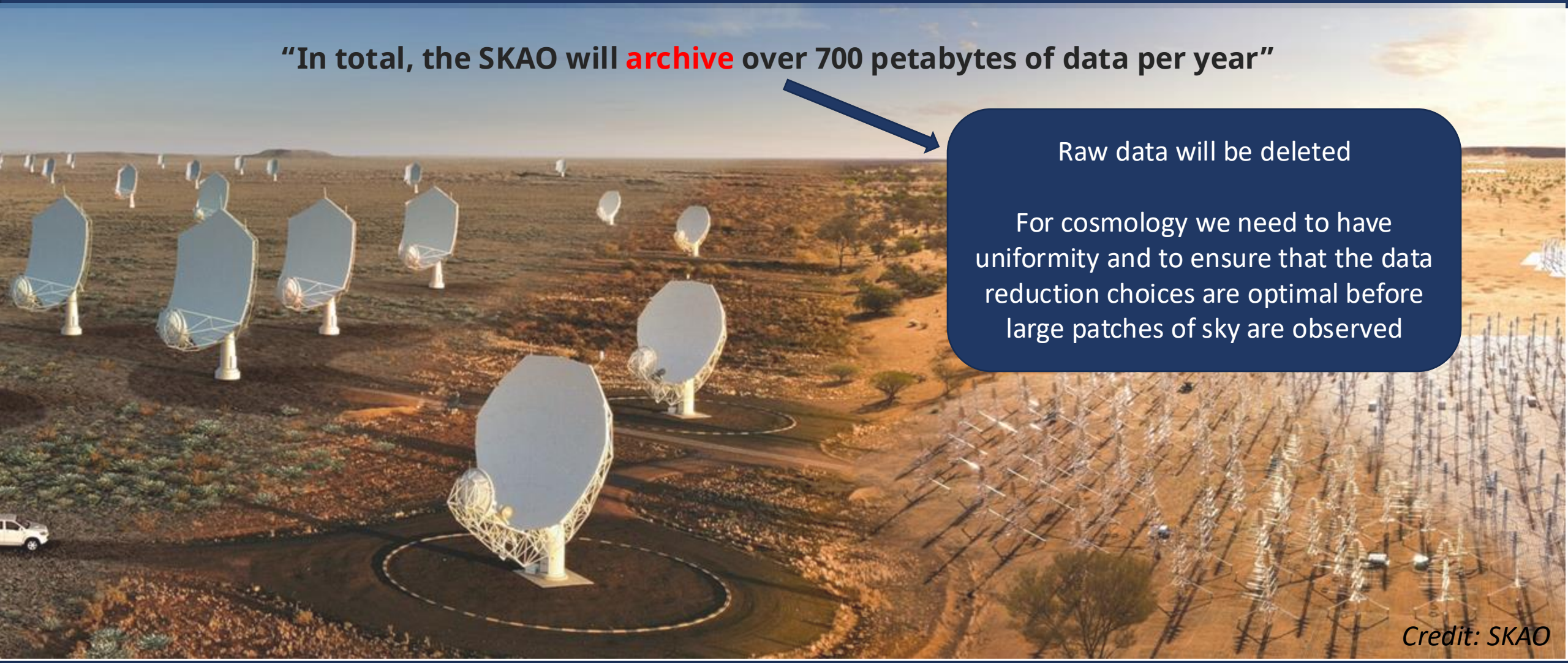

“In total, the SKAO will archive over 700 petabytes of data per year”

Raw data will be deleted

For cosmology we need to have uniformity and to ensure that the data reduction choices are optimal before large patches of sky are observed

Credit: SKAO

Cosmology with the SKAO

Cosmology with Phase 1 of the Square Kilometre Array

Red Book 2018: Technical specifications and performance forecasts

Square Kilometre Array Cosmology Science Working Group: David J. Bacon[1], Richard A. Battye[2,*], Philip Bull[3], Stefano Camera[4,5,6,2], Pedro G. Ferreira[7], Ian Harrison[2,7], David Parkinson[8], Alkistis Pourtsidou[3], Mário G. Santos[9,10,11], Laura Wolz[12,*], Filipe Abdalla[13,14], Yashar Akrami[15,16], David Alonso[7], Sambatra Andrianomena[9,10,17], Mario Ballardini[9,18], José Luis Bernal[19,20], Daniele Bertacca[21,36], Carlos A.P. Bengaly[9], Anna Bonaldi[22], Camille Bonvin[23], Michael L. Brown[2], Emma Chapman[24], Song Chen[9], Xuelei Chen[25], Steven Cunnington[1], Tamara M. Davis[27], Clive Dickinson[2], José Fonseca[9,36], Keith Grainge[2], Stuart Harper[2], Matt J. Jarvis[7,9], Roy Maartens[1,9], Natasha Maddox[28], Hamsa Padmanabhan[29], Jonathan R. Pritchard[24], Alvise Raccanelli[19], Marzia Rivi[13,18], Sambit Roychowdhury[2], Martin Sahlén[30], Dominik J. Schwarz[31], Thilo M. Siewert[31], Matteo Viel[32], Francisco Villaescusa-Navarro[33], Yidong Xu[25], Daisuke Yamauchi[34], Joe Zuntz[35]

Affiliations listed after references

https://arxiv.org/pdf/1811.02743

Cosmology with the SKAO

Cosmology with Phase 1 of the Square Kilometre Array

Red Book 2018: Technical specifications and performance forecasts

- *Medium-Deep Band 2 Survey* : SKA1-MID in Band 2 covering $5,000\,\mathrm{deg}^2$ and an integration time of approximately $t_{\mathrm{tot}} = 10,000$ hrs on sky. Main goals: a continuum weak lensing survey and an HI galaxy redshift survey out to $z \sim 0.4$ (see sections 3.2 and 4).

- *Wide Band 1 Survey* : SKA1-MID in Band 1 covering $20,000\,\mathrm{deg}^2$ and an integration time of approximately $t_{\mathrm{tot}} = 10,000$ hrs on sky. Main goals: a wide continuum galaxy survey and HI intensity mapping in the redshift range $z = 0.35 - 3$ (see sections 3.3, 3.4 and 5).

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Continuum Cosmology Science Goals:

Angular Clustering and ISW **Cosmic Dipole** **Cosmic Shear**

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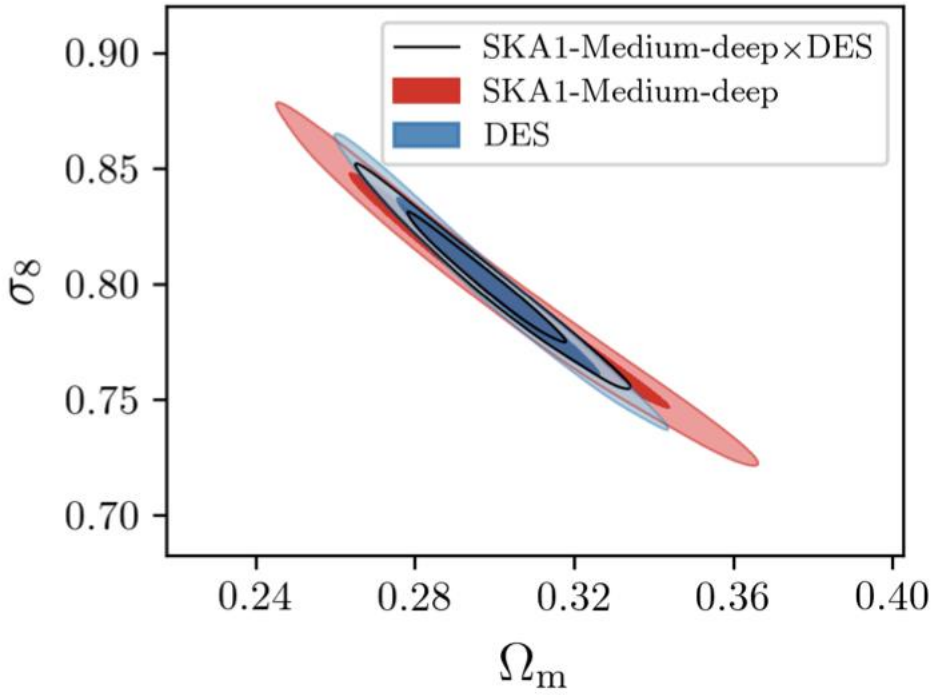
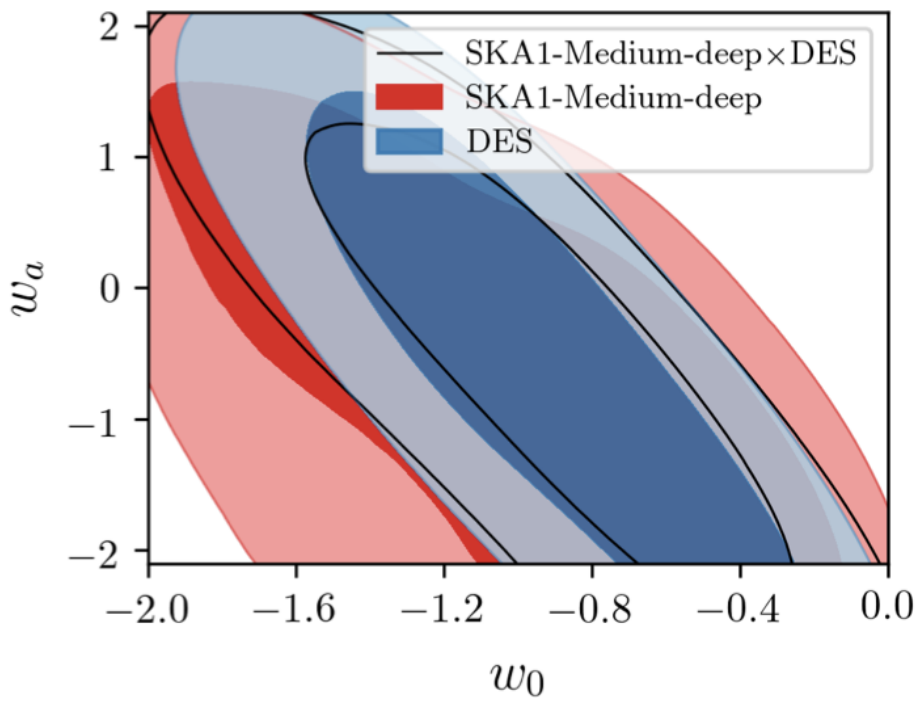
Cosmic Shear





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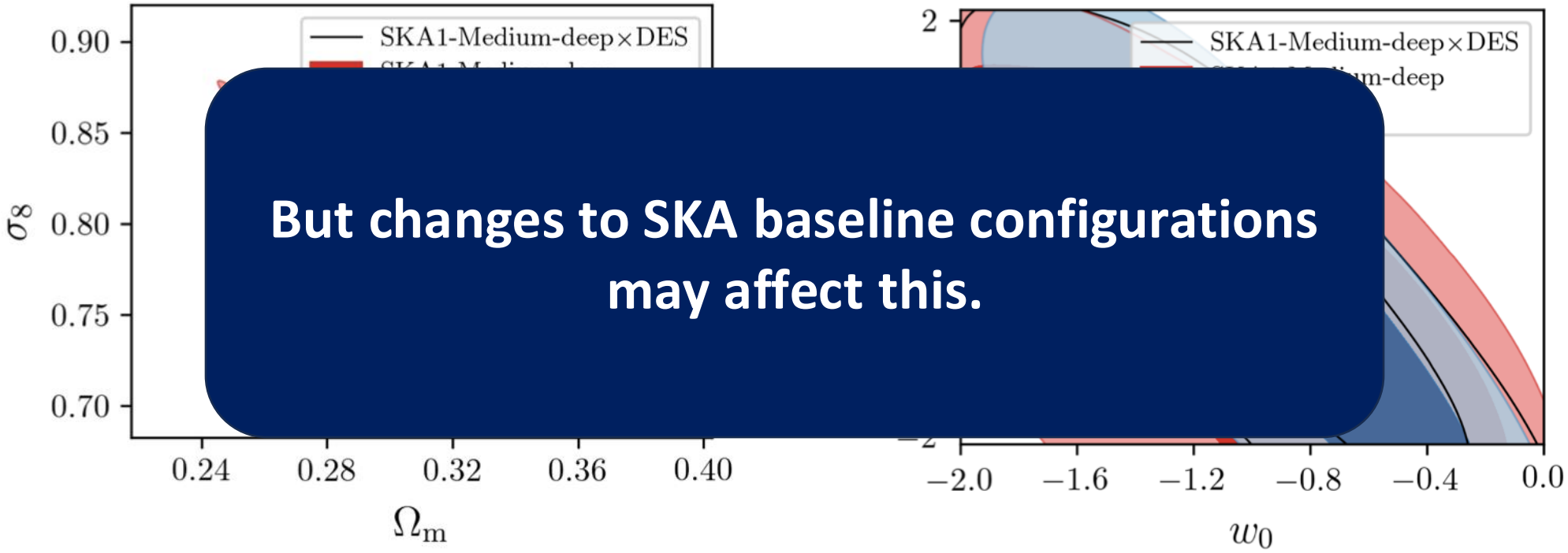
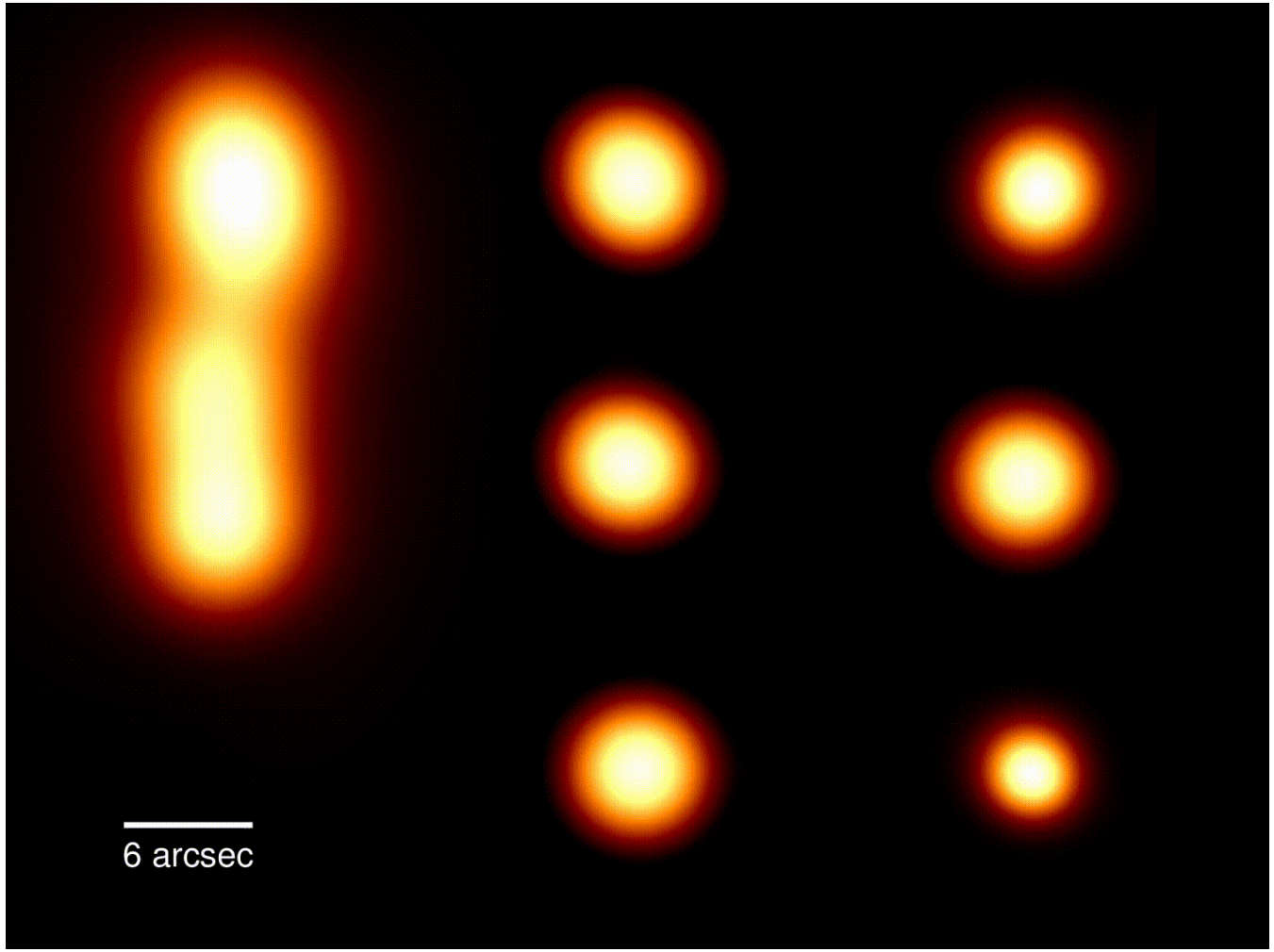


But changes to SKA baseline configurations may affect this.

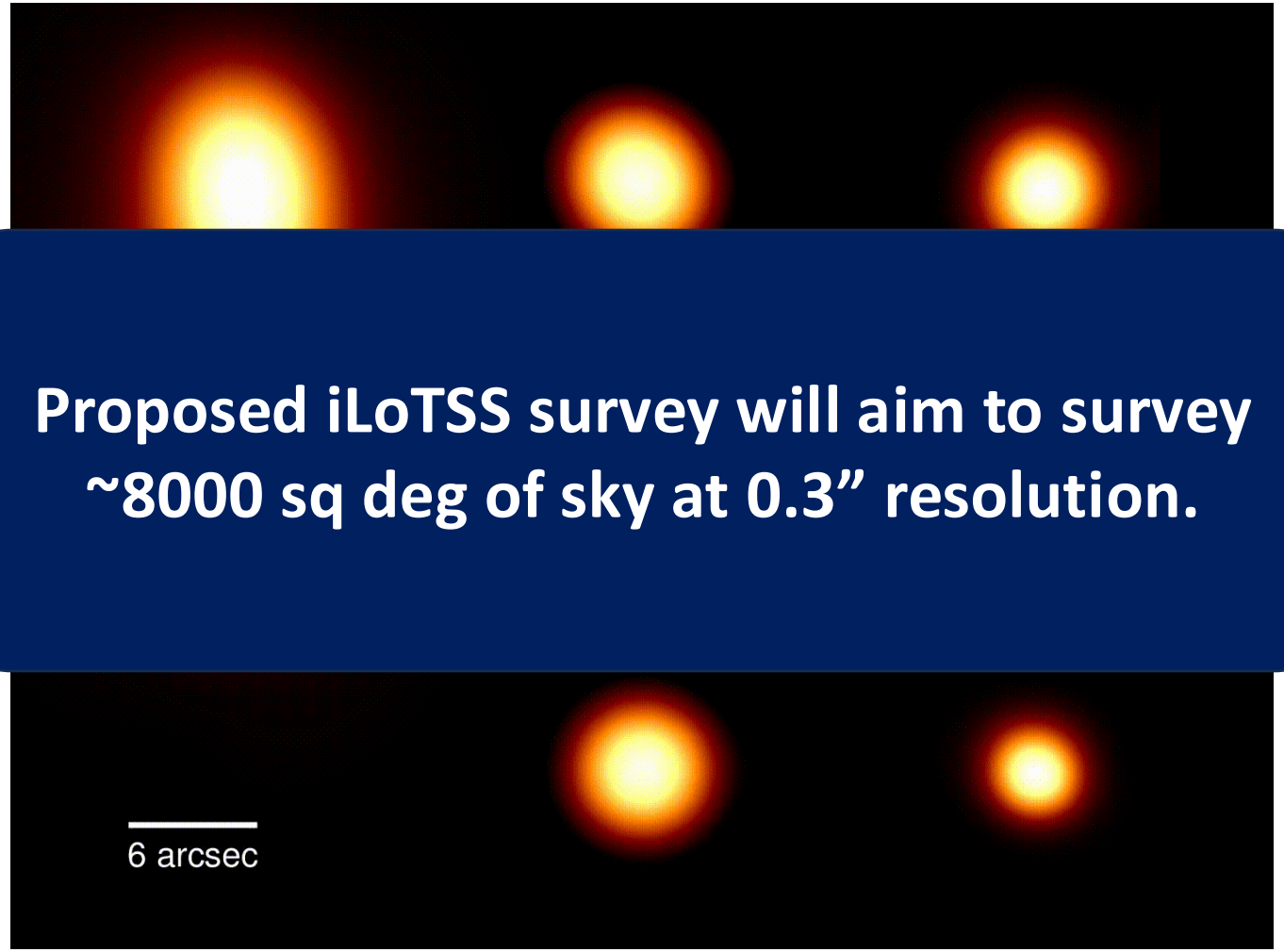
https://arxiv.org/pdf/1811.02743

Angular Resolution of Radio Surveys



Courtesy of L. Morabito (Durham)

Angular Resolution of Radio Surveys



Proposed iLoTSS survey will aim to survey ~8000 sq deg of sky at 0.3” resolution.

Courtesy of L. Morabito (Durham)

SKAO Expectations and Requirements

We need simulations which account for as many observational expectations/systematics as possible

SKAO Expectations and Requirements

Generate Pointing Strategy across the sky and estimate noise and beam properties using sensitivity predictions

In progress by Hale, von Hausegger, Wagenveld+

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+ Any other systematics we can think to add!

In progress by Hale, von Hausegger, Wagenveld+

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Challenge is computational ability to fully probe systematics through end-to-end simulations

In progress by Hale, von Hausegger, Wagenveld+

SKAO Expectations and Requirements

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Generate random galaxies across the sky using simulated properties (fluxes, redshifts)

SKAO Science working groups currently working on updating forecasts using updated telescope specifications for a new book

Apply completeness limits and test homogeneity

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In progress by Hale, von Hausegger, Wagenveld+

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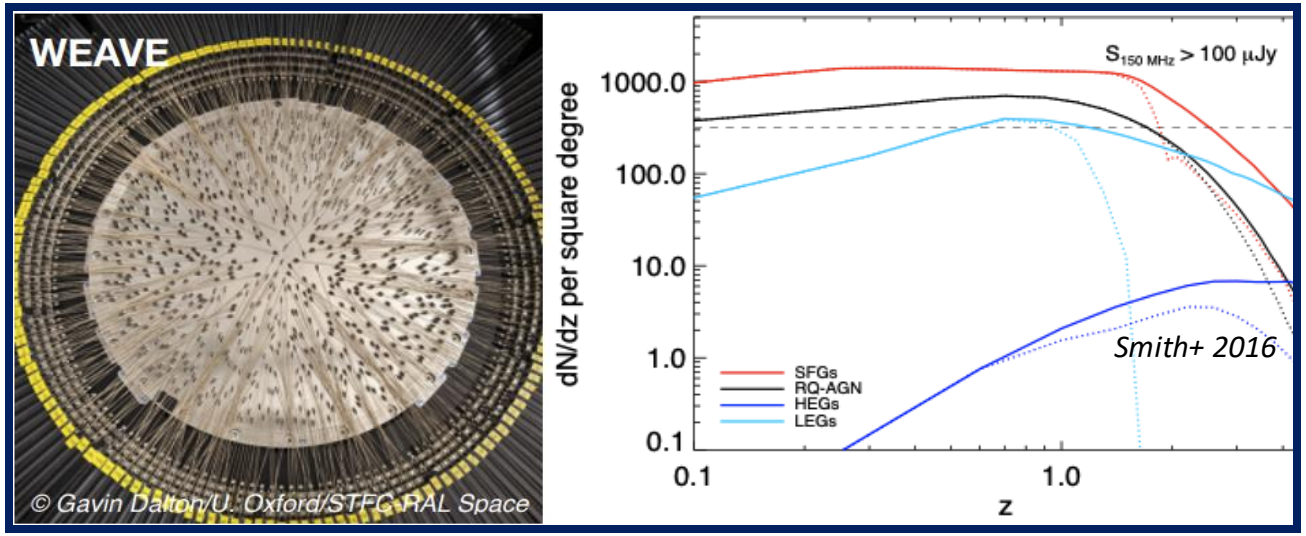
Synergies with other Stage IV surveys will be crucial for maximizing this science

Other Upcoming Cosmology Prospects pre-SKAO

Follow up Redshift Surveys:
WEAVE-LOFAR (Smith+ 2016)
ORCHIDSS (Duncan+ 2022)



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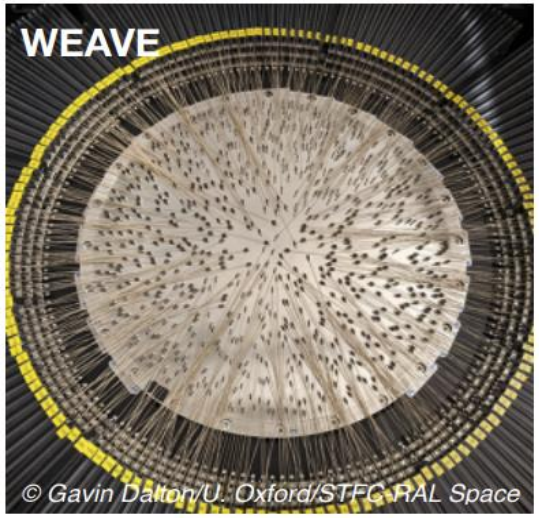
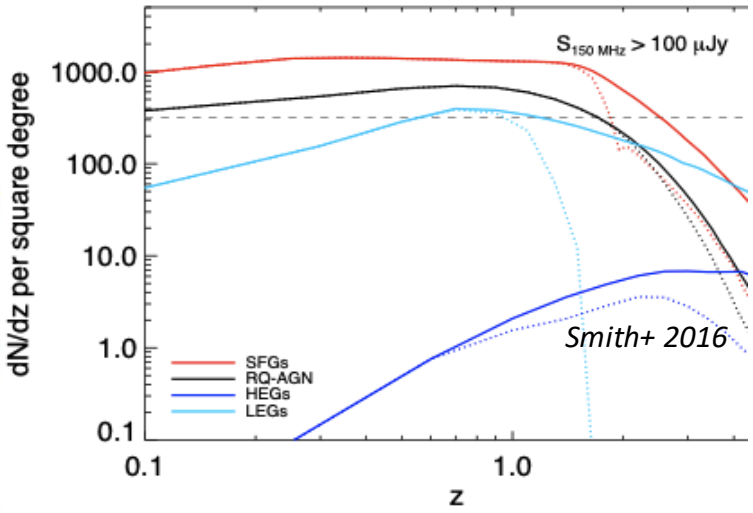
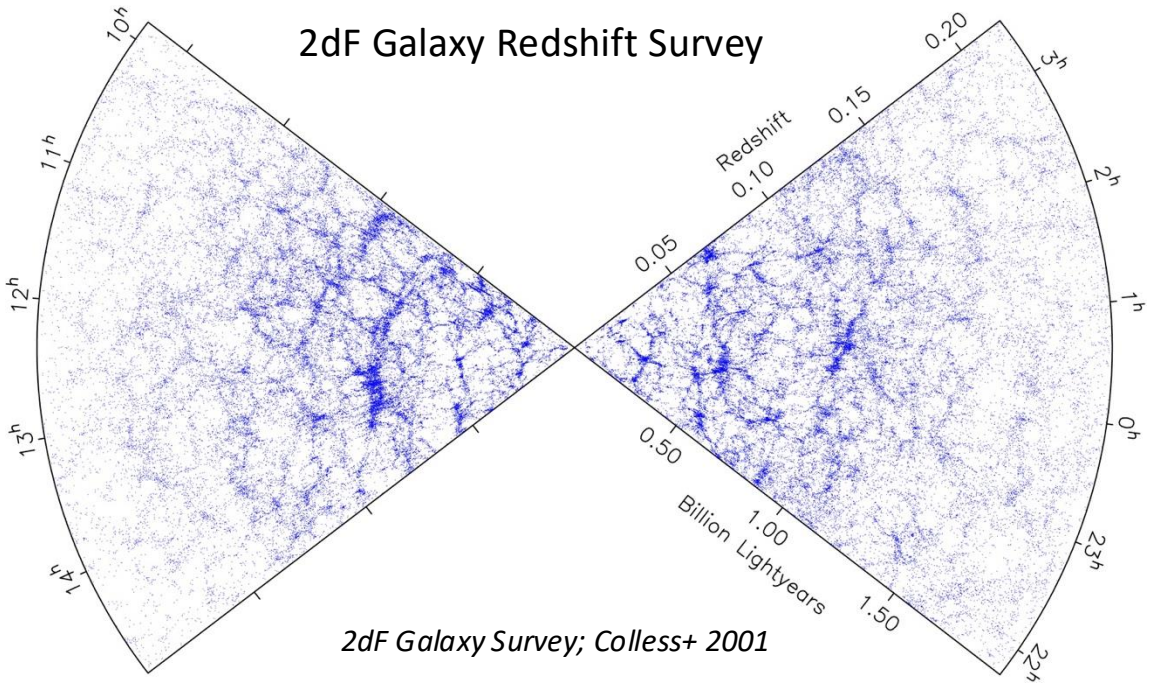




2dF Galaxy Redshift Survey

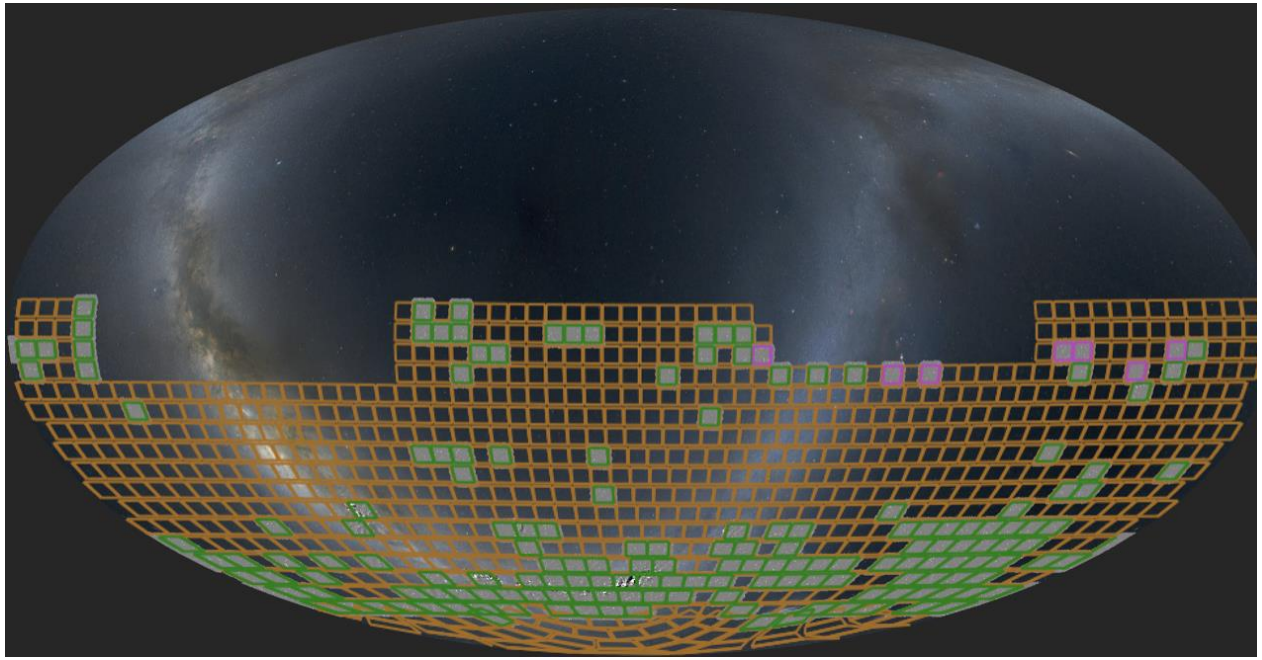


2dF Galaxy Survey; Colless+ 2001

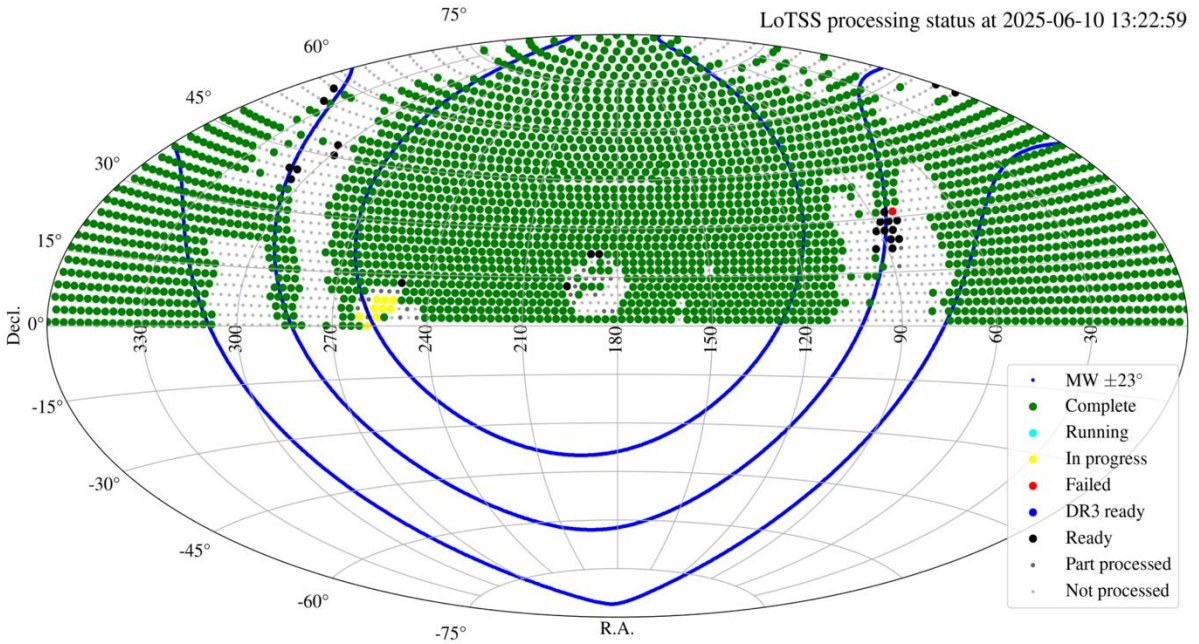
Other Upcoming Cosmology Prospects pre-SKAO

Expansion of Surveys and Upcoming Surveys:

EMU

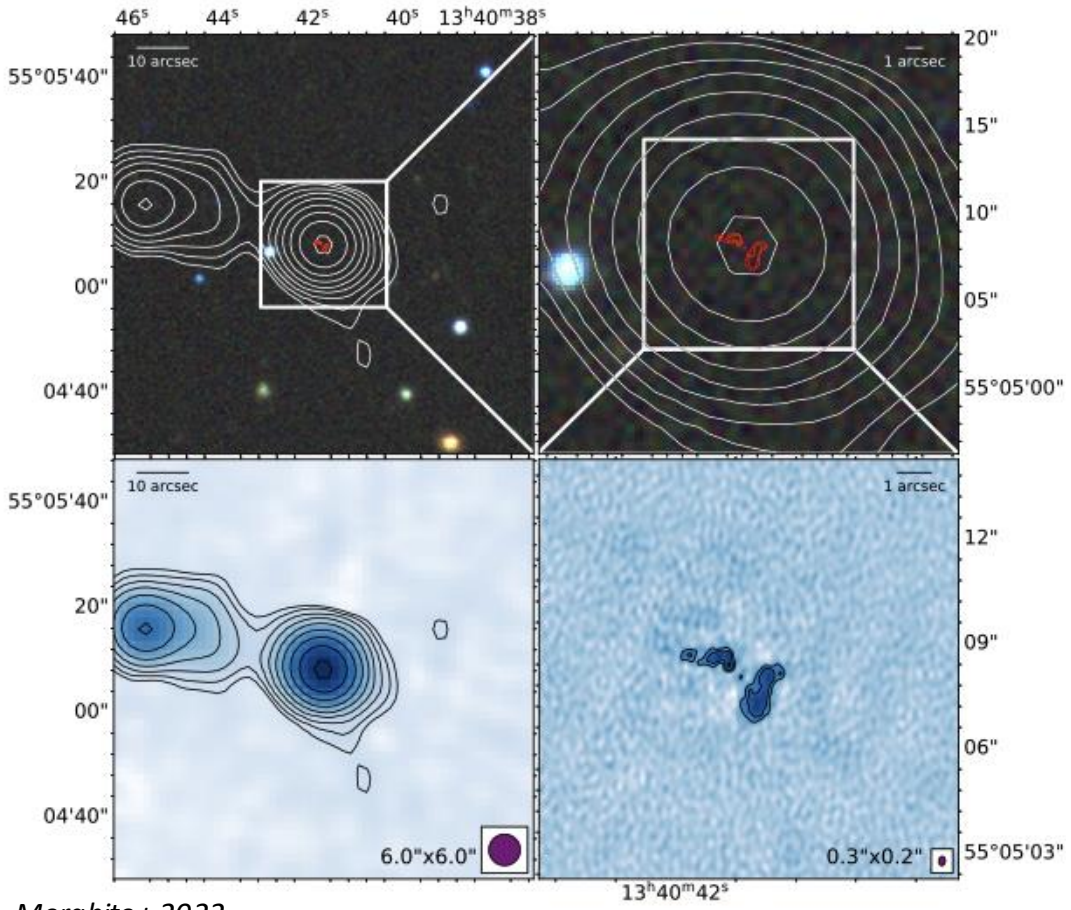


LoTSS DR3



Other Upcoming Cosmology Prospects pre-SKAO

LOFAR High Resolution



Morabito+ 2022

Other Upcoming Cosmology Prospects pre-SKAO

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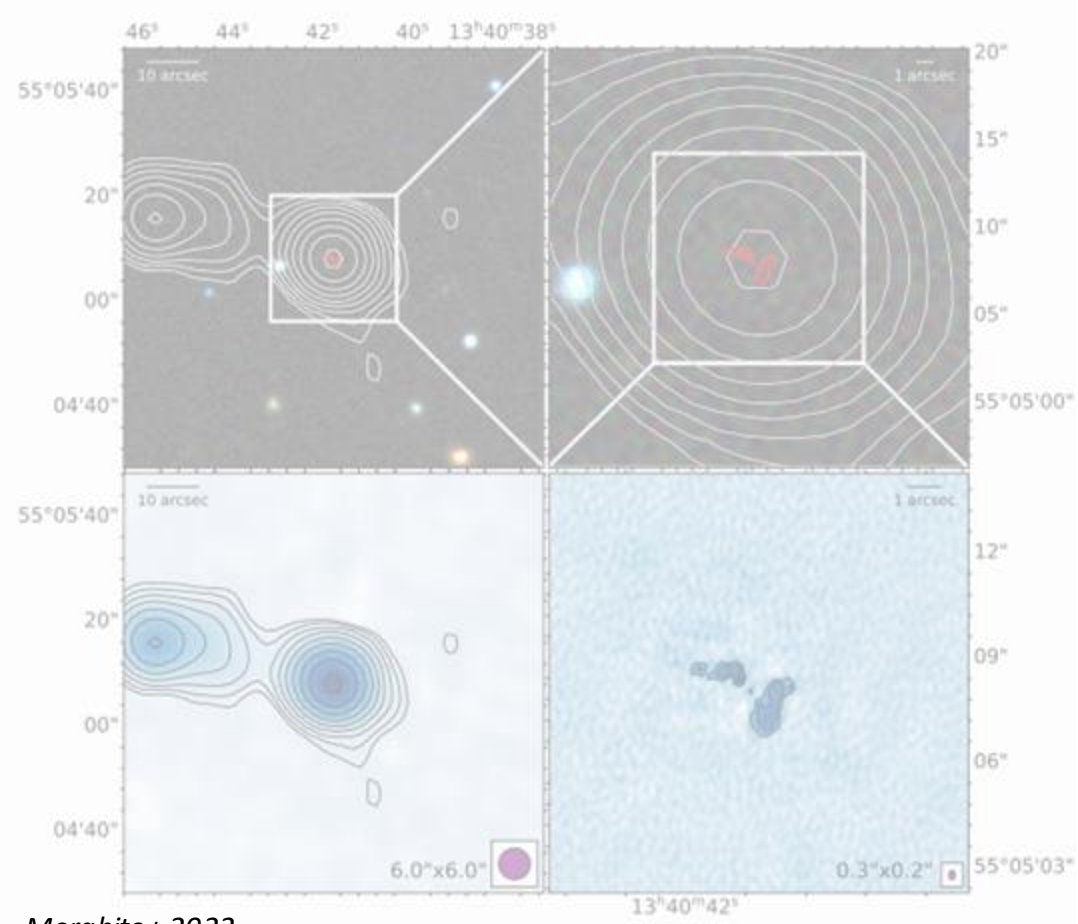
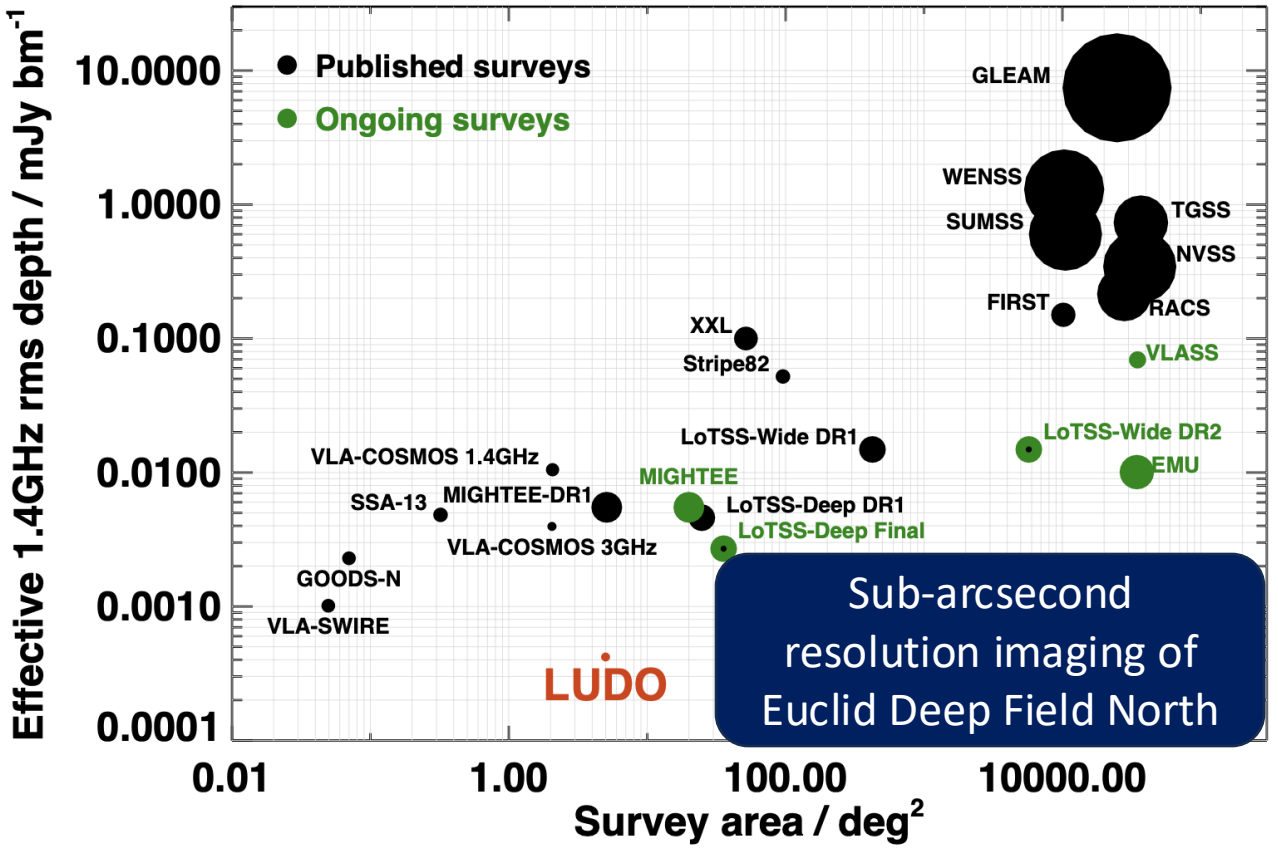


Morabito+ 2022

LUDO Survey



Summary

- Radio surveys offer a unique window on the Universe for **cosmology** studies:
  - Combination of **large area** observations + **deep fields** with a **wealth of ancillary data**
- **Systematics** are **key** to understand to accurately trace the **large-scale structure**:
  - Numerous **systematic effects** to account for e.g. incompleteness, smearing, measurement errors – this is the biggest challenge
- **Precursor/Pathfinder** telescopes to the SKAO are already allowing us to **probe cosmological parameters** through a combination of auto- and cross-correlation measurements
  - Cosmic Dipole (e.g. Wagenveld+ 2023), Angular clustering (e.g. Hale+ 2024), CMB cross-correlations (e.g. Tandis+ 2025), Galaxy survey cross correlations (e.g. Zheng+ 2025), bias evolution using deep fields (e.g. Hale+ 2018 & subm.)
- Future is exciting:
  - **Spectroscopic surveys** which target radio sources (e.g. **WEAVE-LOFAR**, Smith+ 2016, and **ORCHIDSS**, Duncan+2023) will allow us to **directly** measure **the spatial correlation function**
  - **SKAO & LOFAR2.0** will produce **deep imaging** over large areas at much **higher resolution**