Source populations in the Extragalactic Radio Sky

Dr Catherine Hale

Leverhulme Trust Early Career Research Fellow

University of Edinburgh

LEVERHULME TRUST

THE UNIVERSITY of EDINBURGH

Email: Catherine.Hale@ed.ac.uk

Talk Overview

- Extragalactic Radio Source Populations
- Radio Surveys past, present and future
- Deep Radio Source Counts
- Using Multi-wavelength Information to investigate source populations
- Future work

Email: Catherine.Hale@ed.ac.uk

Extragalactic Sources of Radio Emission

NGC 6946

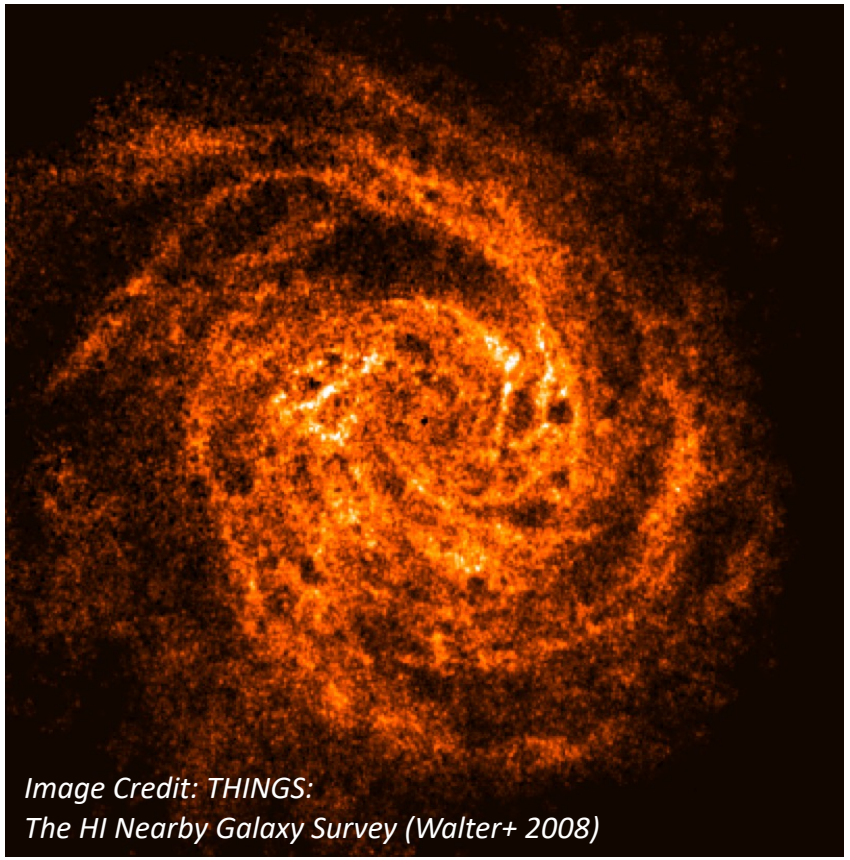


Image Credit: THINGS:
The HI Nearby Galaxy Survey (Walter+ 2008)

Email: Catherine.Hale@ed.ac.uk

Extragalactic Sources of Radio Emission

NGC 6946

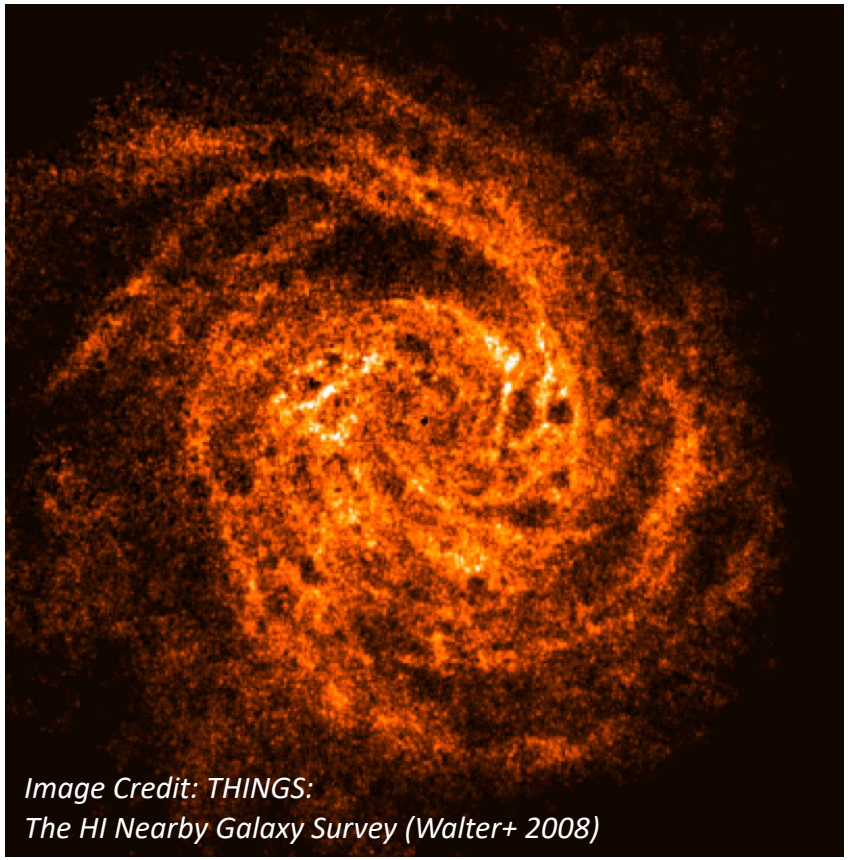
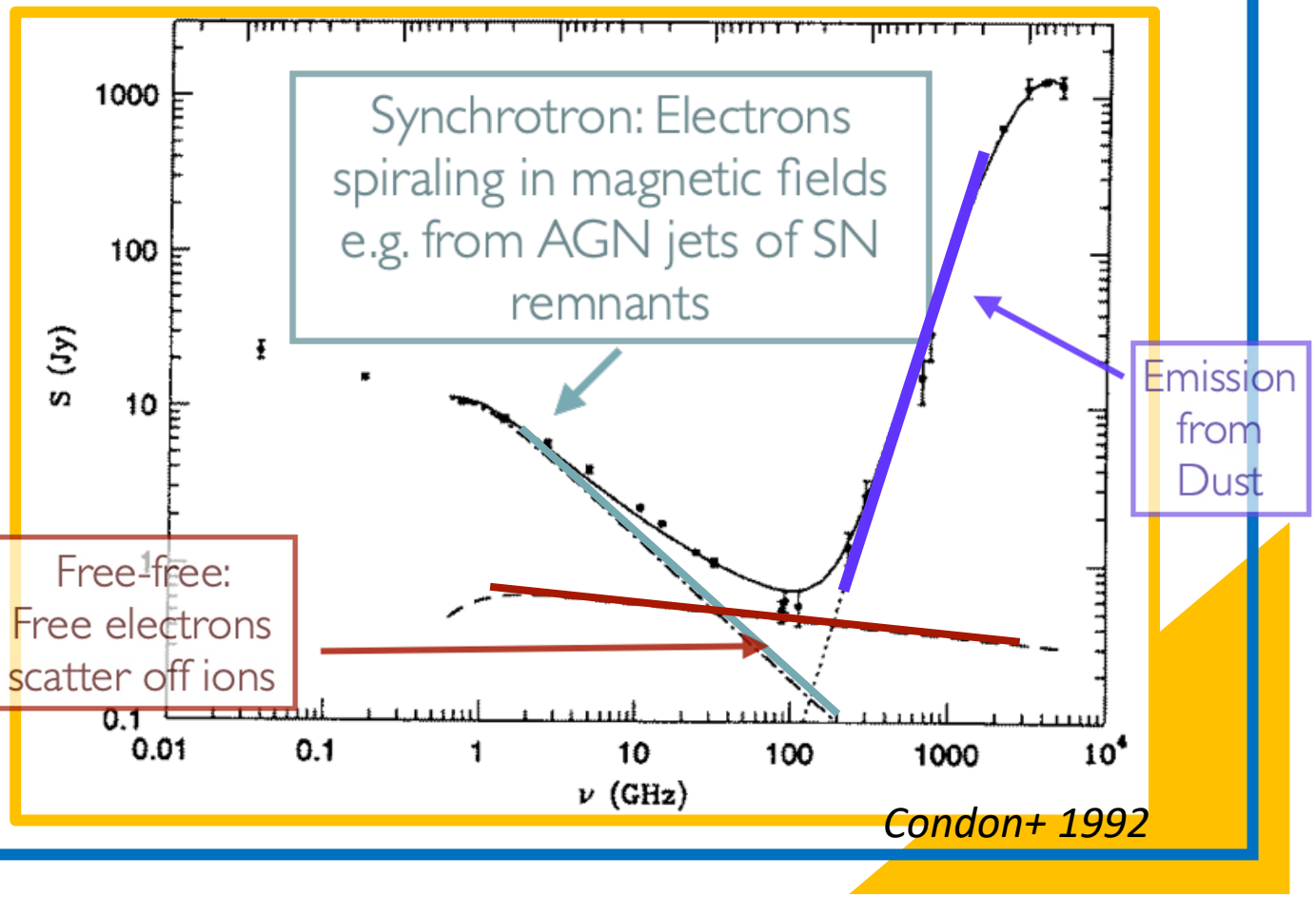


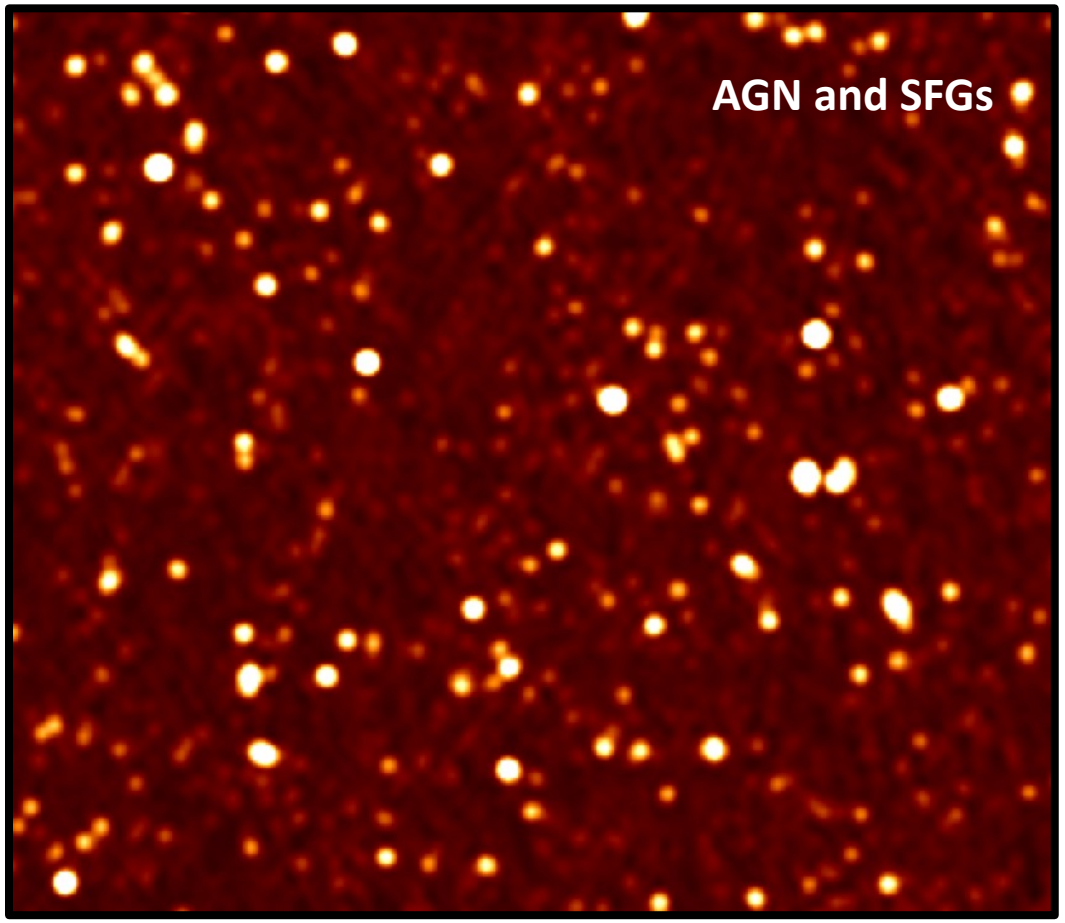
Image Credit: THINGS:
The HI Nearby Galaxy Survey (Walter+ 2008)



Condon+ 1992

Email: Catherine.Hale@ed.ac.uk

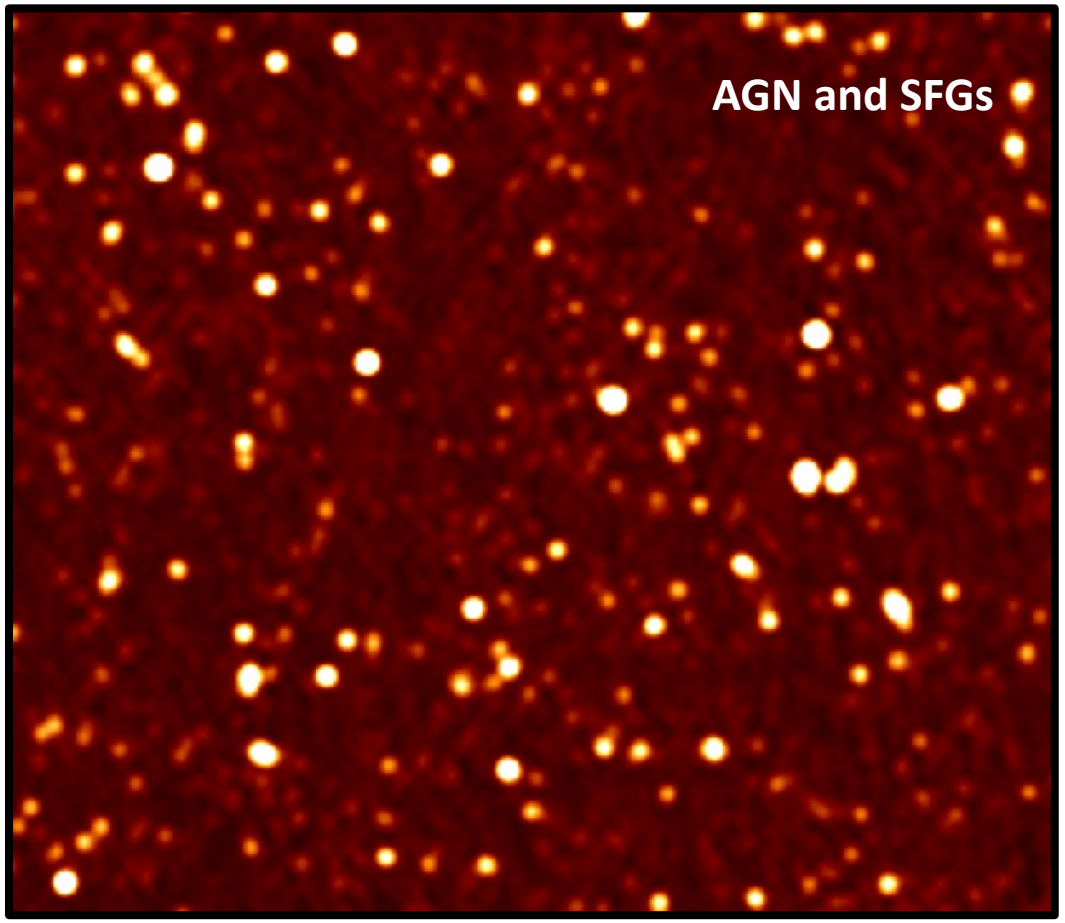
Extragalactic Sources of Radio Emission

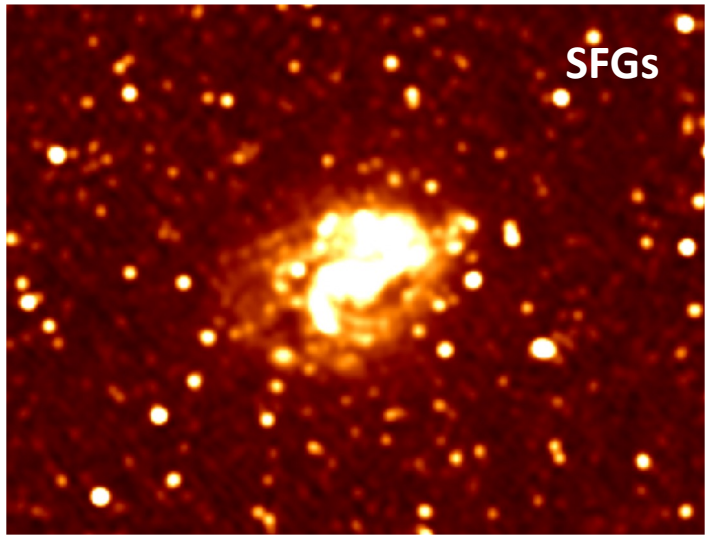


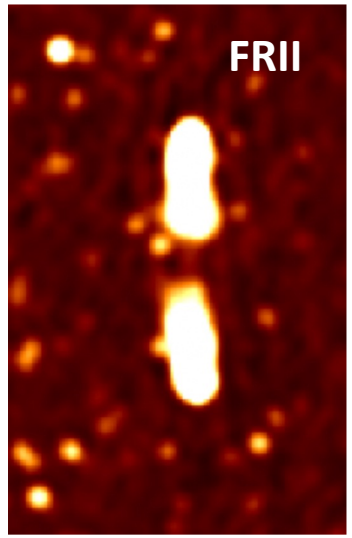
Ian Heywood, MIGHTEE Collaboration, Heywood+ 2021

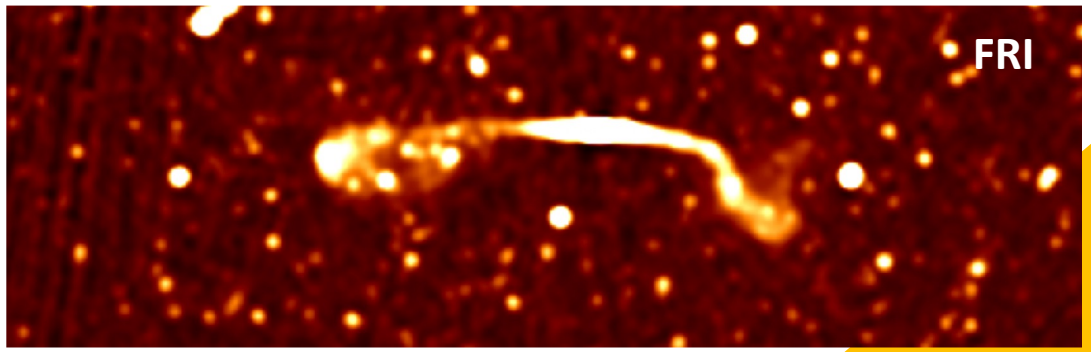
Email: Catherine.Hale@ed.ac.uk

Extragalactic Sources of Radio Emission







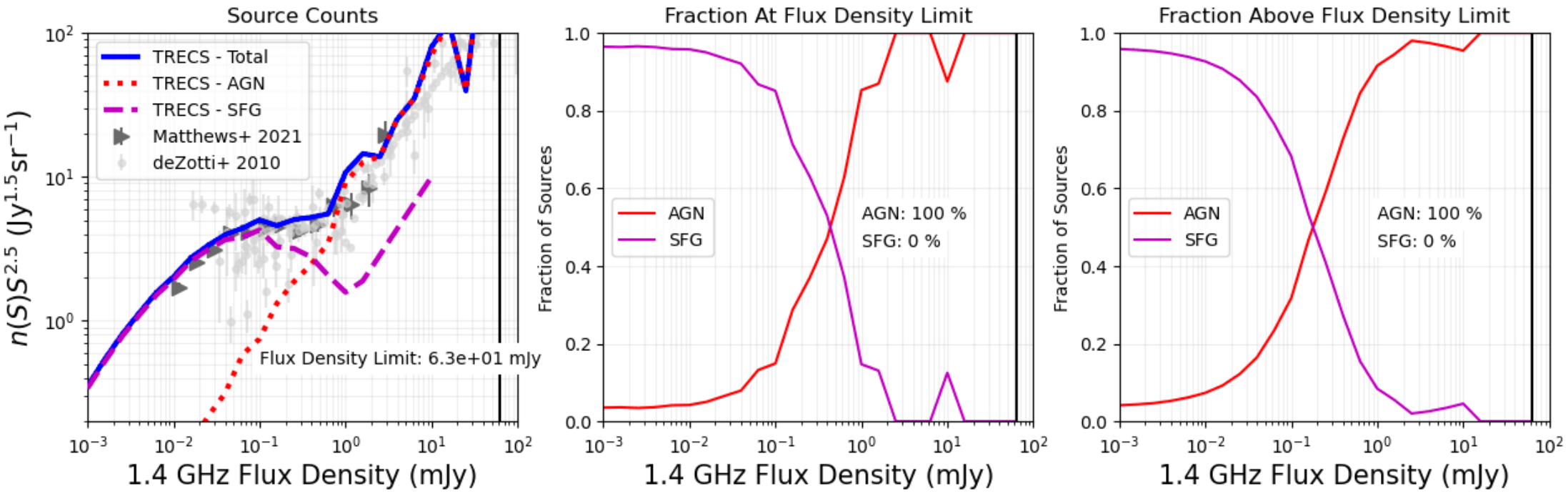


Ian Heywood, MIGHTEE Collaboration, Heywood+ 2021

Email: Catherine.Hale@ed.ac.uk

Radio Source Populations

Using T-RECS Simulations (Bonaldi+ 2019)



Email: Catherine.Hale@ed.ac.uk

Current Radio Facilities

MeerKAT

Credit: South African Radio Astronomy Observatory (SARAO)

VLA

Credit: NRAO/AUI/NSF

LOFAR

Credit: ASTRON

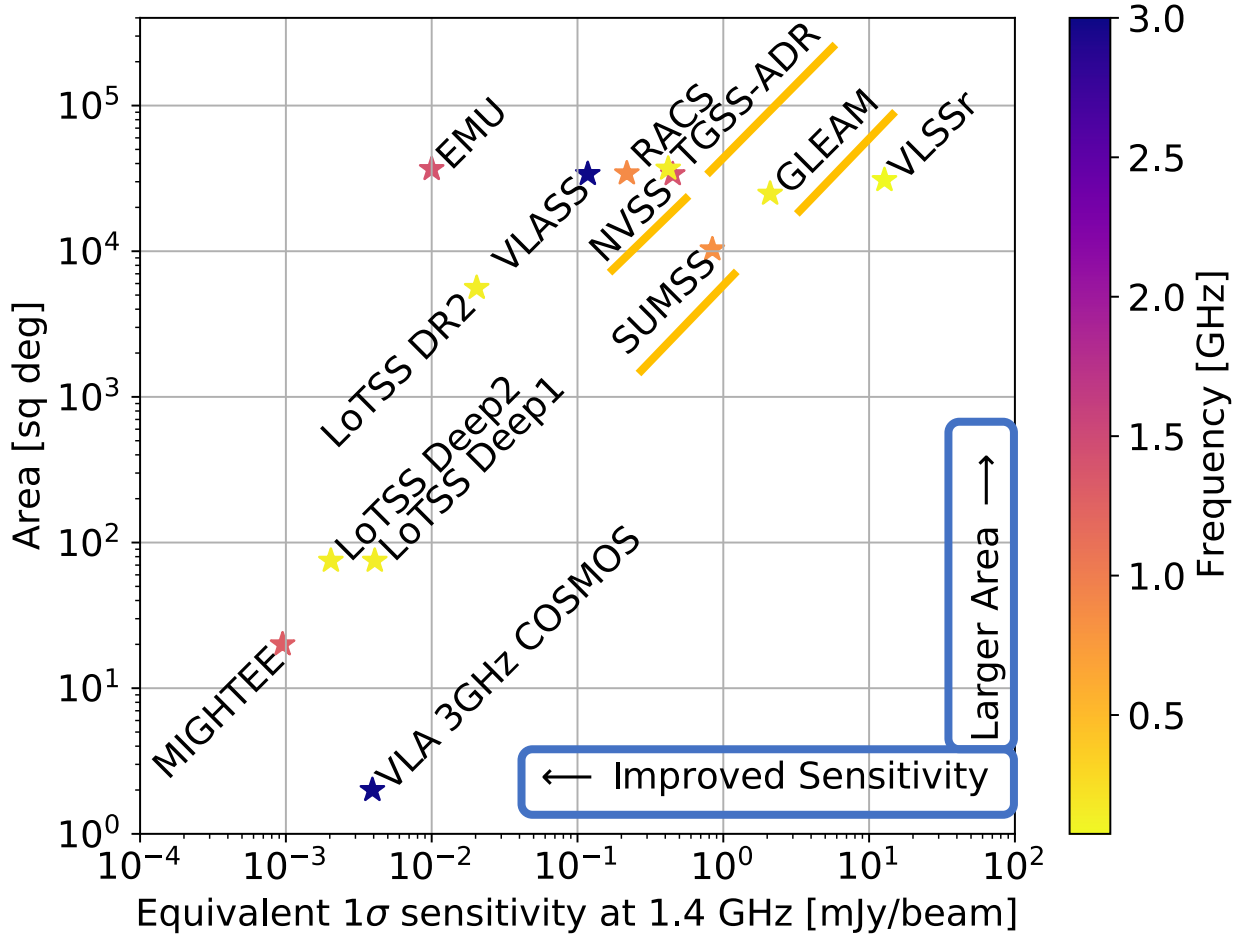
ASKAP

Credit: CSIRO

Email: Catherine.Hale@ed.ac.uk

Extragalactic Radio Surveys

Good for detecting rare sources
e.g. giant radio galaxies



Past Large Area Surveys:

GLEAM (Hurley-Walker+ 2017)

$\delta \leq +30°$ with VLA, 70-230 MHz, ~6-10 mJy/beam RMS

TGSS-ADR (Intema+2019)

$\delta \geq -53°$ with GMRT, 150 MHz, ~3.5 mJy/beam RMS

NVSS (Condon+ 1998)

$\delta \geq -40°$ with VLA, 1.4 GHz, ~2.5 mJy/beam RMS

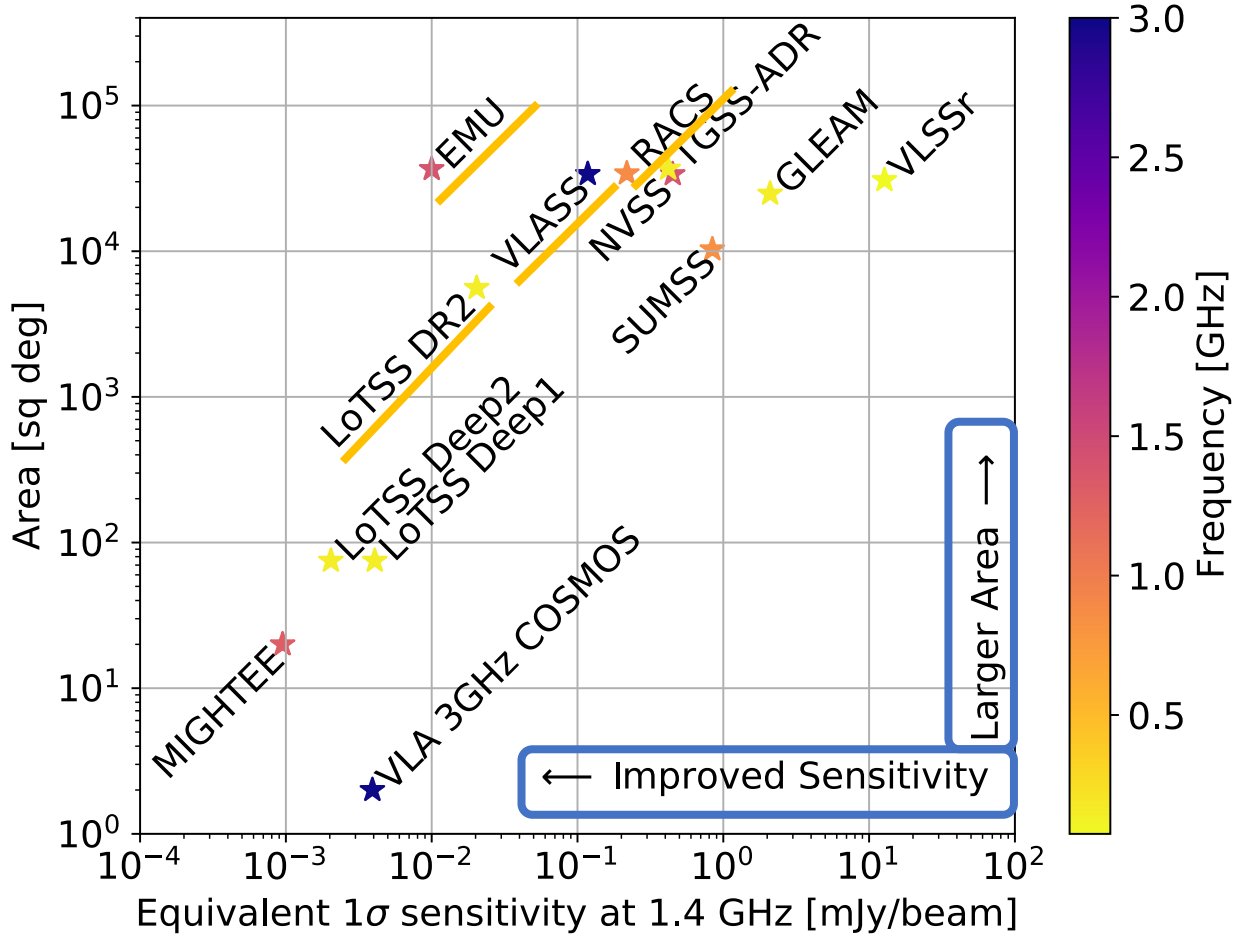
SUMSS (Mauch+ 2003)

$\delta \leq -30°$ with Molongolo, 843 MHz, ~2 mJy/beam RMS

Email: Catherine.Hale@ed.ac.uk

Extragalactic Radio Surveys

Good for detecting rare sources
e.g. giant radio galaxies



Present/Future Large Area Surveys:

LoTSS-DR2 (Shimwell+ 2022)

$\delta \geq 0°$ with LOFAR, 150 MHz, ~100 μJy/beam RMS
Current: 5,600 deg^2, Final ~25,000 deg^2

RACS (McConnell+ 2020, Hale+ 2021)

$\delta \leq +40°$ with ASKAP, 0.8-1.6 GHz, 0.25 mJy/beam RMS
Current: 888 MHz, Final 0.8-1.6 GHz

EMU (Norris+ 2021)

$\delta \leq +30°$ with ASKAP, ~1 GHz, ~30 μJy/beam RMS
Current: 270 deg^2, Final ~30,000 deg^2

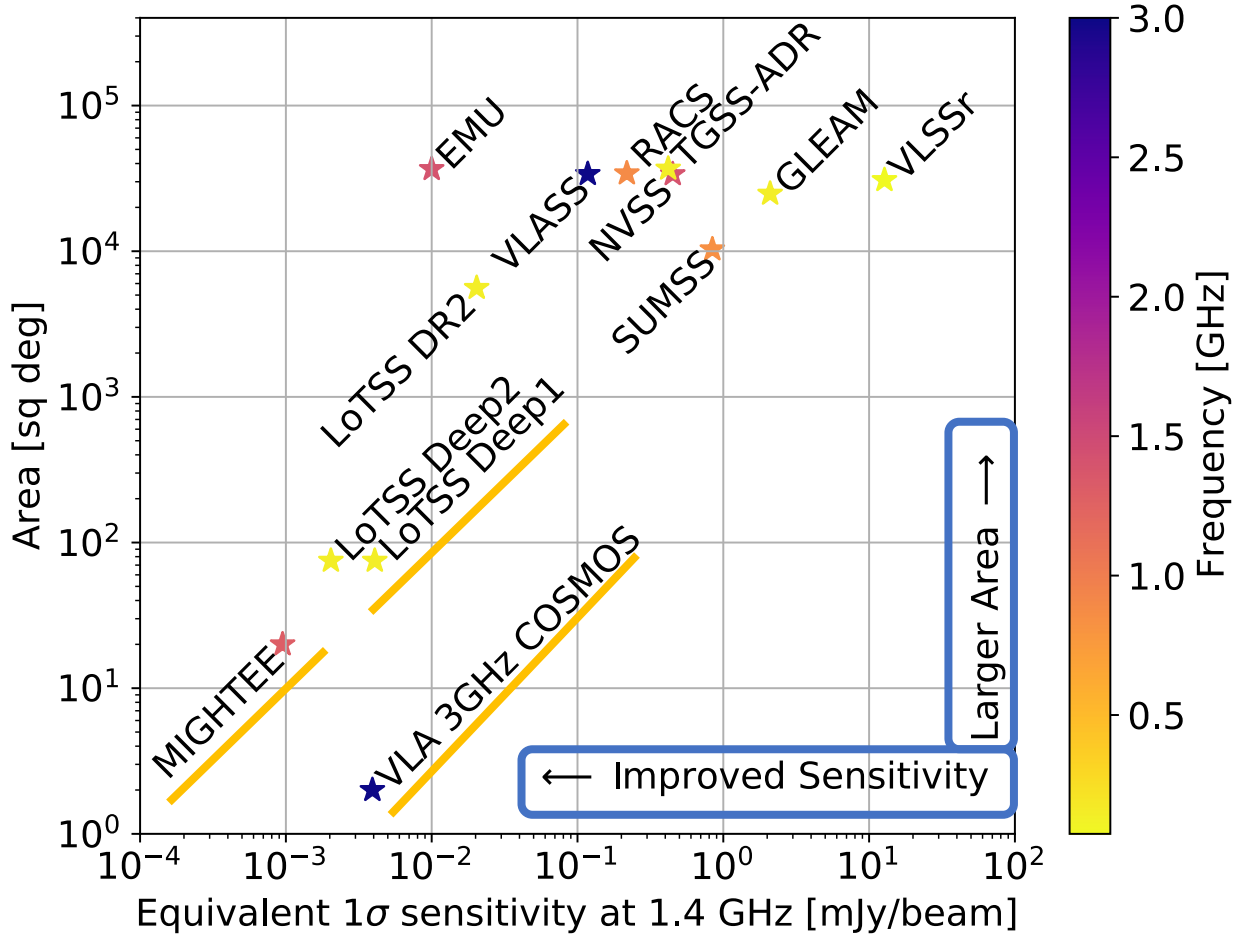
VLASS (Lacy+ 2020)

$\delta \geq -40°$ with VLA, 3 GHz, ~70 μ Jy/beam RMS
Current: 1 mJy/beam, Final ~70 μ Jy/beam RMS

Email: Catherine.Hale@ed.ac.uk

Extragalactic Radio Surveys

Good for detecting faint populations
e.g. SFGs, RQQ, high z sources



Present/Future Small Area Surveys:

LOFAR Deep Fields (Tasse+2021, Sabater+2021)

Elais-N1, Boötes, Lockman with LOFAR, 150 MHz, ~30 μJy/beam RMS

Deep-2 (Mauch+ 2020)

DEEP-2 with MeerKAT, 1.3 GHz, ~2 μJy/beam RMS

MIGHTEE (Jarvis+ 2017, Heywood+ 2021)

COSMOS, XMM-LSS, Elais-S1, E-CDFS with MeerKAT, 1.3 GHz, ~2 μJy/beam RMS

E-MERGE (Muxlow+ 2020)

GOODS-N with VLA and e-MERLIN, 1.5 GHz, 0.2-0.7" , ~1.5 μJy/beam RMS

VLA 3 GHz COSMOS (Smolčic+ 2017)

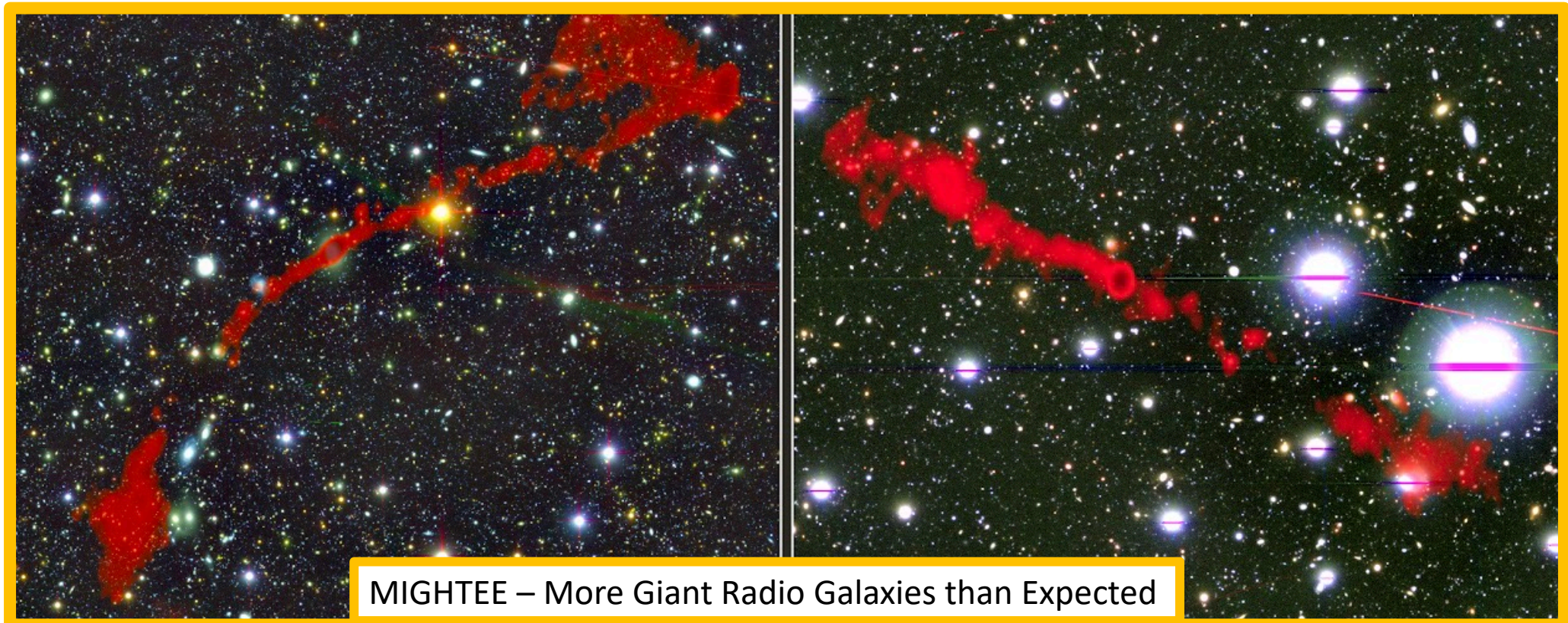
COSMOS with VLA, 3 GHz, 2.3 μJy/beam RMS

Email: Catherine.Hale@ed.ac.uk

Future Radio Facilities

Email: Catherine.Hale@ed.ac.uk

Interesting Sources

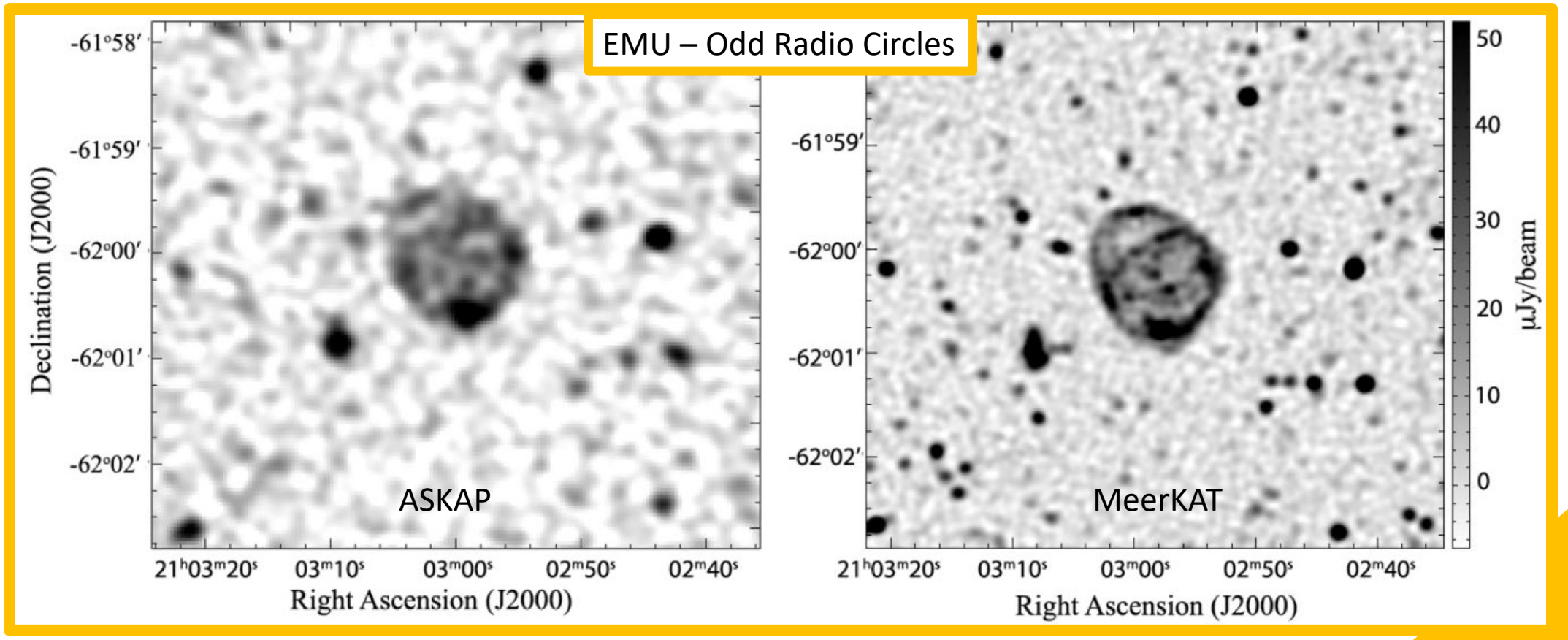


MIGHTEE – More Giant Radio Galaxies than Expected

Credit: Delhaize+ 2020

Email: Catherine.Hale@ed.ac.uk

Interesting Sources



Credit: Norris+ 2022

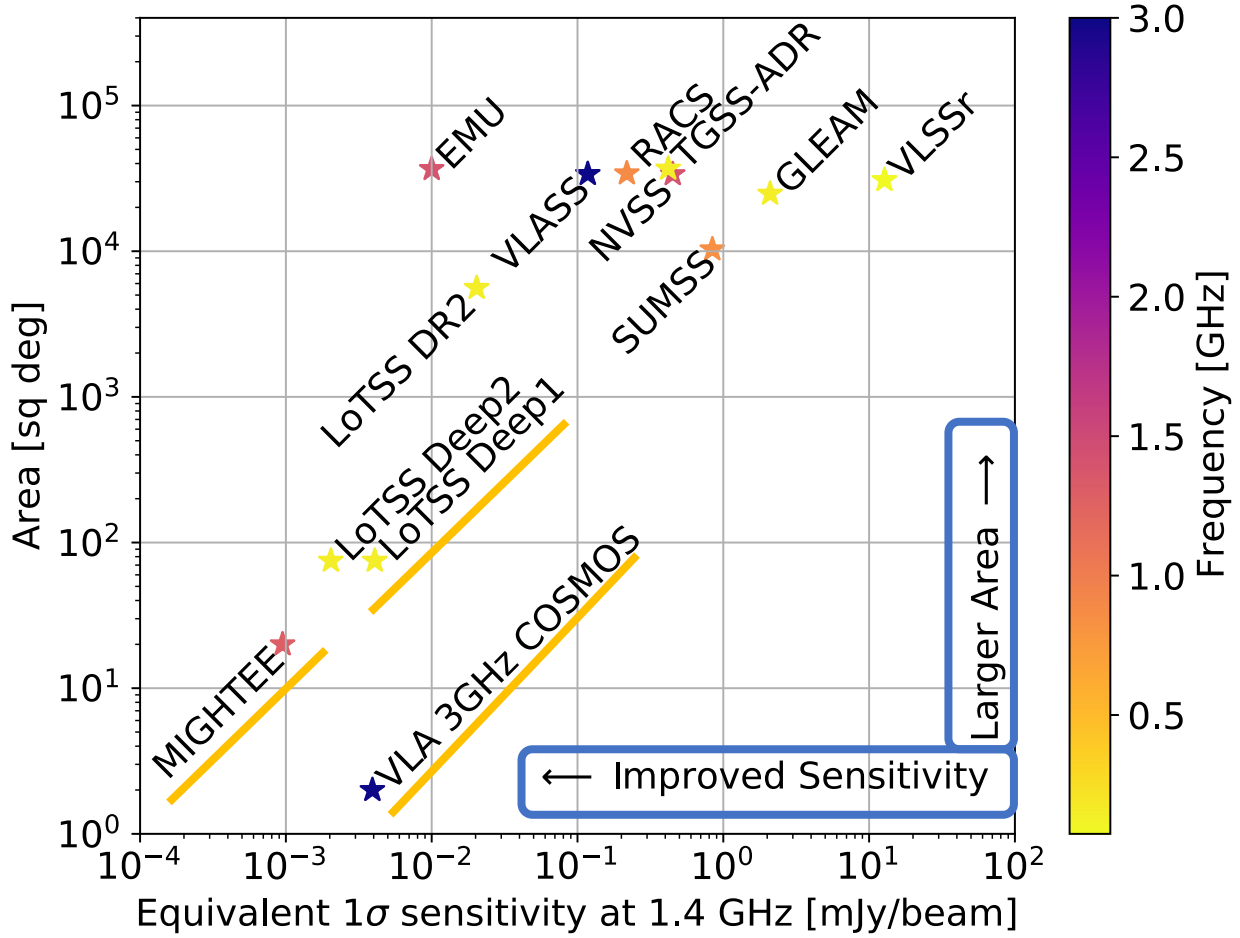
Email: Catherine.Hale@ed.ac.uk

Probing the Faint Extragalactic Source Populations

Email: Catherine.Hale@ed.ac.uk

Extragalactic Radio Surveys

Good for detecting faint populations
e.g. SFGs, RQQ, high z sources



Present/Future Small Area Surveys:

LOFAR Deep Fields (Tasse+2021, Sabater+2021)
Elais-N1, Boötes, Lockman with LOFAR, 150 MHz, ~30 μJy/beam RMS

E-MERGE (Muxlow+ 2020)
GOODS-N with VLA and e-MERLIN, 1.5 GHz, 0.2-0.7" , ~1.5 μJy/beam RMS

VLA 3 GHz COSMOS (Smolčic+ 2017)
COSMOS with VLA, 3 GHz, 2.3 μJy/beam RMS

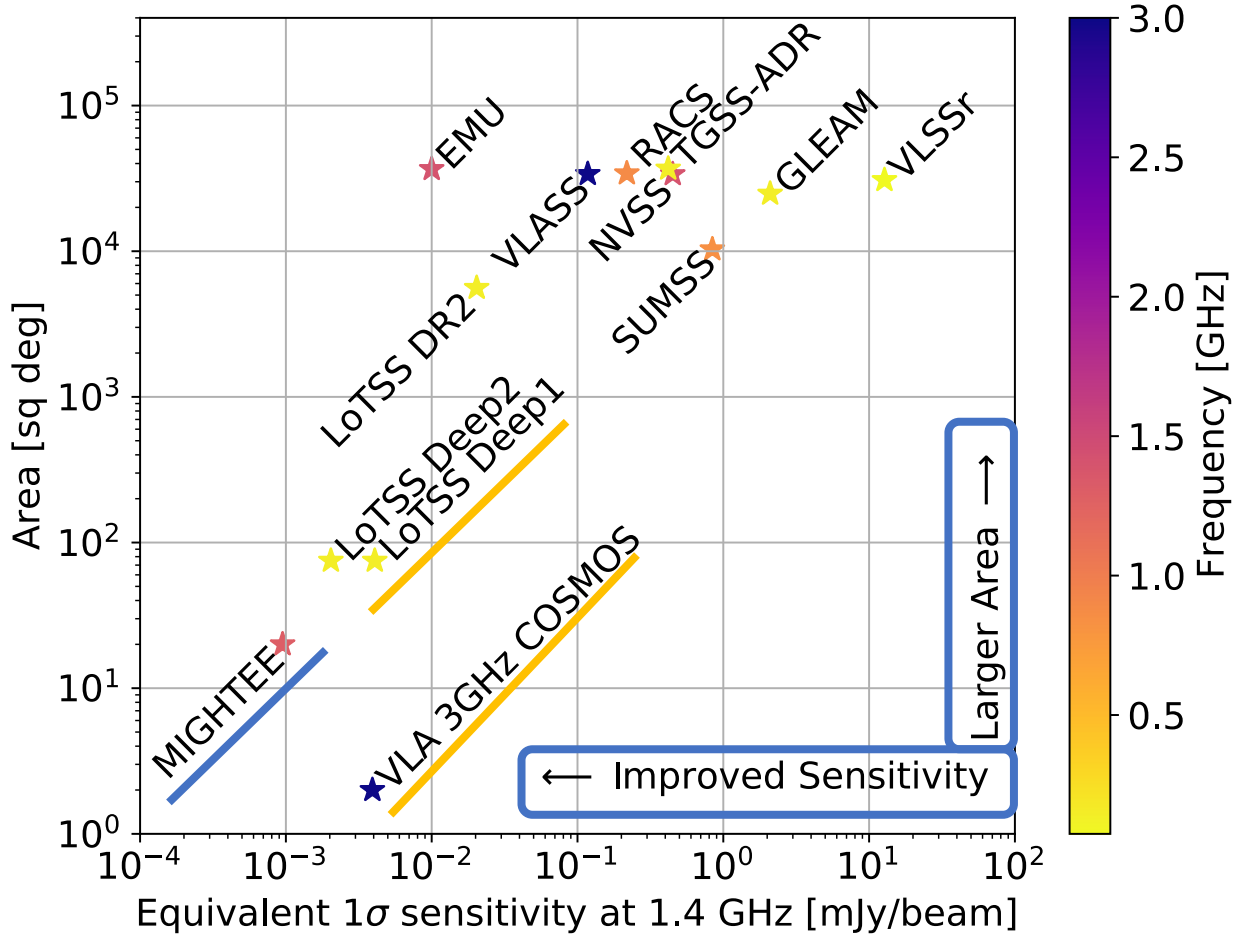
Deep-2 (Mauch+ 2020)
DEEP-2 with MeerKAT, 1.3 GHz, ~2 μJy/beam RMS

MIGHTEE (Jarvis+ 2017, Heywood+ 2021)
COSMOS, XMM-LSS, Elais-S1, E-CDFS with MeerKAT, 1.3 GHz, ~2 μJy/beam RMS

Email: Catherine.Hale@ed.ac.uk

Extragalactic Radio Surveys

Good for detecting faint populations
e.g. SFGs, RQQ, high z sources



Present/Future Small Area Surveys:

LOFAR Deep Fields (Tasse+2021, Sabater+2021)
Elais-N1, Boötes, Lockman with LOFAR, 150 MHz, ~30 μJy/beam RMS

E-MERGE (Muxlow+ 2020)
GOODS-N with VLA and e-MERLIN, 1.5 GHz, 0.2-0.7" , ~1.5 μJy/beam RMS

VLA 3 GHz COSMOS (Smolčic+ 2017)
COSMOS with VLA, 3 GHz, 2.3 μJy/beam RMS

Deep-2 (Mauch+ 2020)
DEEP-2 with MeerKAT, 1.3 GHz, ~2 μJy/beam RMS

MIGHTEE (Jarvis+ 2017, Heywood+ 2021)
COSMOS, XMM-LSS, Elais-S1, E-CDFS with MeerKAT, 1.3 GHz, ~2 μJy/beam RMS

Email: Catherine.Hale@ed.ac.uk

Current Radio Facilities

MeerKAT

Credit: South African Radio Astronomy Observatory (SARAO)

VLA

Credit: NRAO/AUI/NSF

LOFAR

Credit: ASTRON

ASKAP

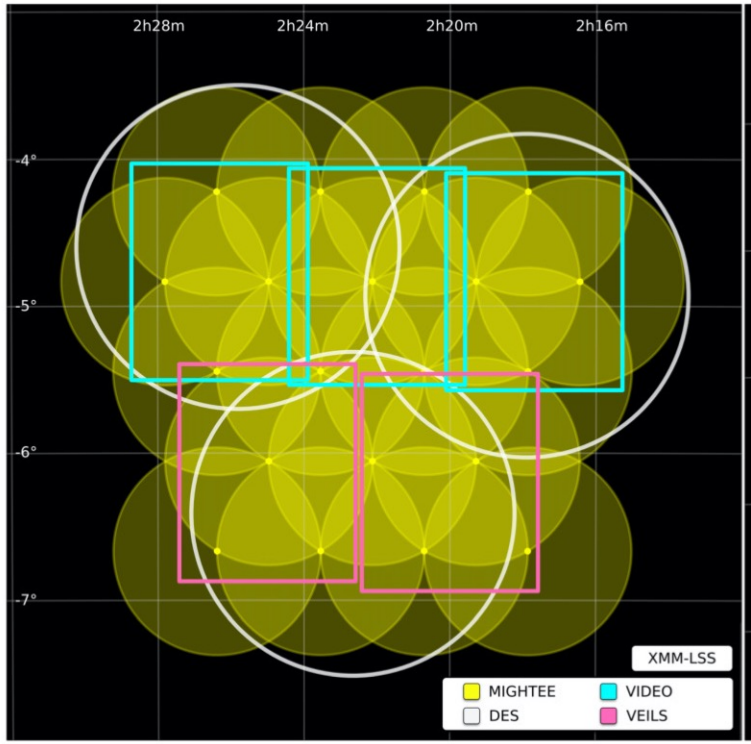
Credit: CSIRO

Email: Catherine.Hale@ed.ac.uk

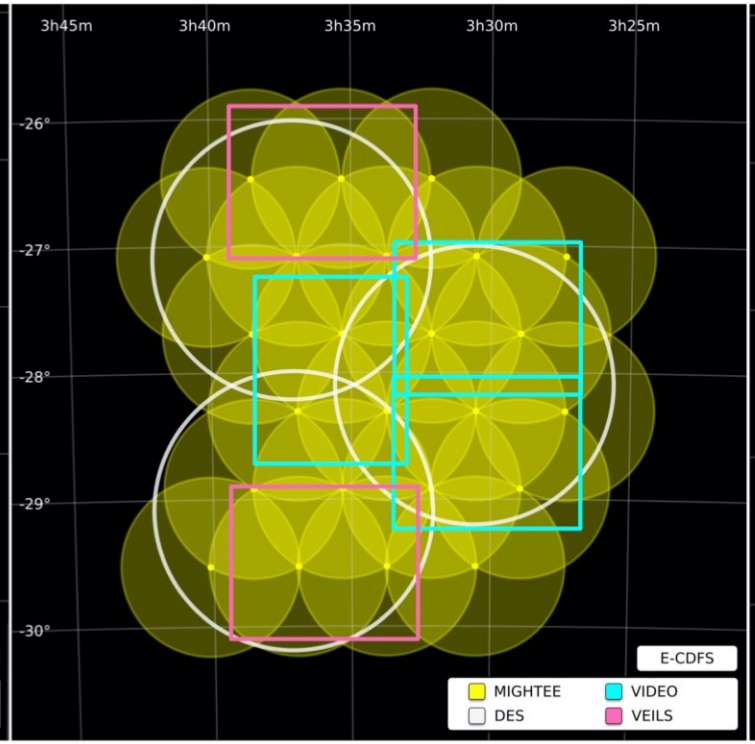
Extragalactic Fields

+ COSMOS

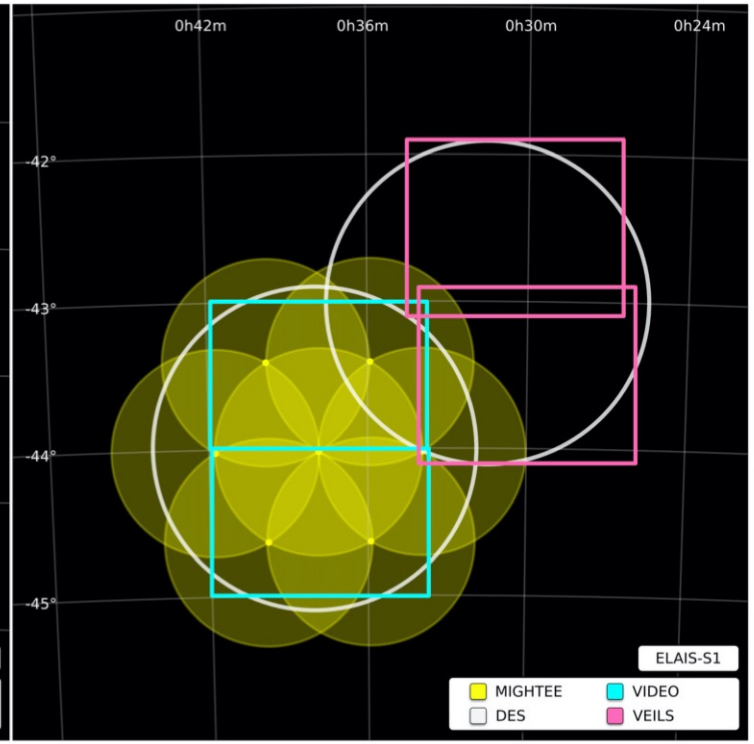
XMM-LSS



E-CDFS



ELAIS-S1



+ Ultra Deep Pointing

Jarvis+ 2016

Email: Catherine.Hale@ed.ac.uk

Improvements with these surveys

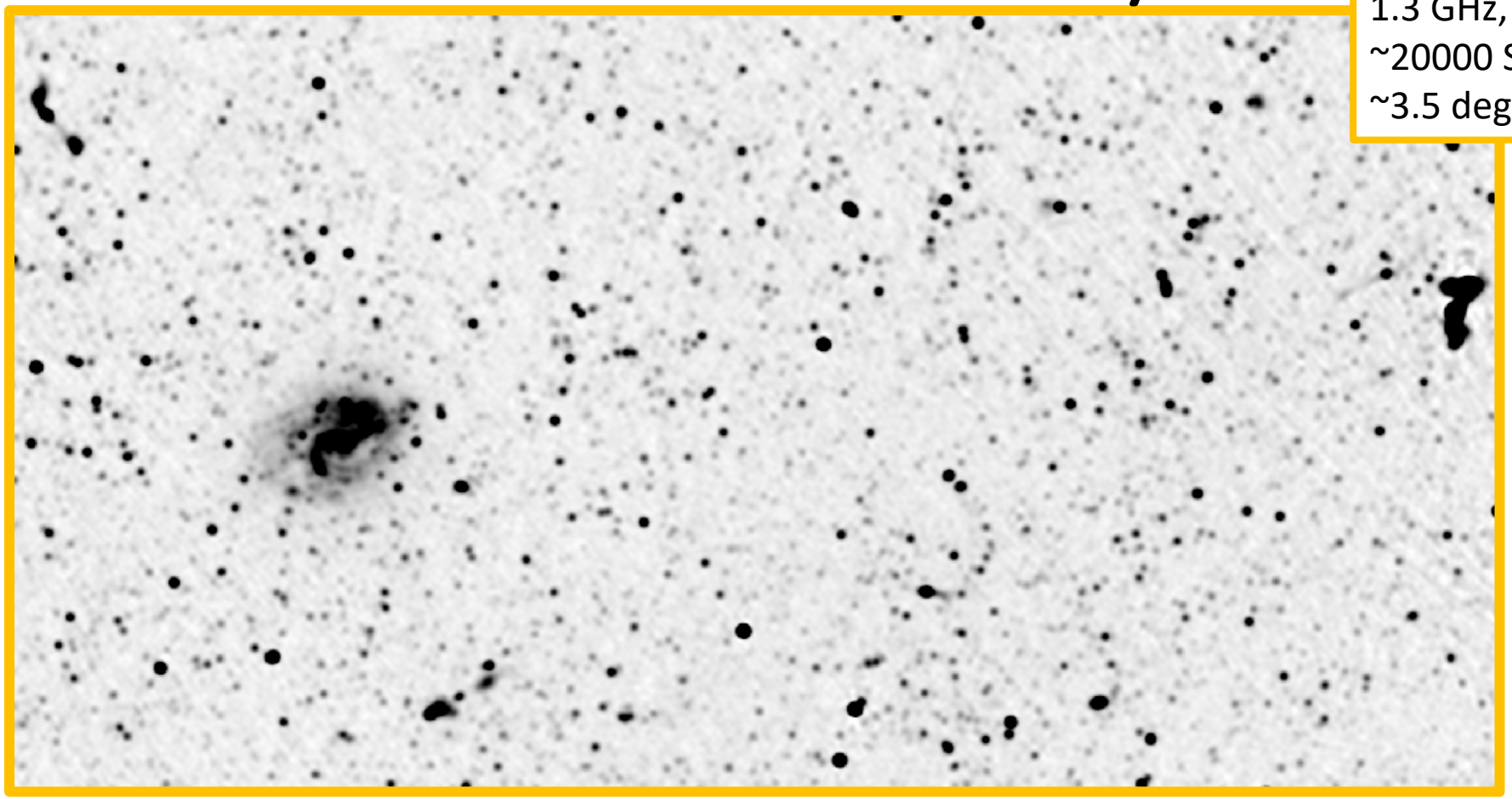
~20 uJy/beam RMS
1.5 GHz
~4.5 arcsec resolution
~6000 Sources
~5 deg^2

Heywood, Hale et al. 2020

Email: Catherine.Hale@ed.ac.uk

Improvements with these surveys

~2 uJy/beam (thermal)
~4 uJy/beam (+ conf.)
1.3 GHz, ~9 arcsec
~20000 Sources
~3.5 deg^2

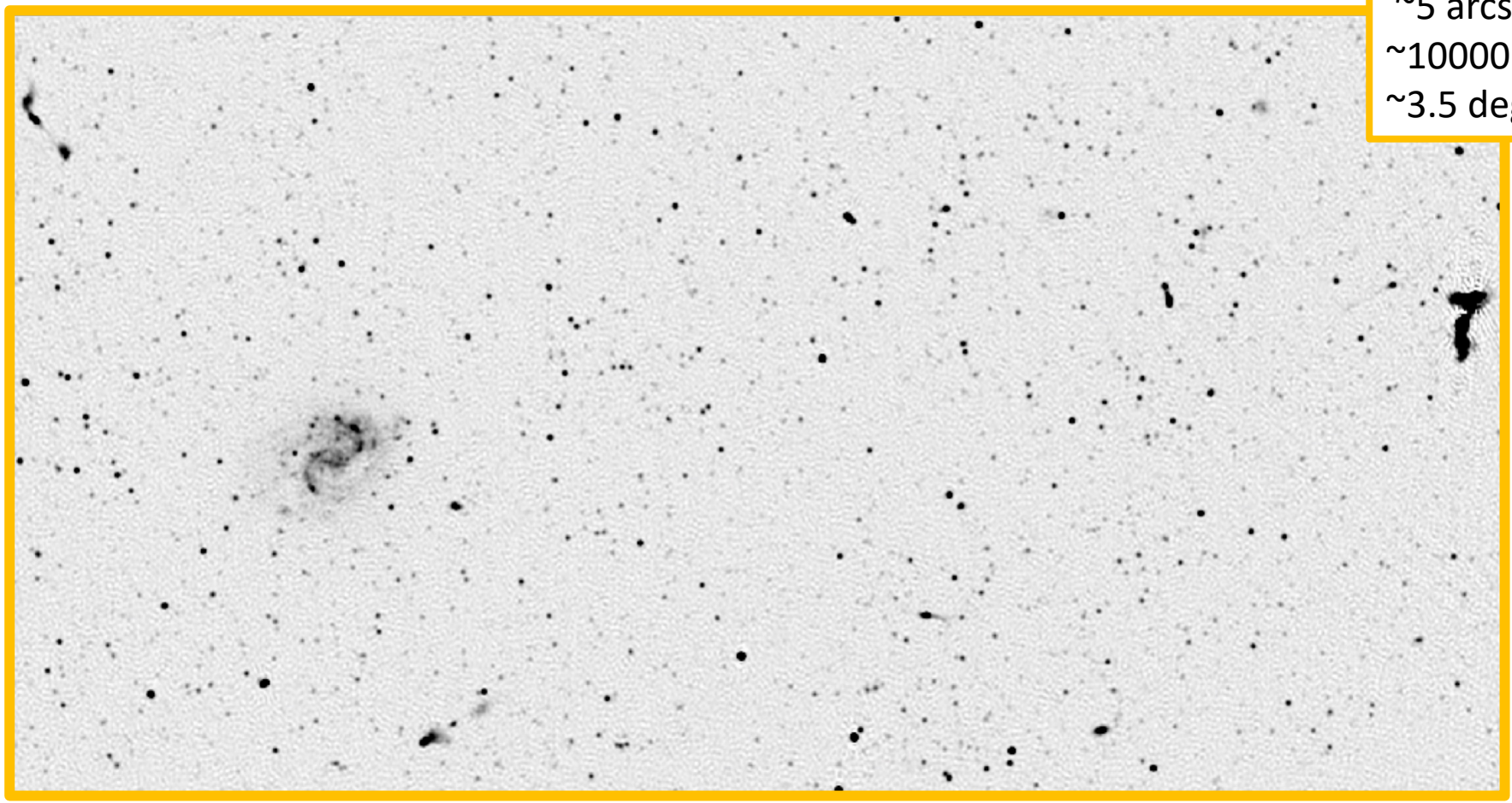


Ian Heywood, MIGHTEE Collaboration, Heywood+ 2021

Email: Catherine.Hale@ed.ac.uk

Why now for Radio Astronomy?

~6 uJy/beam
1.3 GHz
~5 arcsec
~10000 Sources
~3.5 deg^2



Ian Heywood, MIGHTEE Collaboration, Heywood+ 2021

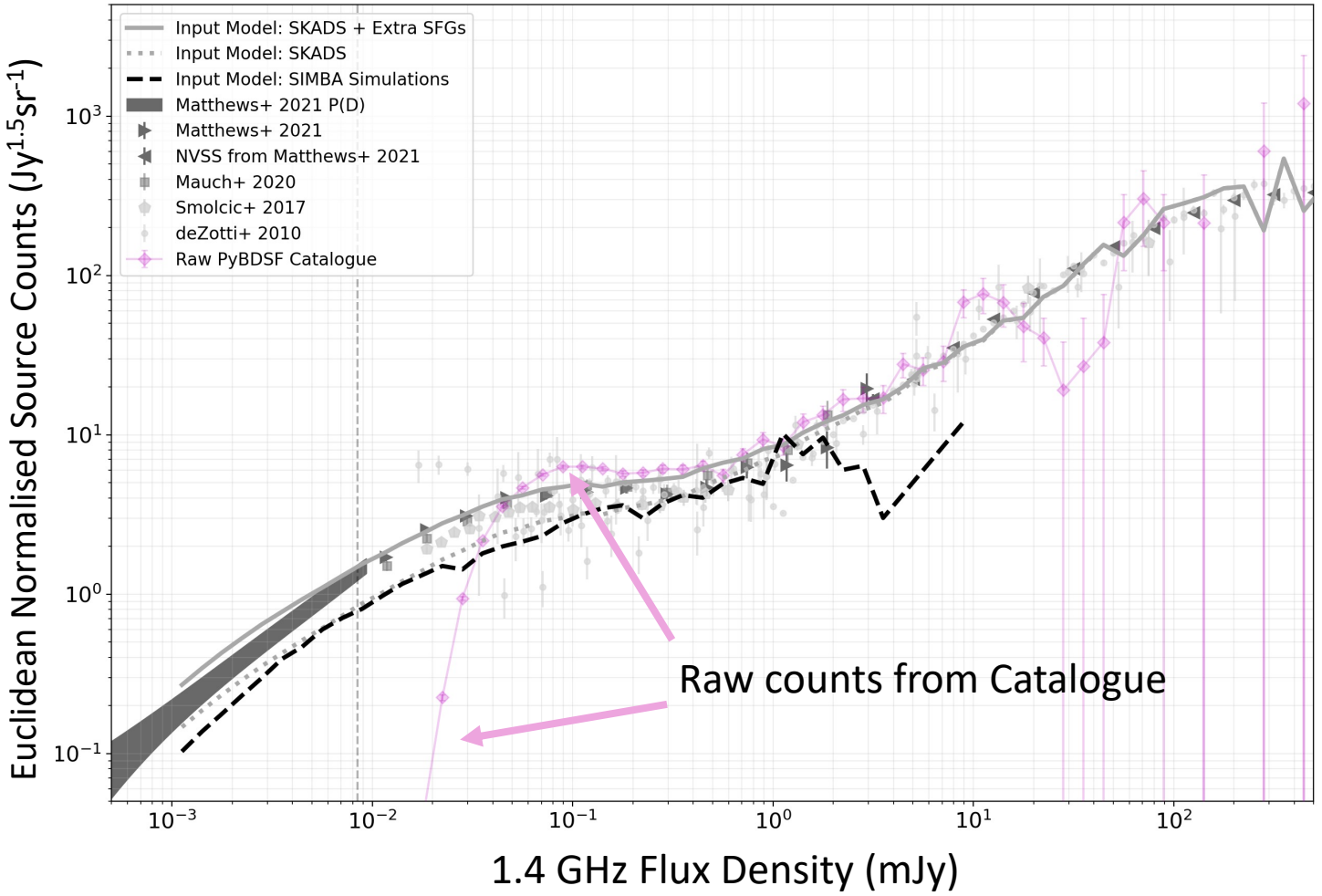
Email: Catherine.Hale@ed.ac.uk

Extragalactic Populations: Source Counts

Email: Catherine.Hale@ed.ac.uk

Hale+ submitted

Extragalactic Source Counts: Raw

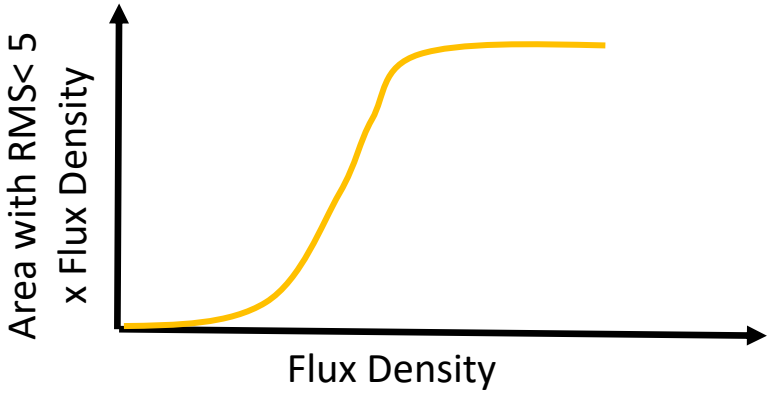


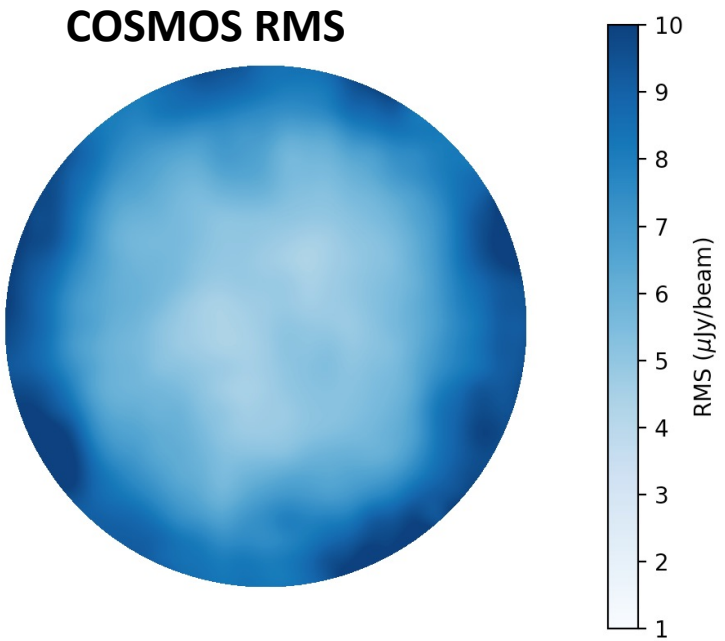
Account for:

- Incompleteness
  - Source finder
  - Sensitivity
- Eddington Bias
- Confusion
- Resolution Bias

Email: Catherine.Hale@ed.ac.uk

Extragalactic Source Counts: Corrections



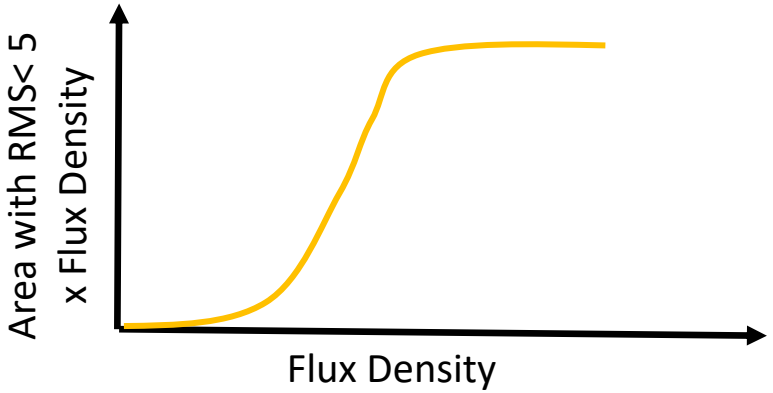


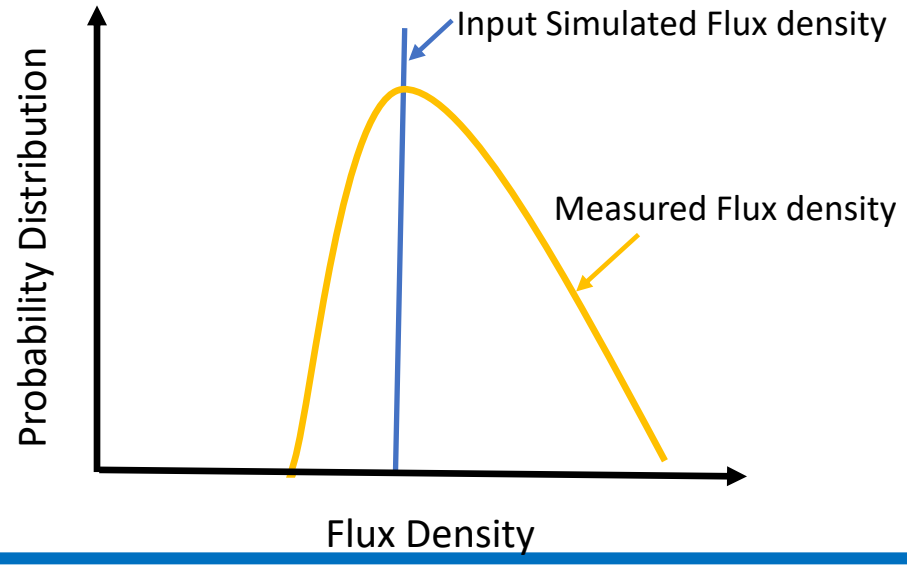
Account for:

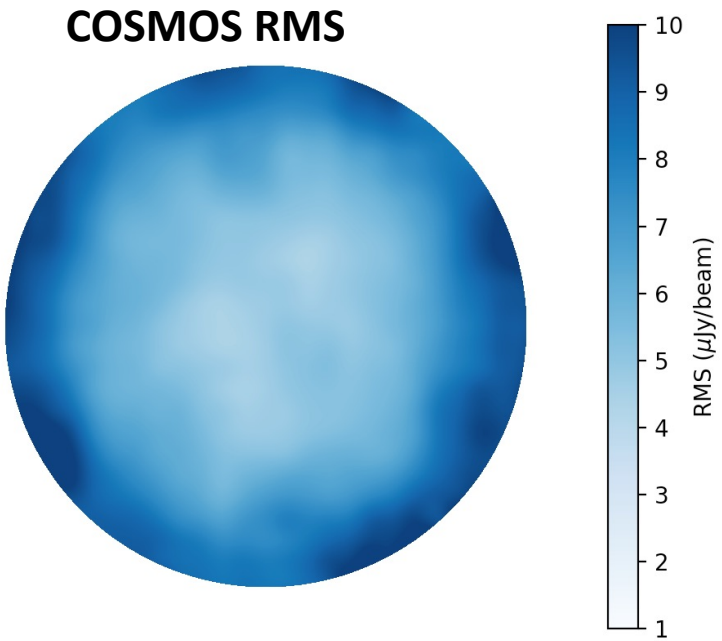
- Incompleteness
  - Source finder
  - Sensitivity
- Eddington Bias
- Confusion
- Resolution Bias

Email: Catherine.Hale@ed.ac.uk

Extragalactic Source Counts: Corrections





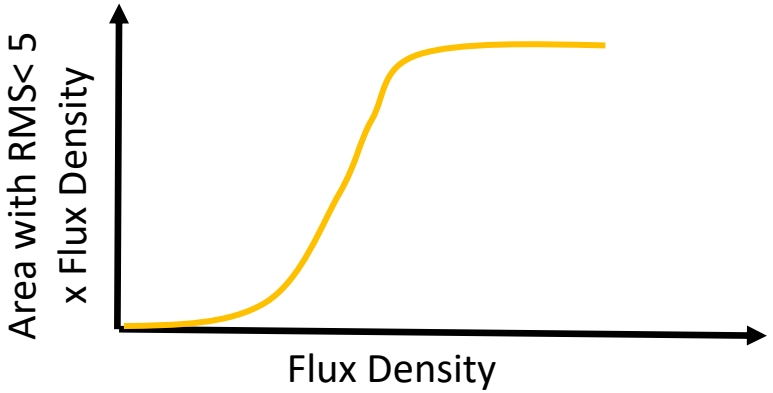


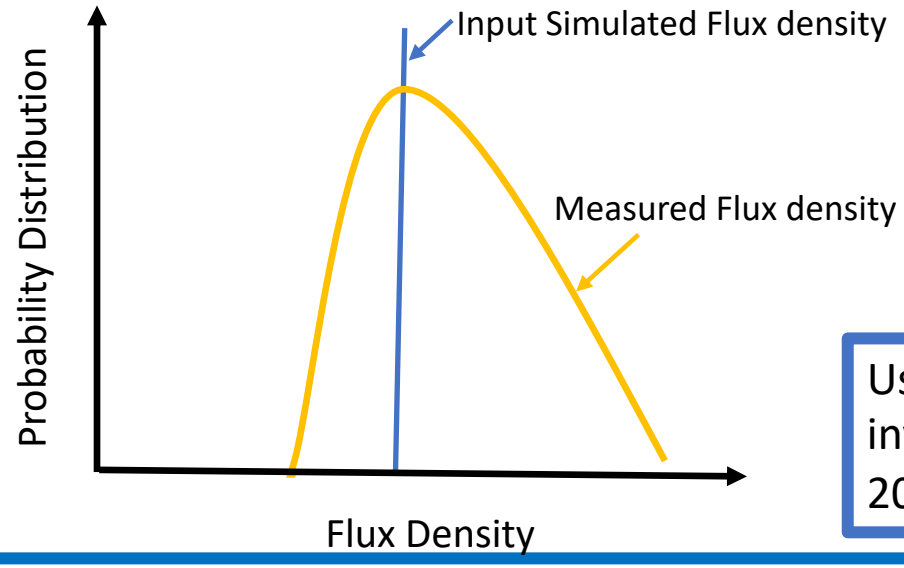
Account for:

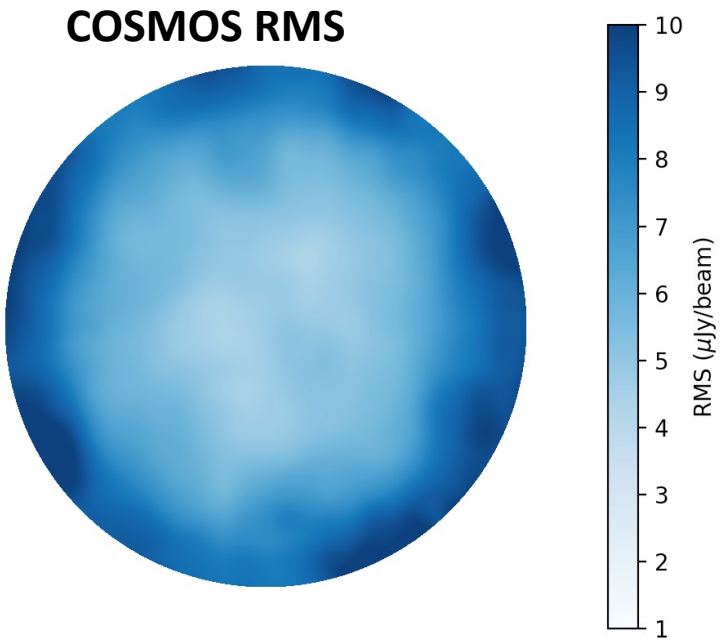
- Incompleteness
  - Source finder
  - Sensitivity
- Eddington Bias
- Confusion
- Resolution Bias

Email: Catherine.Hale@ed.ac.uk

Extragalactic Source Counts: Corrections







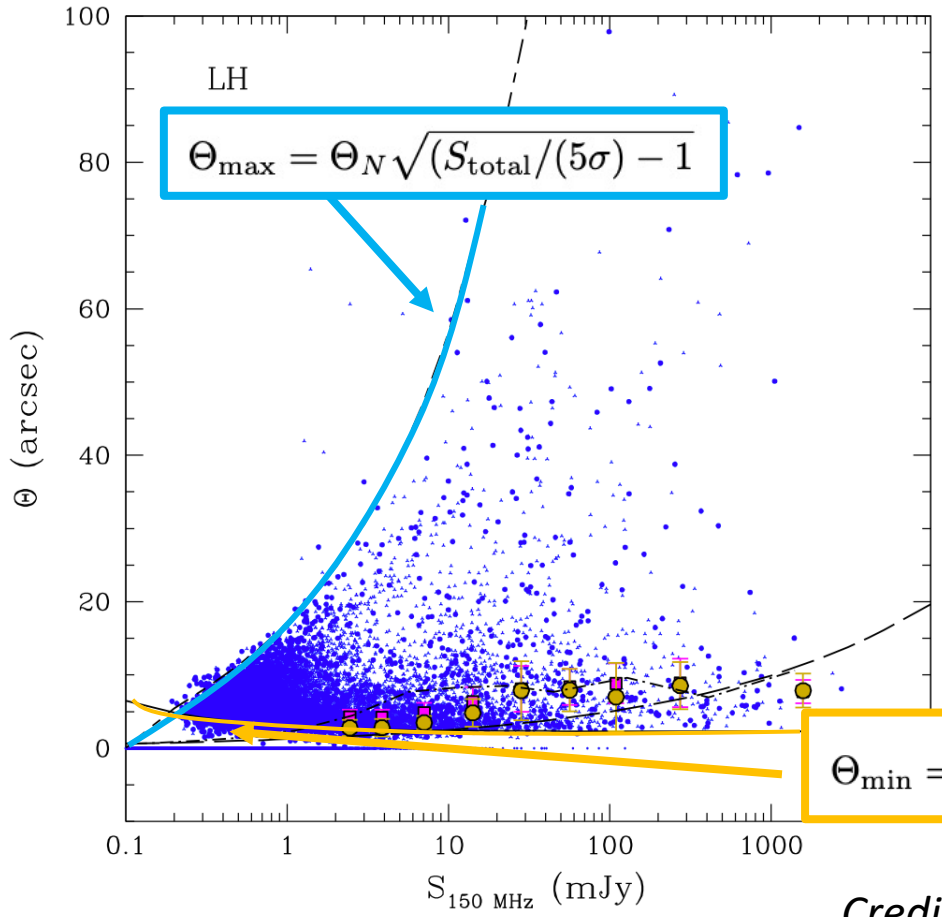
Account for:

- Incompleteness
  - Source finder
  - Sensitivity
- Eddington Bias
- Confusion
- Resolution Bias

Use simulations with realistic clustering invoked e.g. SIMBA (Dave+2019, Lovell+ 2021, Thomas+ 2021)

Email: Catherine.Hale@ed.ac.uk

Extragalactic Source Counts: Corrections



Windhorst Source size model (Windhorst 1990)

Corrections as Prandoni+ 2001

$$c = 1/[1 - h(> \Theta_{\rm lim})]$$

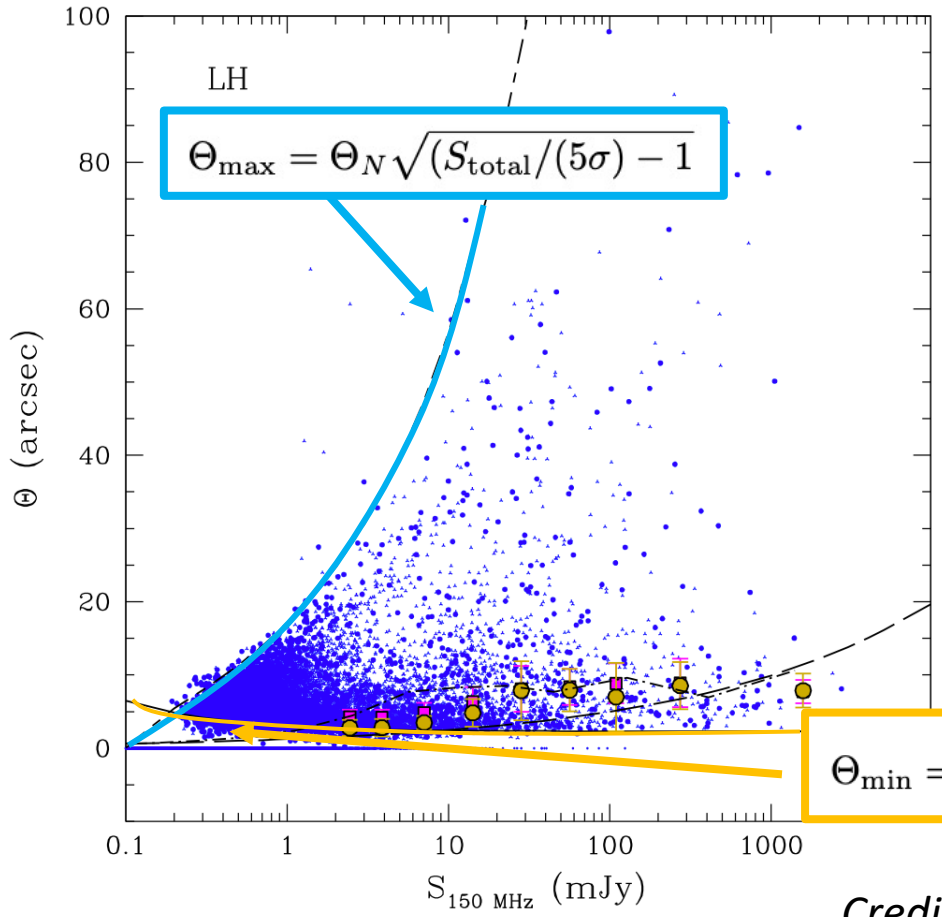
Account for:

- Incompleteness
  - Source finder
  - Sensitivity
- Eddington Bias
- Confusion
- Resolution Bias

Credit: Mandal+ 2021

Email: Catherine.Hale@ed.ac.uk

Extragalactic Source Counts: Corrections



Credit: Mandal+ 2021

Windhorst Source size model (Windhorst 1990)

Corrections as Prandoni+ 2001

$$c = 1/[1 - h(> \Theta_{\rm lim})]$$

Account for:

- Incompleteness
  - Source finder
  - Sensitivity
- Eddington Bias
- Confusion
- Resolution Bias

Or assume a source model and inject into image

Email: Catherine.Hale@ed.ac.uk

Extragalactic Source Counts: Corrections

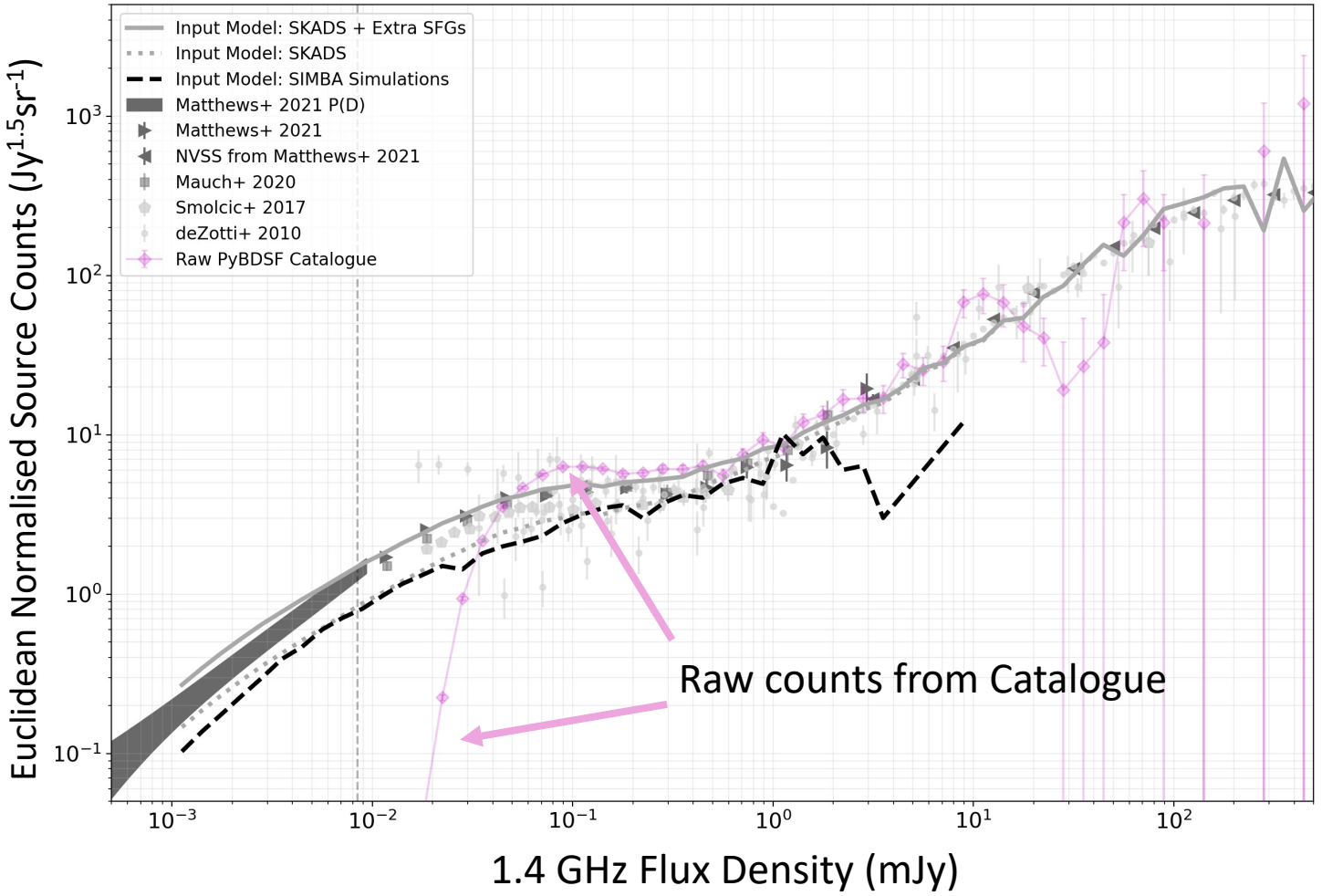
Create a range of simulations to account for these factors:

- Flux density distribution from simulations (Wilman+ 2008, Thomas+ 2021)
- Source size information (Wilman+ 2008)
- Clustering from hydrodynamical simualtions (Dave+ 2019, Thomas+ 2019)

Email: Catherine.Hale@ed.ac.uk

Hale+ submitted

Extragalactic Source Counts: Raw



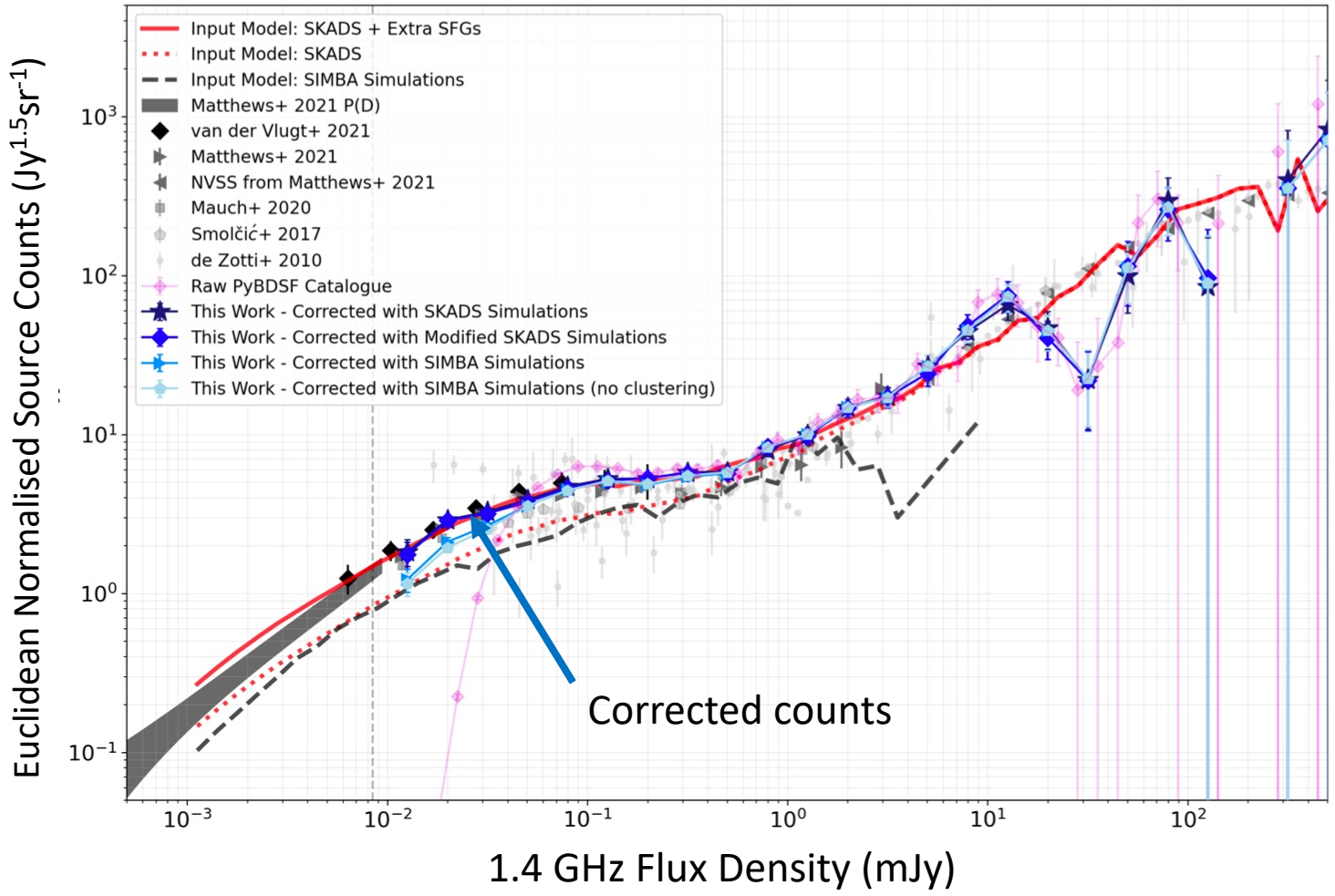
Account for:

- Incompleteness
  - Source finder
  - Sensitivity
- Eddington Bias
- Resolution Bias
- Confusion

Email: Catherine.Hale@ed.ac.uk

Hale+ submitted

Extragalactic Source Counts: Corrected



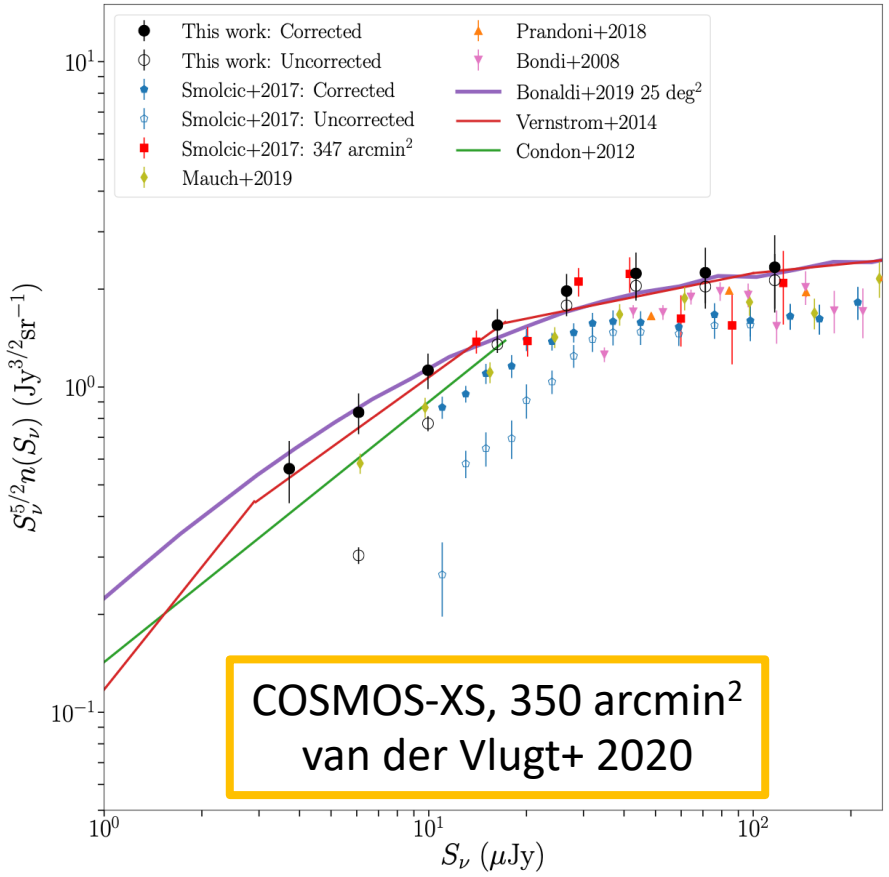
Account for:

- Incompleteness
  - Source finder
  - Sensitivity
- Eddington Bias
- Resolution Bias
- Confusion

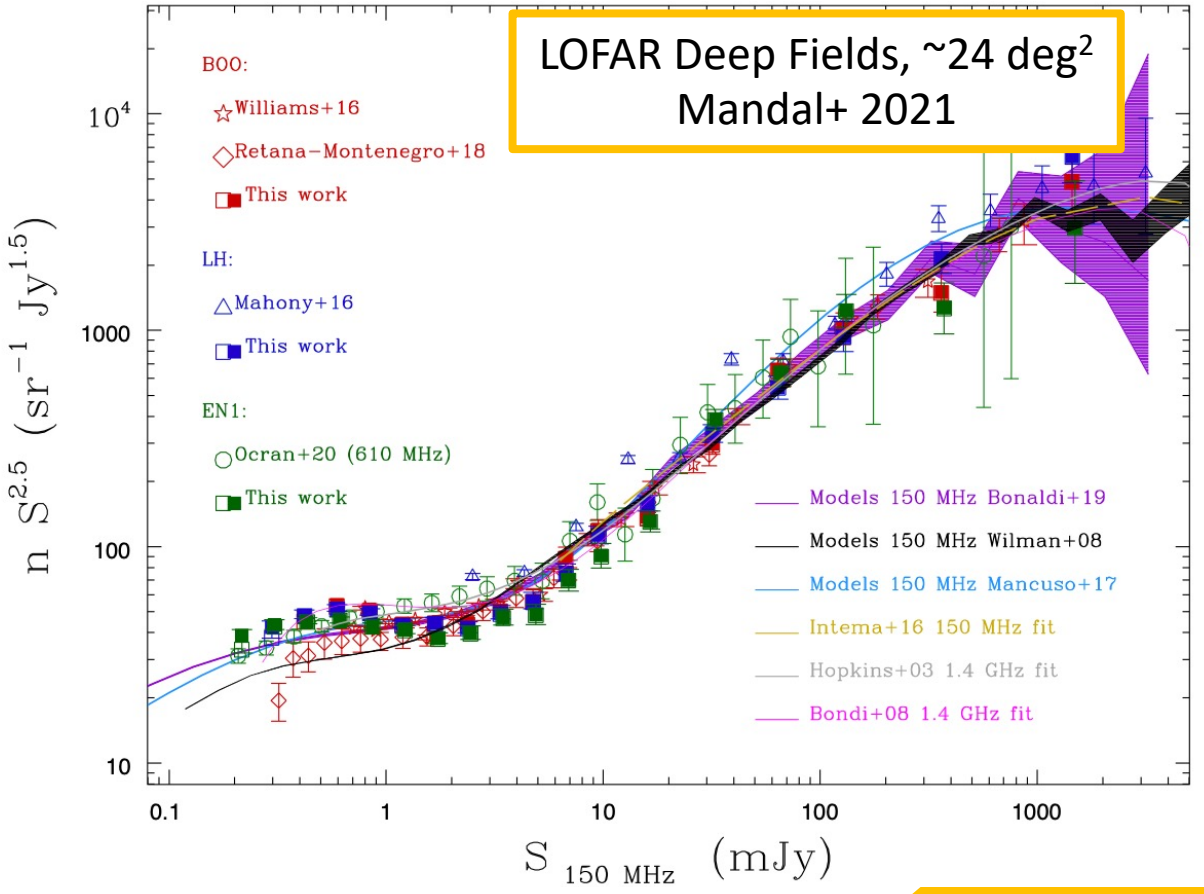
Email: Catherine.Hale@ed.ac.uk

Deep Extragalactic Source Counts

Also see:
- Smolcic+ 2017
- Mauch+ 2020
- Matthews+ 2020



COSMOS-XS, 350 arcmin^2
van der Vlugt+ 2020



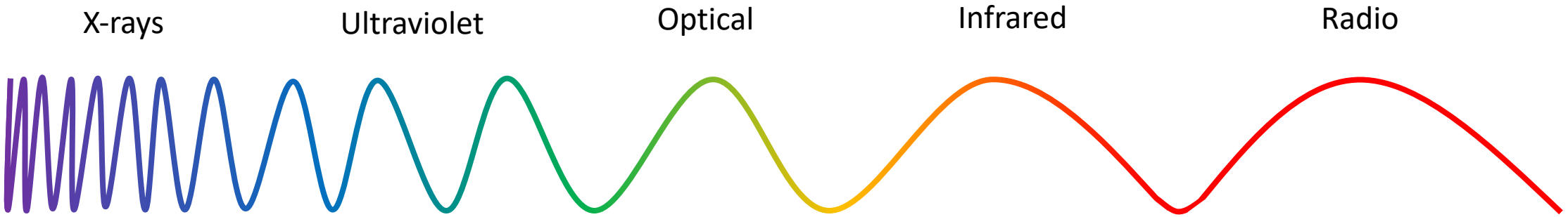
LOFAR Deep Fields, ~24 deg^2
Mandal+ 2021

Email: Catherine.Hale@ed.ac.uk

Extragalactic Source Populations

Email: Catherine.Hale@ed.ac.uk

MIGHTEE - Multi-Wavelength Data



XMM-Newton
Chandra

GALEX

CFHT
HSC
DES

VISTA
Spitzer
Herschel

VLA ~1-5 GHz
GMRT 150-610 MHz
LOFAR 150 MHz
ASKAP ~1 GHz

Email: Catherine.Hale@ed.ac.uk

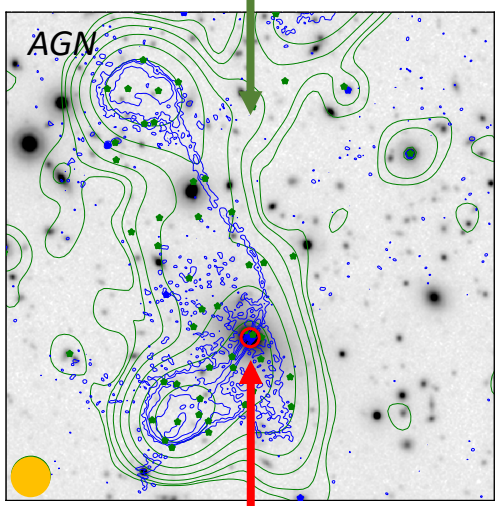
Prescott+ in prep

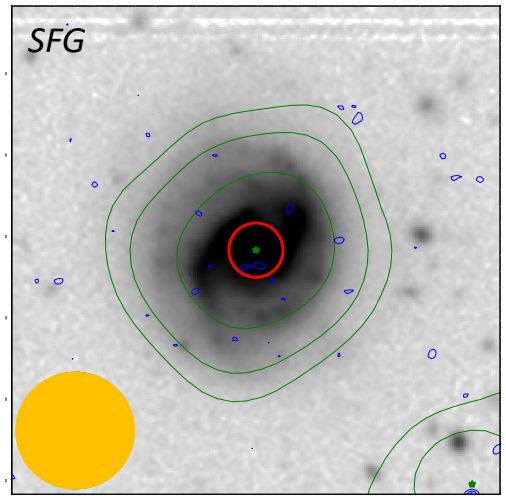
Host Identification and Classification

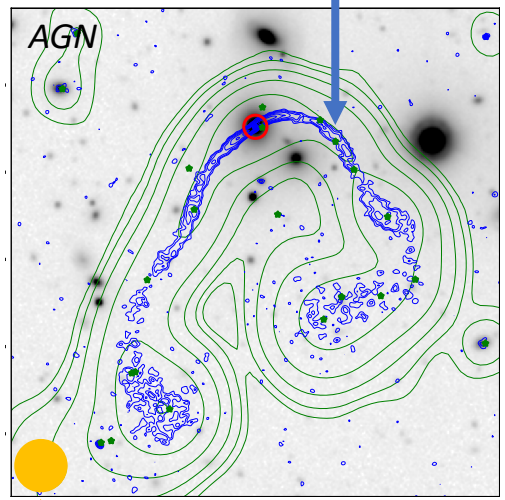
Initially over
1 deg^2 of COSMOS

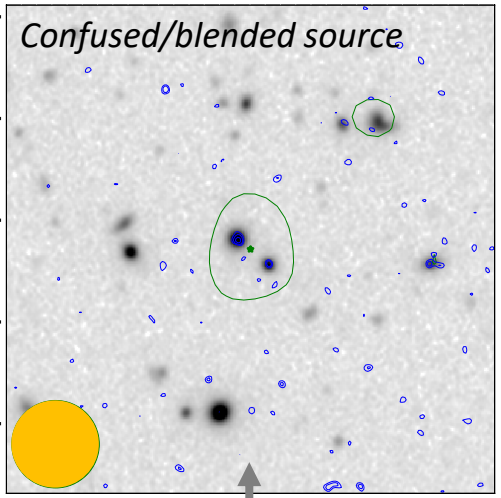
Green Contours – Low Resolution MIGHTEE

Blue Contours– VLA 3 GHz COSMOS (Smolcic+ 2017)









Red Circle – Identified Host source

MIGHTEE Beam Size

UltraVISTA Background (McCracken+ 2012)

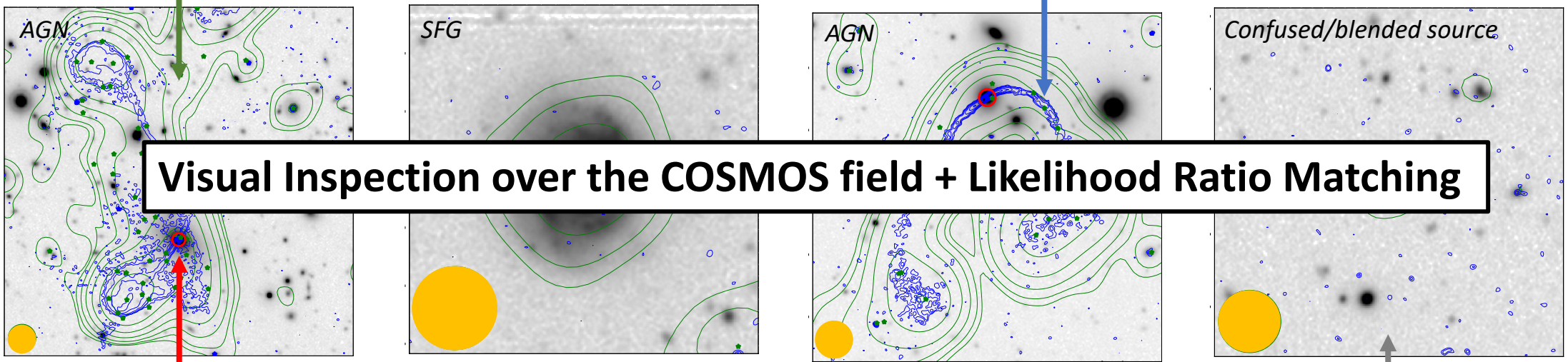
Email: Catherine.Hale@ed.ac.uk

Host Identification and Classification

Initially over
1 deg^2 of COSMOS

Green Contours – Low Resolution MIGHTEE

Blue Contours– VLA 3 GHz COSMOS (Smolcic+ 2017)



Visual Inspection over the COSMOS field + Likelihood Ratio Matching

Red Circle – Identified Host source

MIGHTEE Beam Size

UltraVISTA Background (McCracken+ 2012)

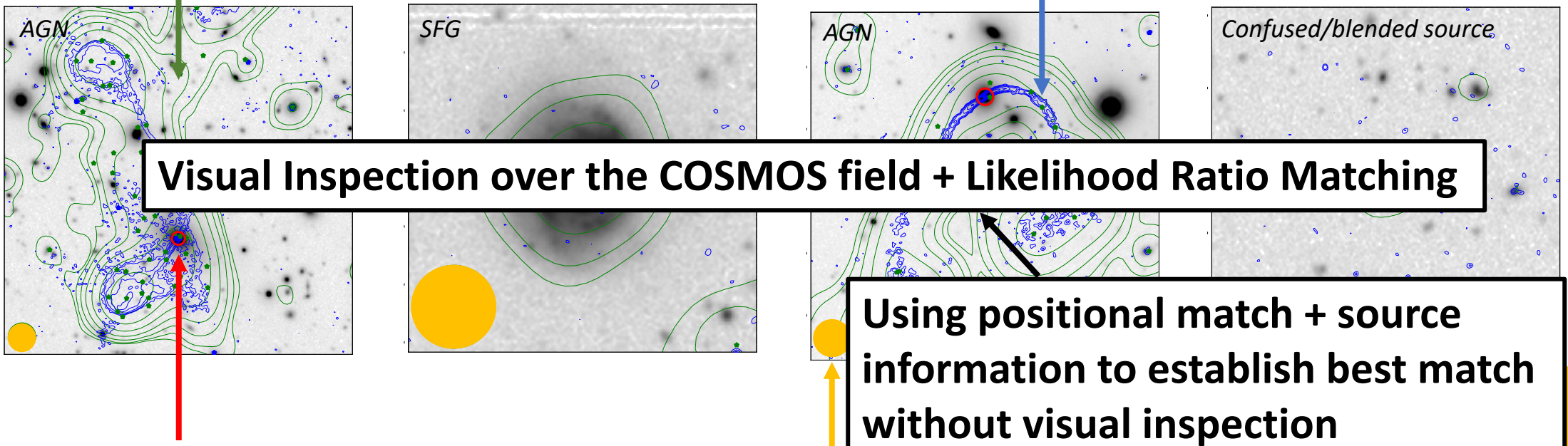
Email: Catherine.Hale@ed.ac.uk

Host Identification and Classification

Initially over
1 deg^2 of COSMOS

Green Contours – Low Resolution MIGHTEE

Blue Contours– VLA 3 GHz COSMOS (Smolcic+ 2017)



Visual Inspection over the COSMOS field + Likelihood Ratio Matching

Using positional match + source information to establish best match without visual inspection

Red Circle – Identified Host source

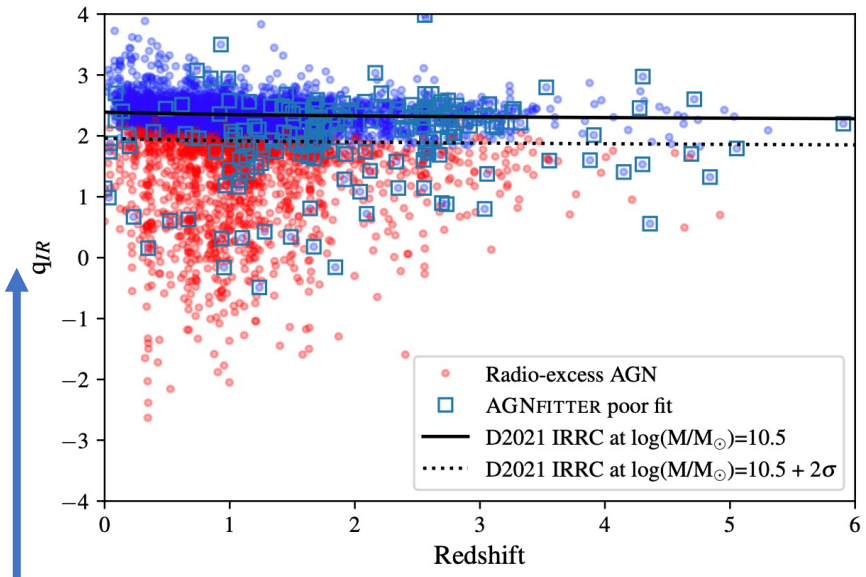
MIGHTEE Beam Size

UltraVISTA Background (McCracken+ 2012)

Email: Catherine.Hale@ed.ac.uk

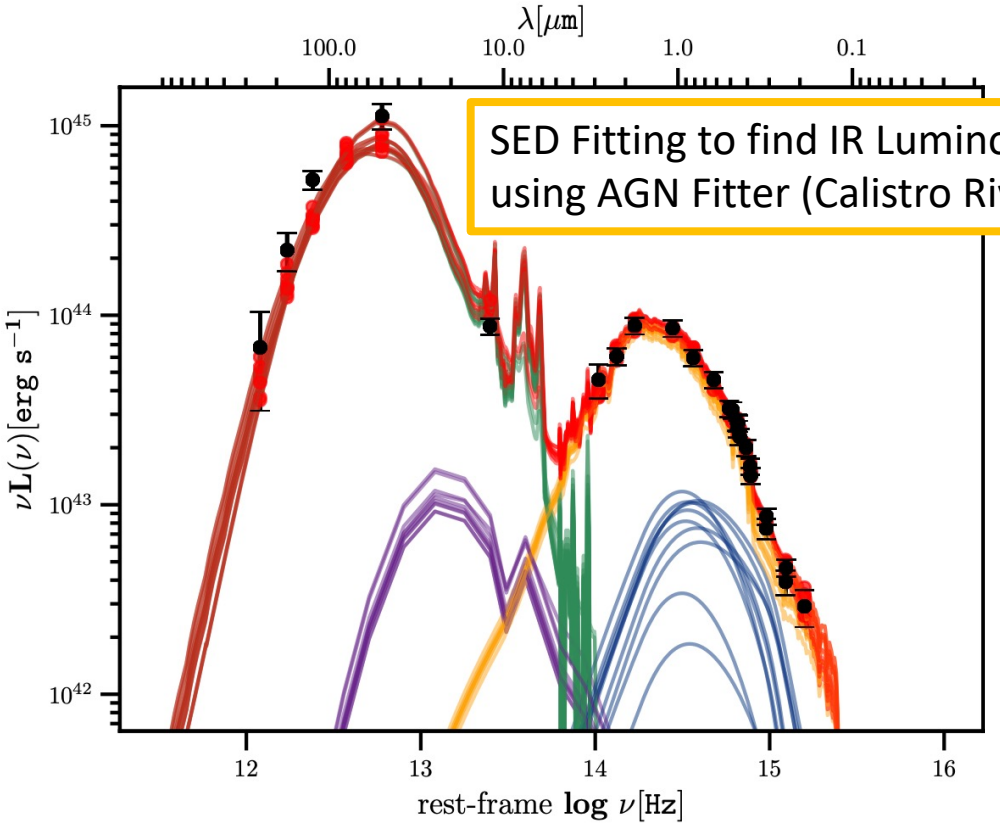
Host Identification and Classification

Infrared-Radio Correlation



See e.g. Delvecchio+ 2017, 2021

$$q_{\mathrm{IR}} = \log_{10} \frac{L_{\mathrm{IR}}\ [\mathrm{W}] \,/\, 3.75 \times 10^{12}\ [\mathrm{Hz}]}{L_{1.4\ \mathrm{GHz}}\ [\mathrm{W\ Hz^{-1}}]}$$

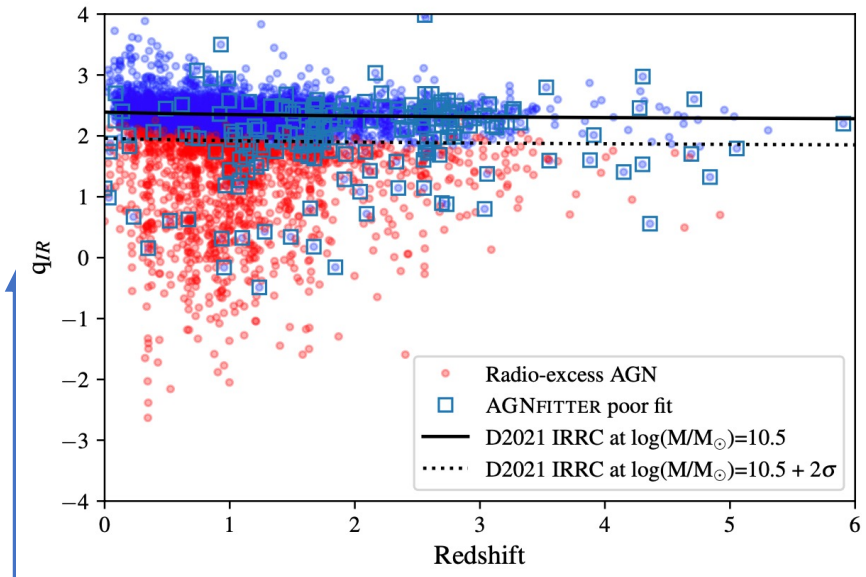


SED Fitting to find IR Luminosity using AGN Fitter (Calistro Rivera+ 2016)

Email: Catherine.Hale@ed.ac.uk

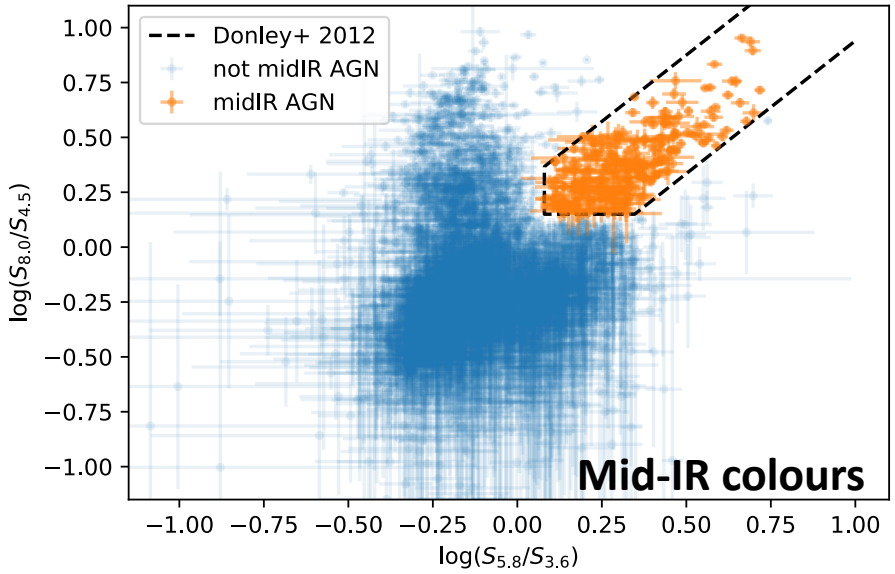
Host Identification and Classification

Infrared-Radio Correlation



See e.g. Delvecchio+ 2017, 2021

$$q_{\mathrm{IR}} = \log_{10} \frac{L_{\mathrm{IR}}\ [\mathrm{W}] \,/\, 3.75 \times 10^{12}\ [\mathrm{Hz}]}{L_{1.4\ \mathrm{GHz}}\ [\mathrm{W\ Hz^{-1}}]}$$



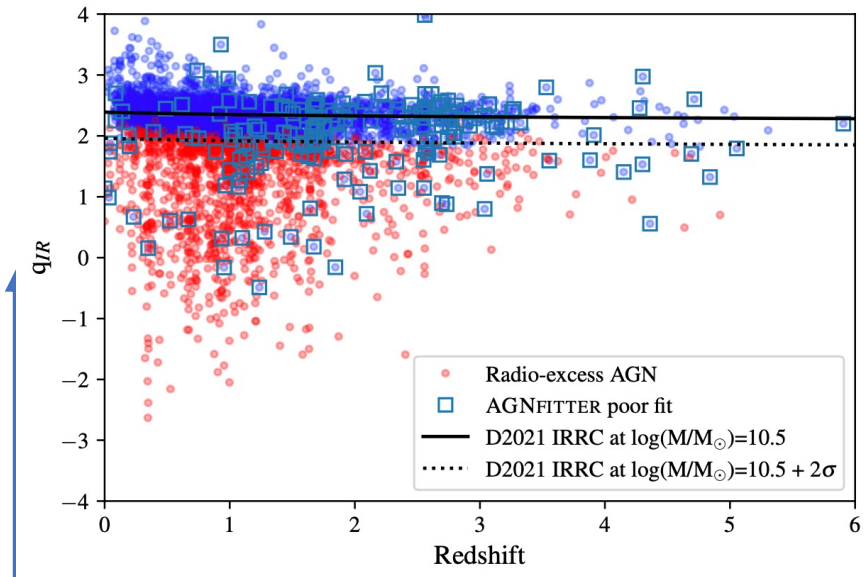
See e.g. Donley+ 2012

Email: Catherine.Hale@ed.ac.uk

Whittam+ submitted

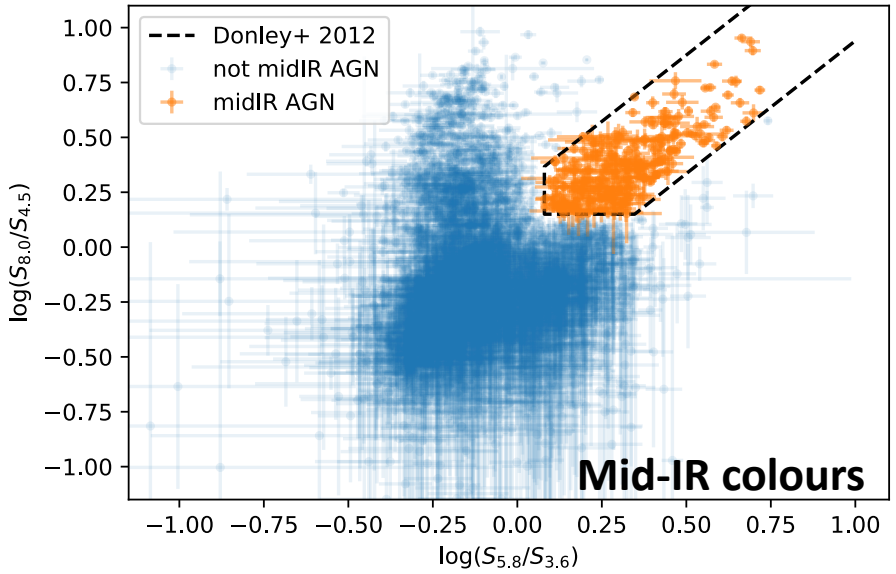
Host Identification and Classification

Infrared-Radio Correlation



See e.g. Delvecchio+ 2017, 2021

$$q_{\mathrm{IR}} = \log_{10} \frac{L_{\mathrm{IR}}\ [\mathrm{W}] \,/\, 3.75 \times 10^{12}\ [\mathrm{Hz}]}{L_{1.4\ \mathrm{GHz}}\ [\mathrm{W\ Hz^{-1}}]}$$



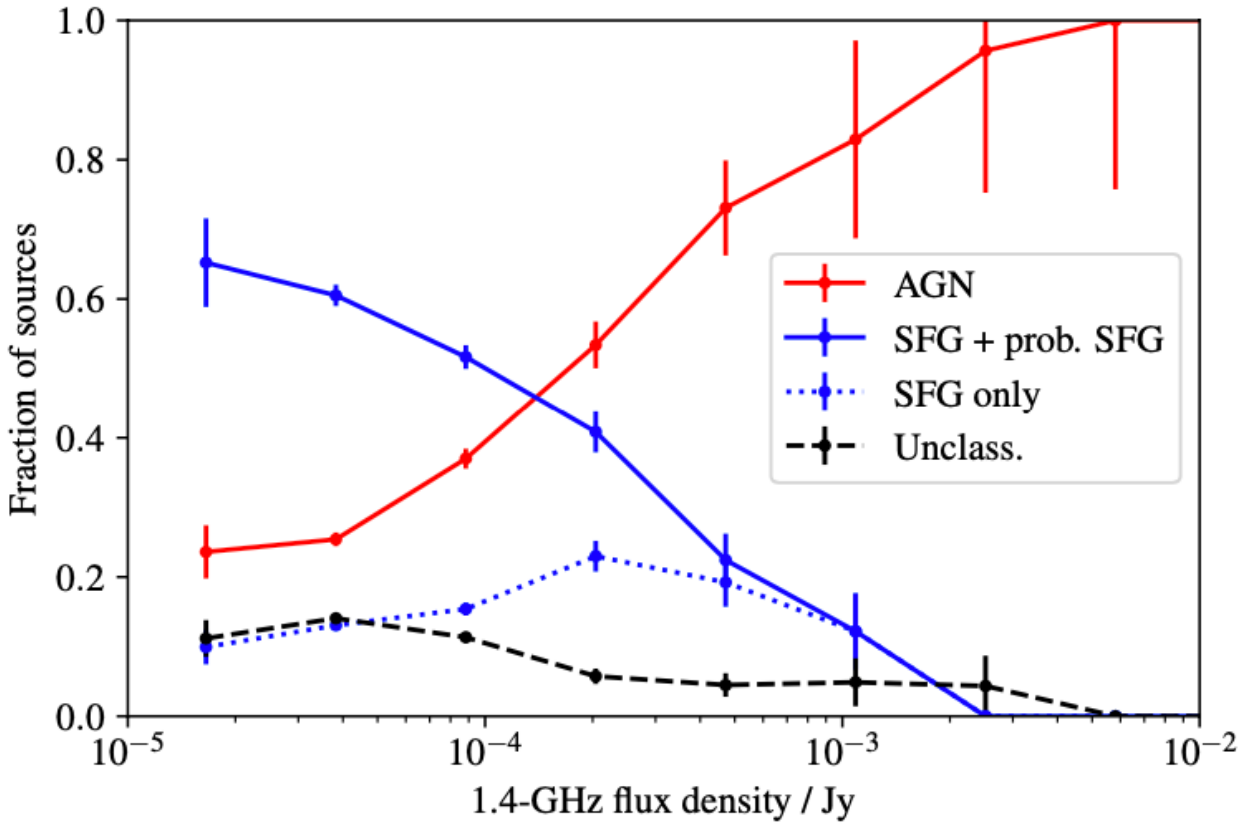
See e.g. Donley+ 2012

+ X-Ray AGN

+ Optical morphology

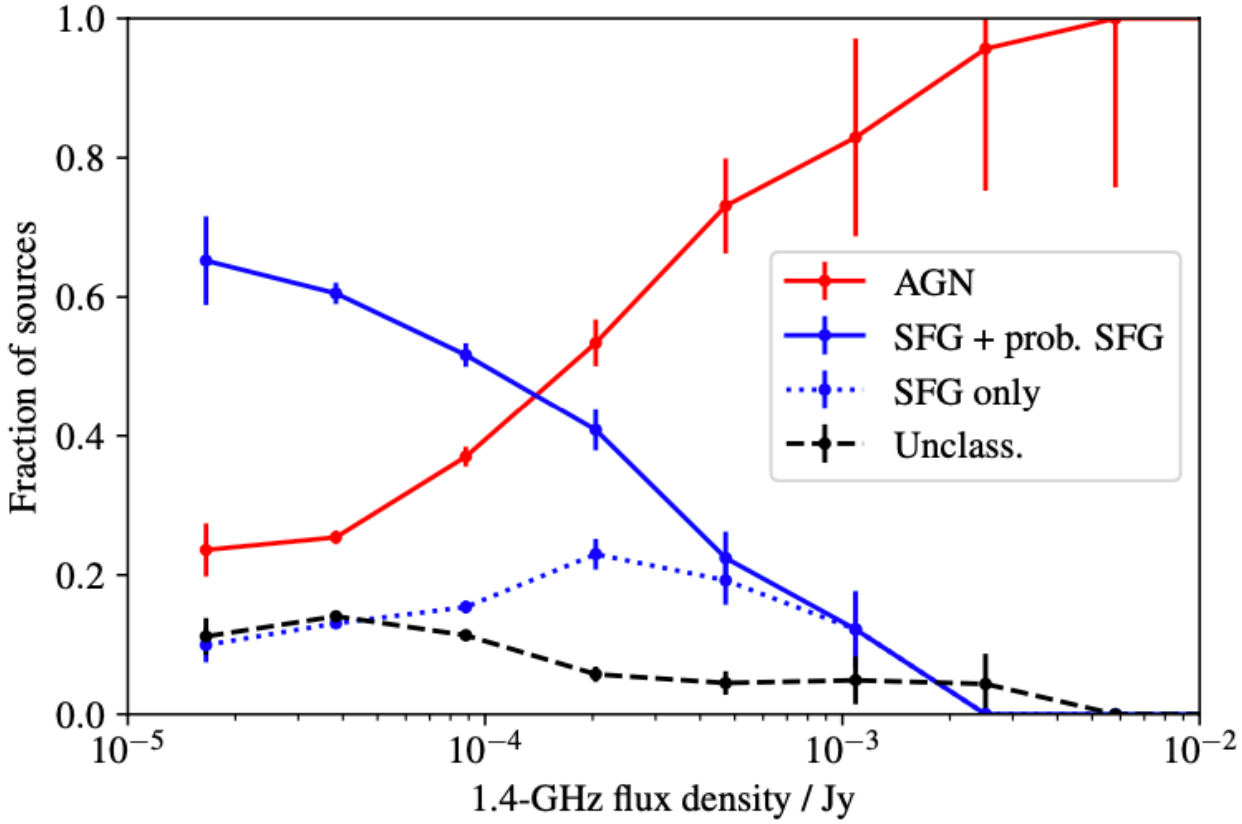
Email: Catherine.Hale@ed.ac.uk

Source Classification



Email: Catherine.Hale@ed.ac.uk

Source Classification



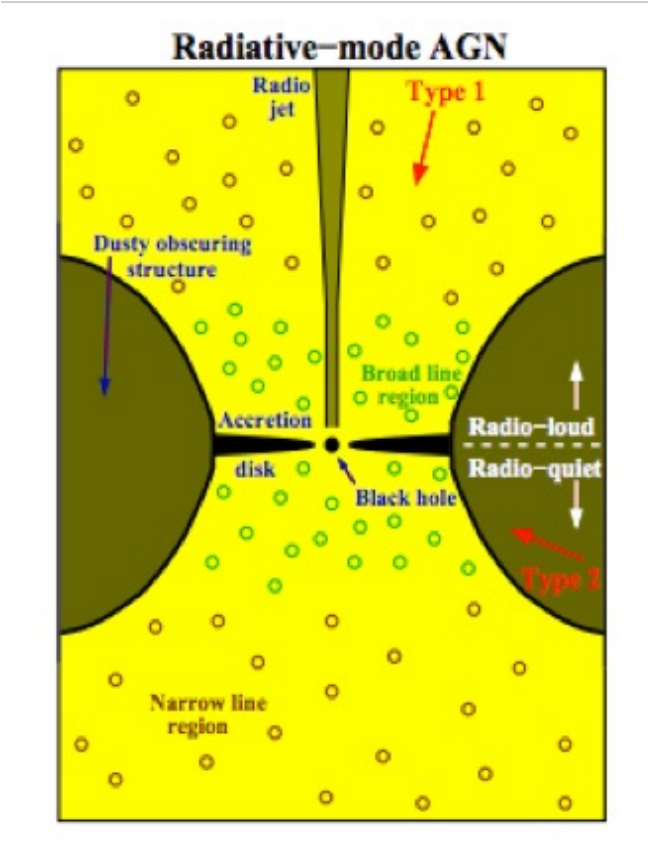
At z>0.5 can no longer use X-ray AGN criterion

Therefore define as probable SFGs

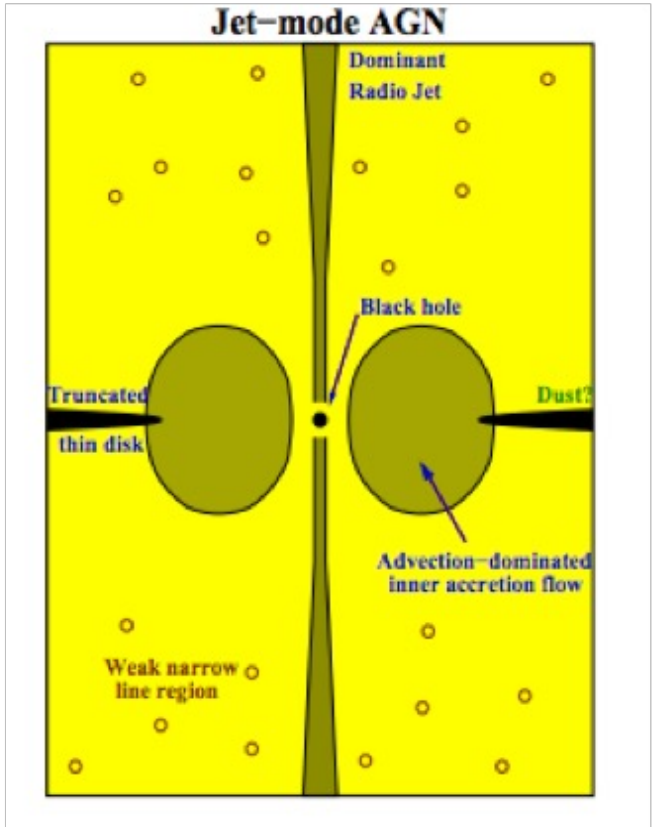
Email: Catherine.Hale@ed.ac.uk

AGN Source Types

Or HERG



Based on physical accretion model



Or LERG

Heckman and Best 2014

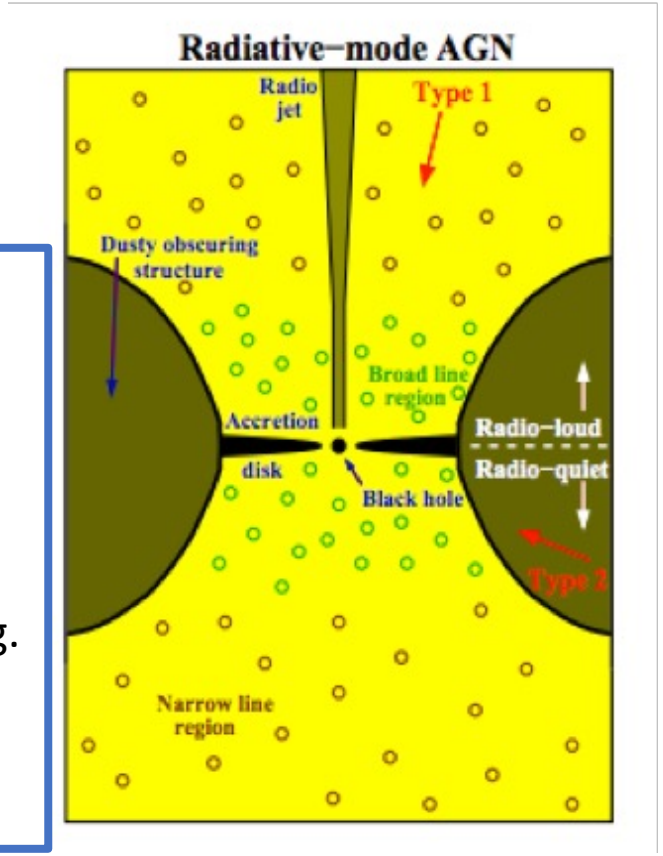
Email: Catherine.Hale@ed.ac.uk

AGN Source Types

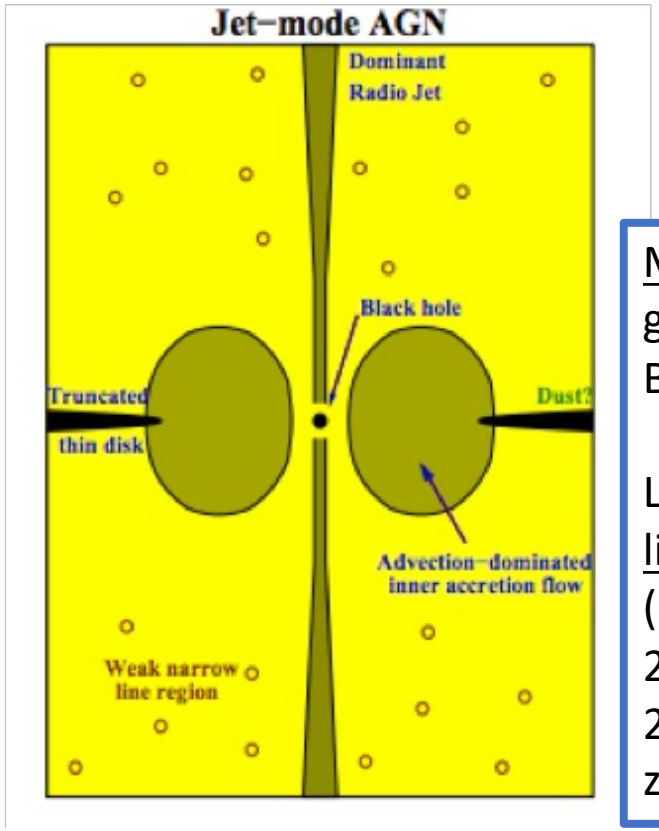
Or HERG

Less massive galaxies (e.g. Best+ 2007)

HERGs show rapid evolution (e.g. Best+ 2014, Pracy+ 2016) up to z~1



Based on physical accretion model



Or LERG

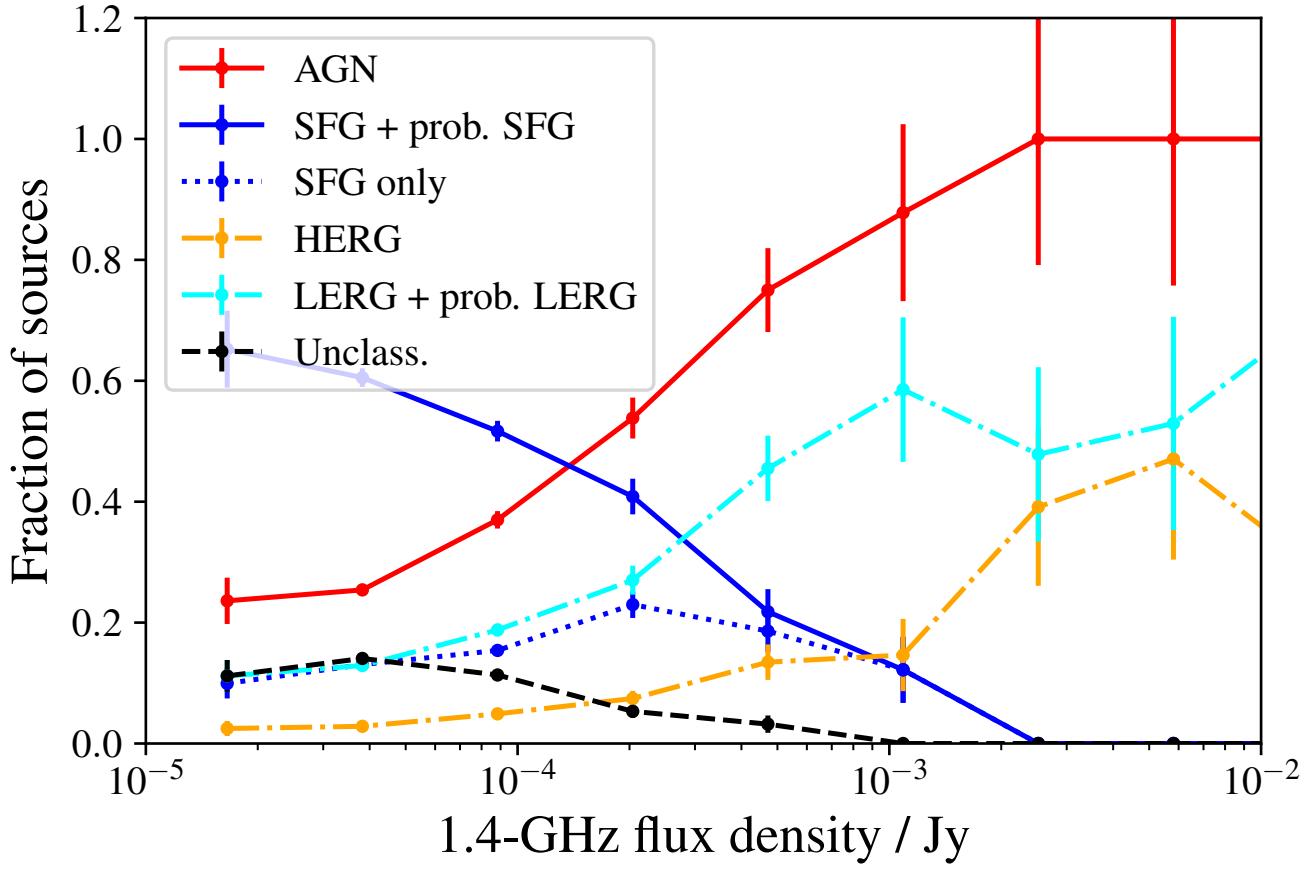
More massive galaxies (e.g. Best+ 2007)

LERGs show little evolution (e.g. Best+ 2014, Pracy+ 2016) up to z~1

Heckman and Best 2014

Email: Catherine.Hale@ed.ac.uk

Source Classification



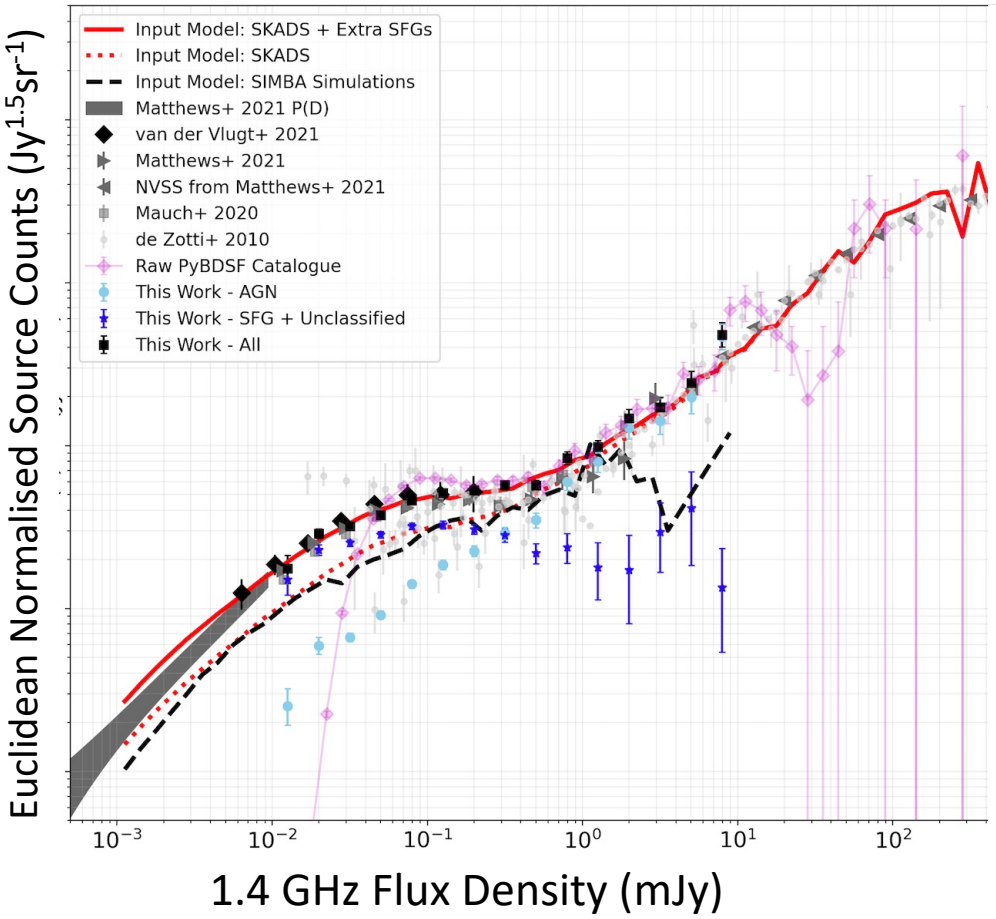
At z>0.5 can no longer use X-ray AGN criterion

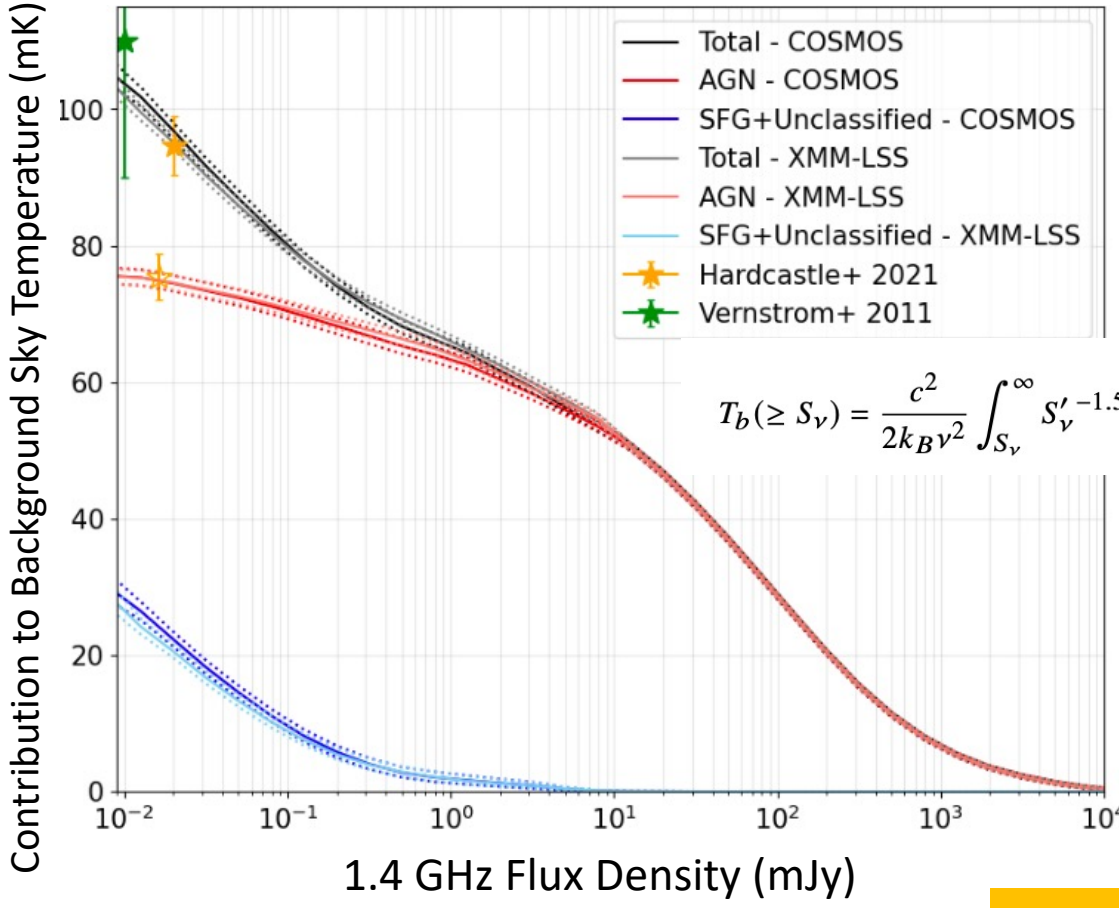
Therefore define as probable SFGs and probable LERGs

Email: Catherine.Hale@ed.ac.uk

Hale+ submitted

Extragalactic Source Counts and Sky Temperature



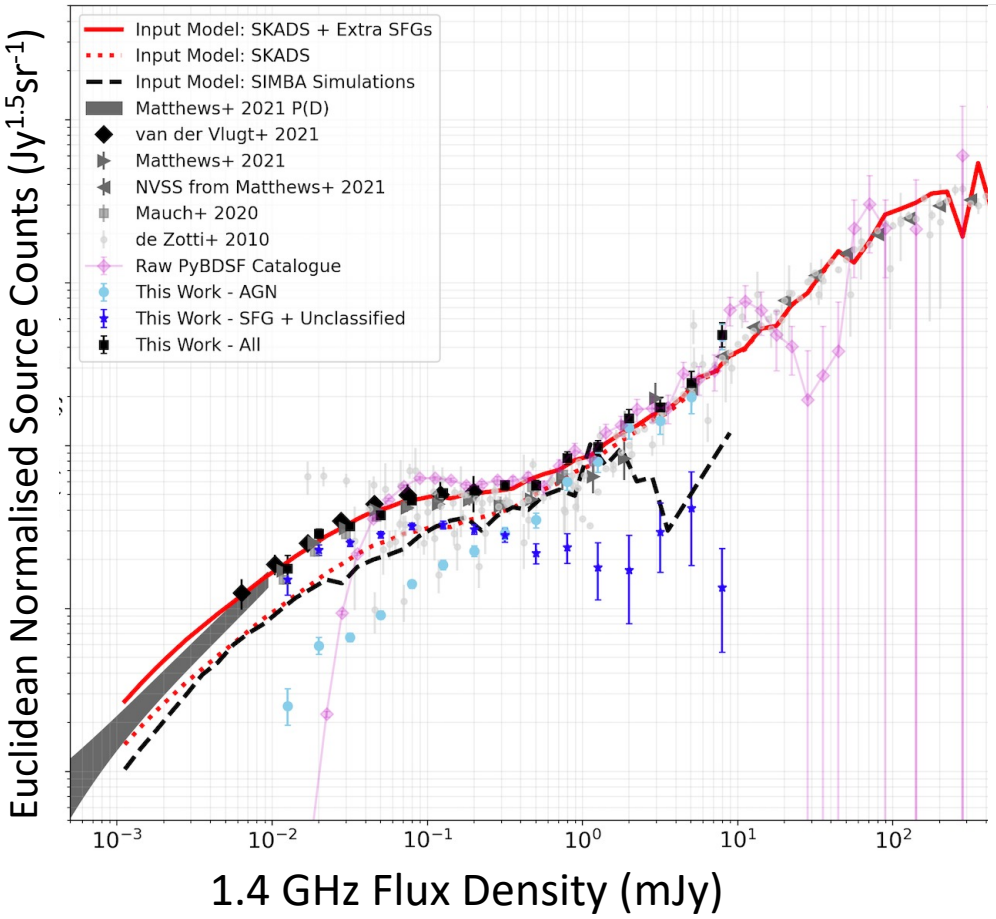


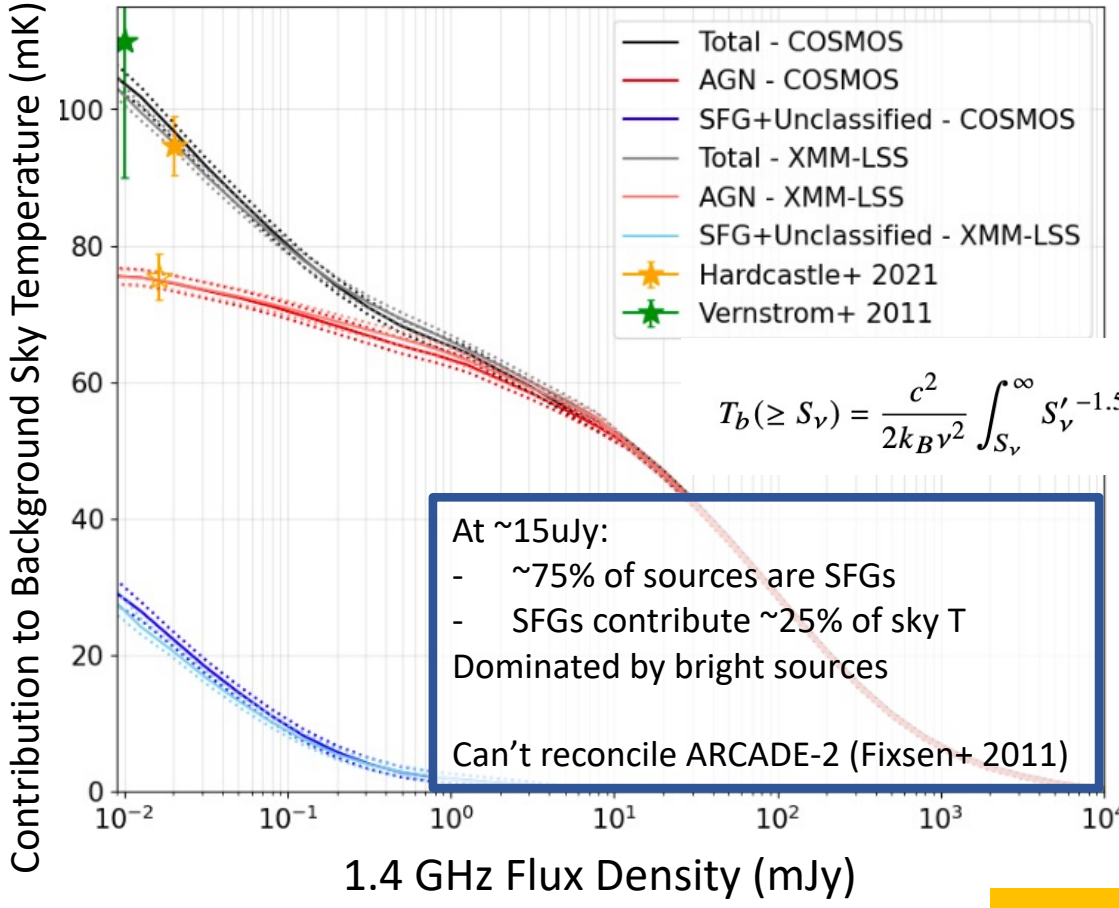
$$T_b(\geq S_\nu) = \frac{c^2}{2k_B\nu^2}\int_{S_\nu}^{\infty} S'^{-1.5}_\nu n(S'_\nu) S'^{2.5}_\nu dS'_\nu.$$

Email: Catherine.Hale@ed.ac.uk

Hale+ submitted

Extragalactic Source Counts and Sky Temperature





$$T_b(\geq S_\nu) = \frac{c^2}{2k_B\nu^2}\int_{S_\nu}^{\infty} S'^{-1.5}_\nu n(S'_\nu) S'^{2.5}_\nu dS'_\nu.$$

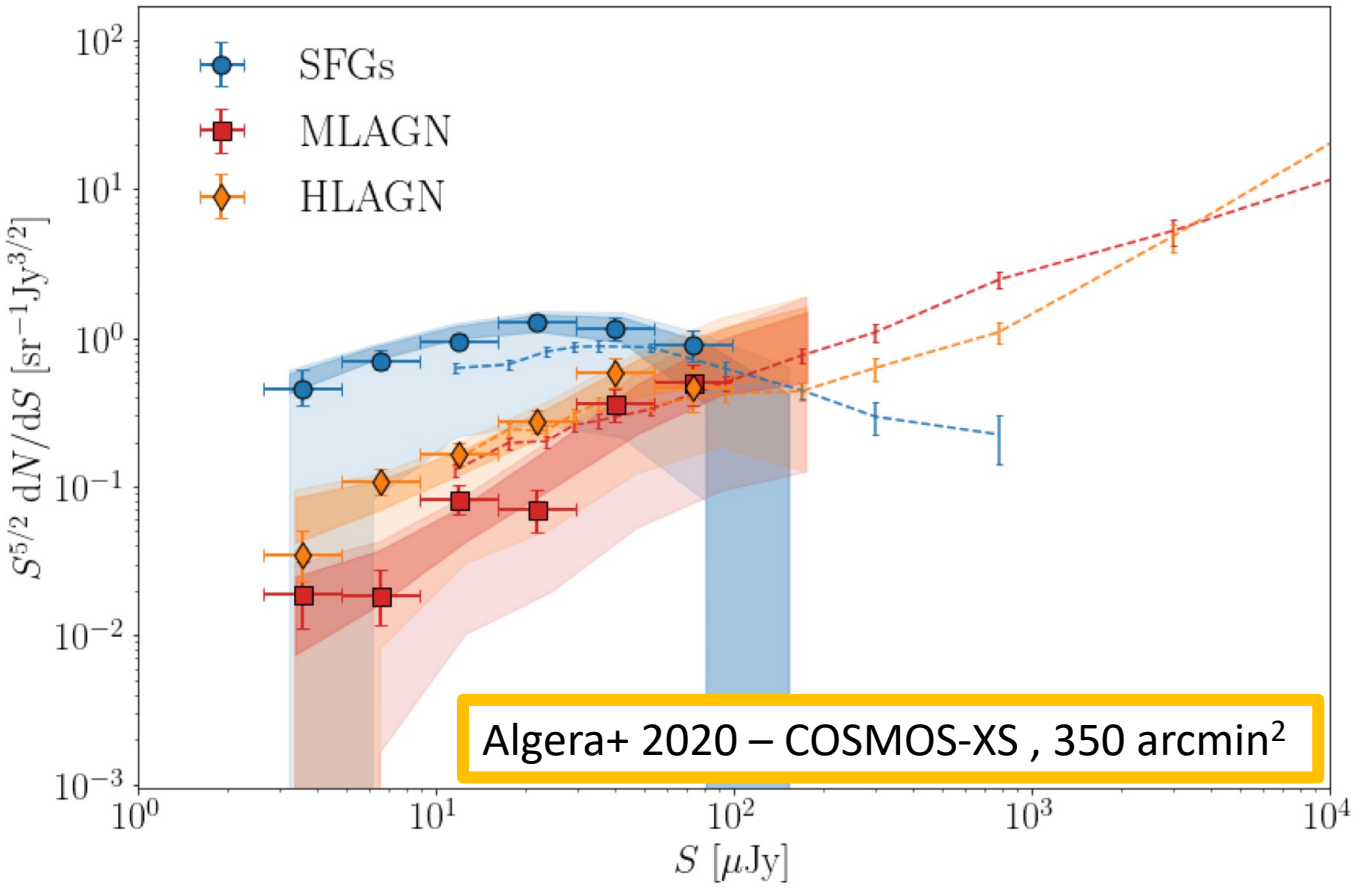
At ~15uJy:
- ~75% of sources are SFGs
- SFGs contribute ~25% of sky T

Dominated by bright sources

Can't reconcile ARCADE-2 (Fixsen+ 2011)

Email: Catherine.Hale@ed.ac.uk

Deep Classified Extragalactic Source Counts



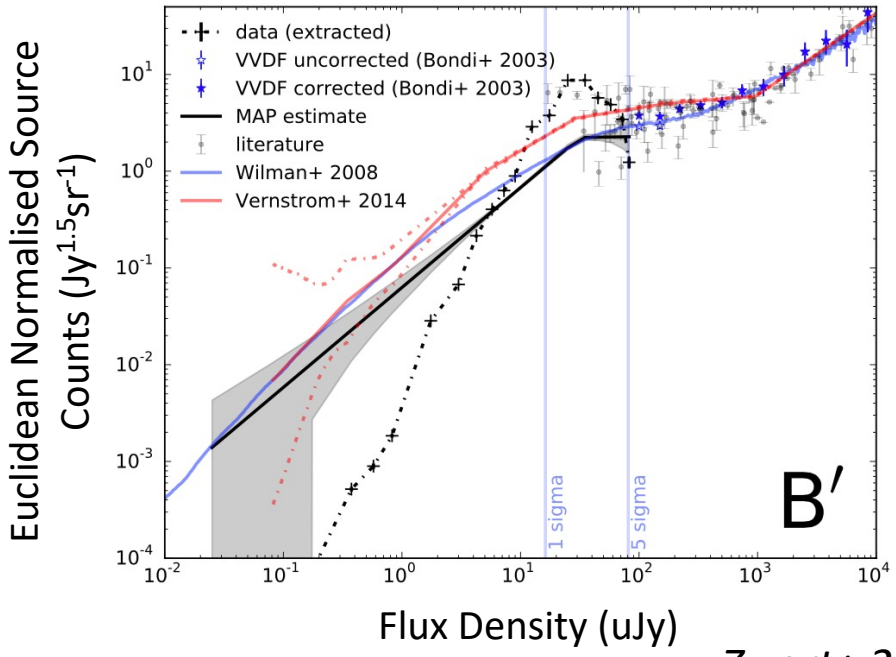
Email: Catherine.Hale@ed.ac.uk

Sub-threshold analysis

Bayesian Stacking

Using the known positions of sources

see e.g. Zwart+ 2015

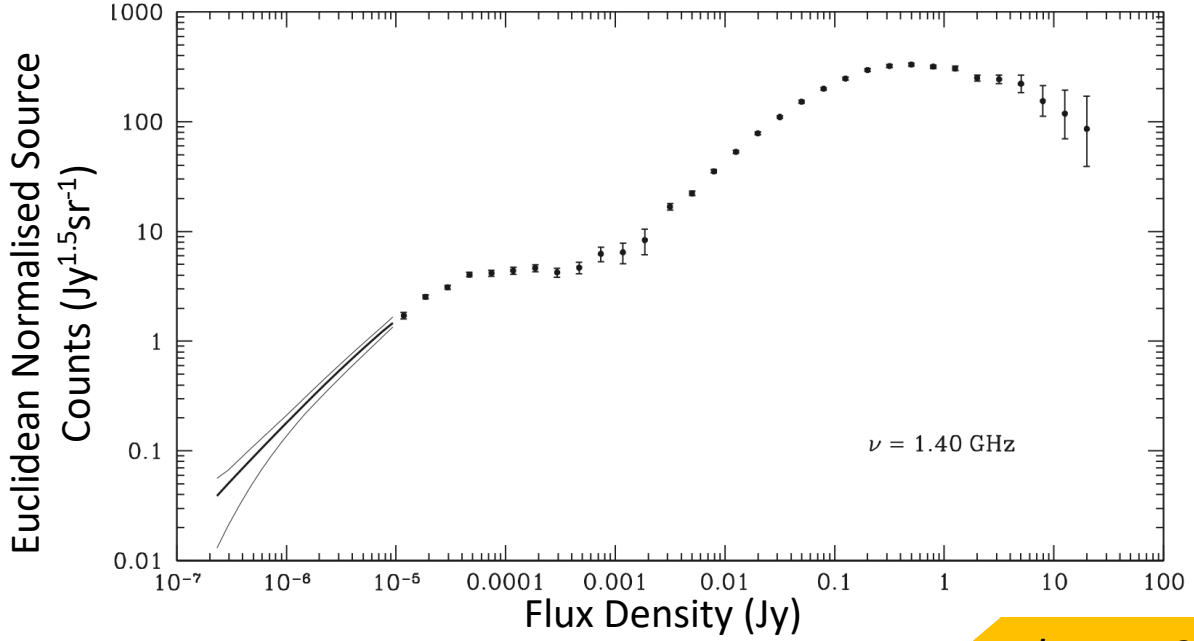


Zwart+ 2015

P(D) Analysis

Using the observed convolution of noise+ sources

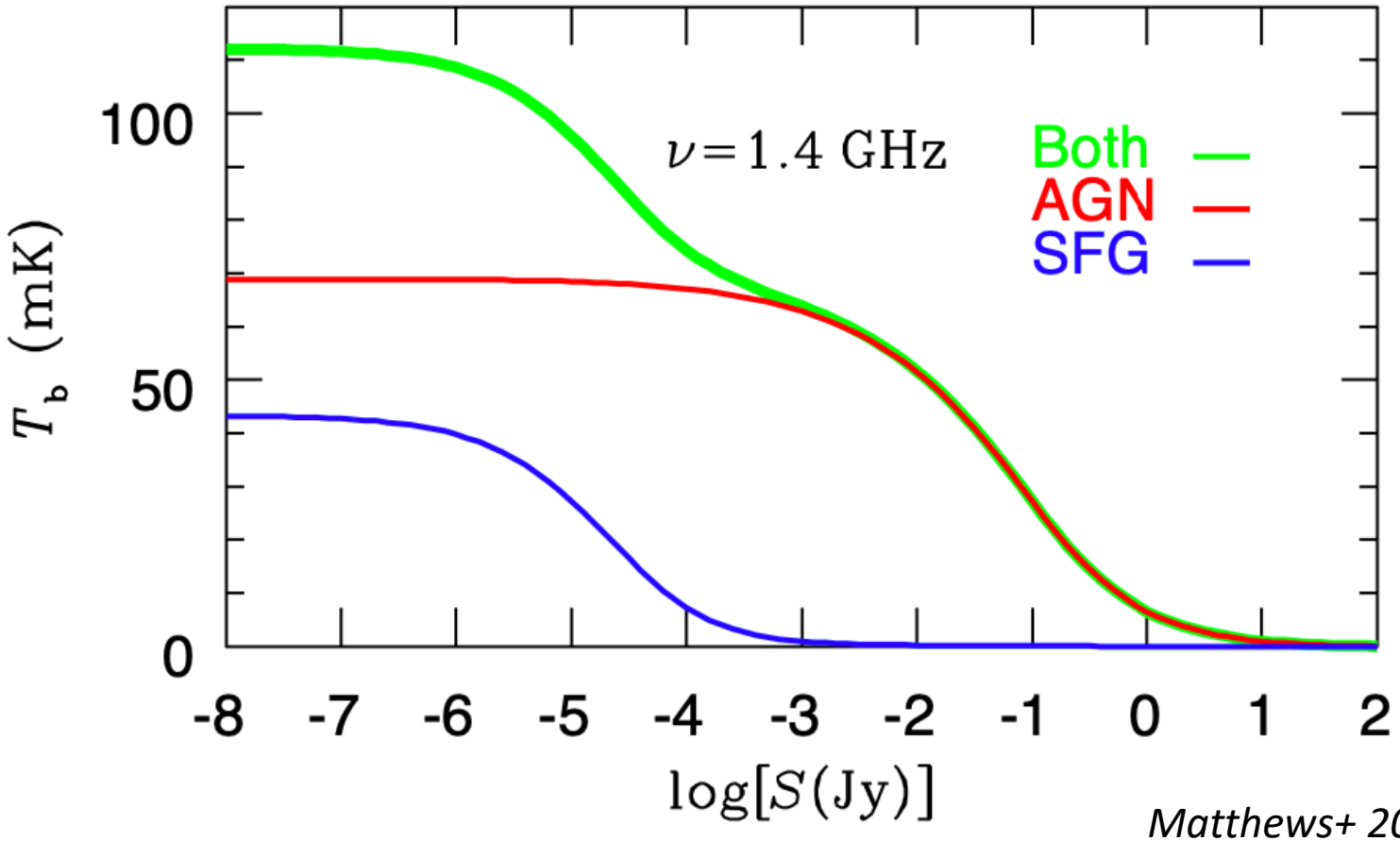
see e.g. Condon+ 2012, Vernstrom+ 2014, Matthews+2021



Matthews+ 2021

Email: Catherine.Hale@ed.ac.uk

Sub-Threshold Sky Temperature Contribution



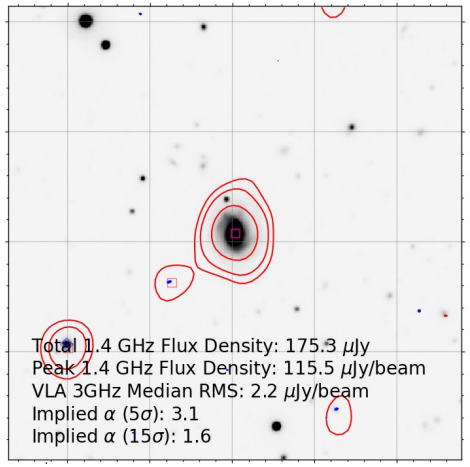
Matthews+ 2021

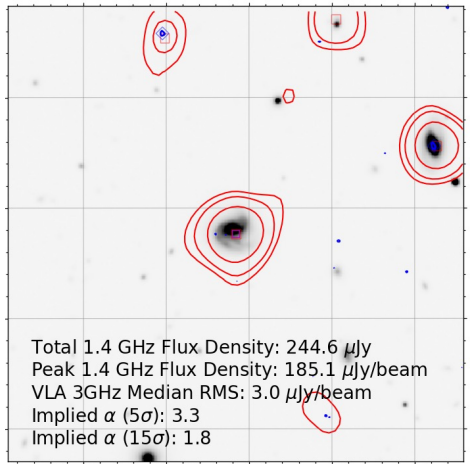
Email: Catherine.Hale@ed.ac.uk

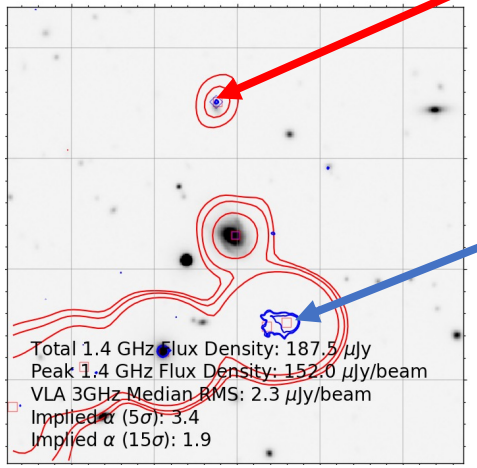
Detection of SFGs

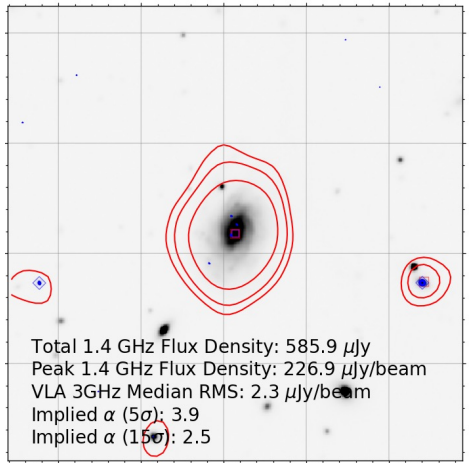
Email: Catherine.Hale@ed.ac.uk

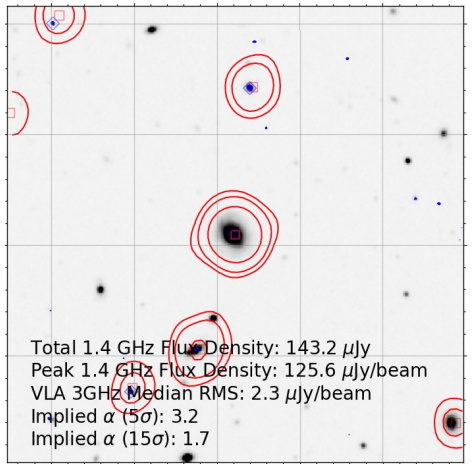
Detection of Extended Sources

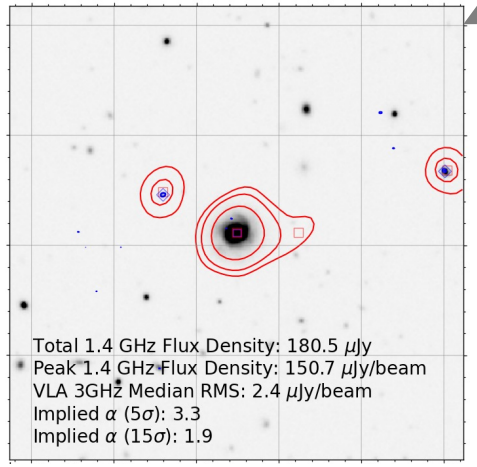












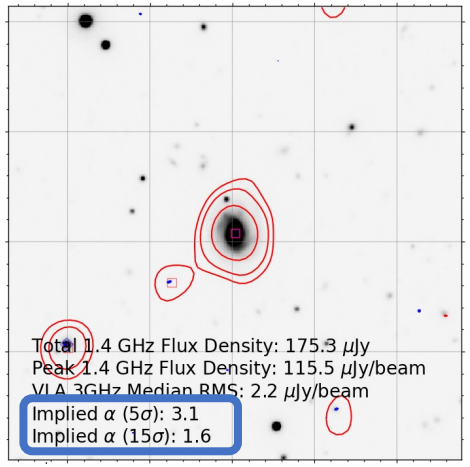
Red Contours –
Low Resolution MIGHTEE

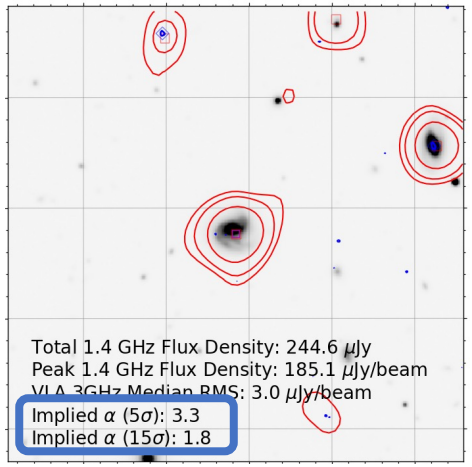
Blue Contours– VLA 3 GHz
COSMOS (Smolcic+ 2017)

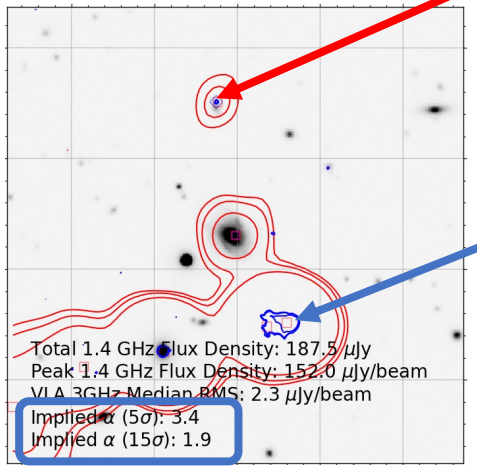
UltraVISTA Background
(McCracken+ 2012)

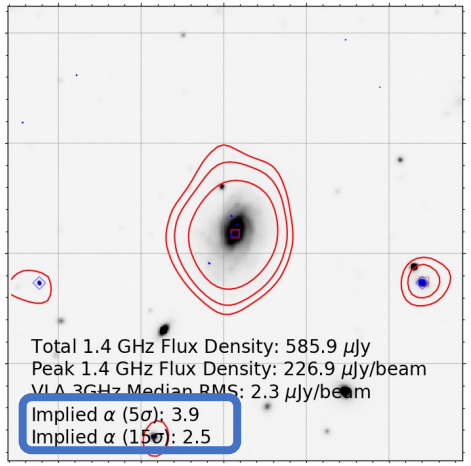
Email: Catherine.Hale@ed.ac.uk

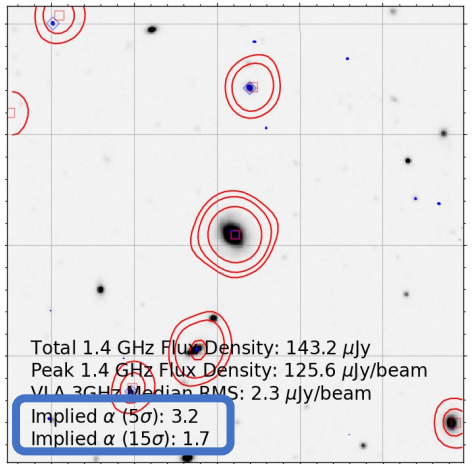
Detection of Extended Sources

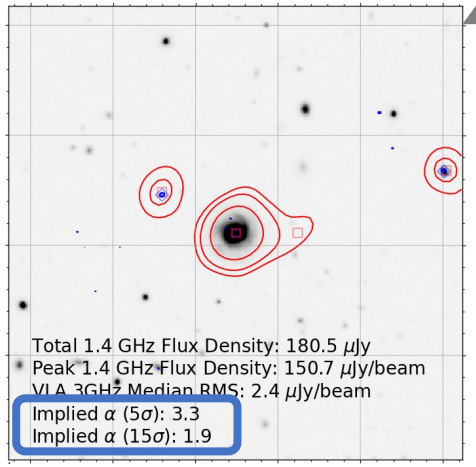












Red Contours – Low Resolution MIGHTEE

Blue Contours– VLA 3 GHz COSMOS (Smolcic+ 2017)

UltraVISTA Background (McCracken+ 2012)

$$S_\nu \propto \nu^{-\alpha}$$

Typical Spectral indices in galaxies: $\alpha \sim 0.7\text{-}0.8$

Email: Catherine.Hale@ed.ac.uk

Future of Deep Extragalactic Source Counts

Email: Catherine.Hale@ed.ac.uk

Current Radio Facilities

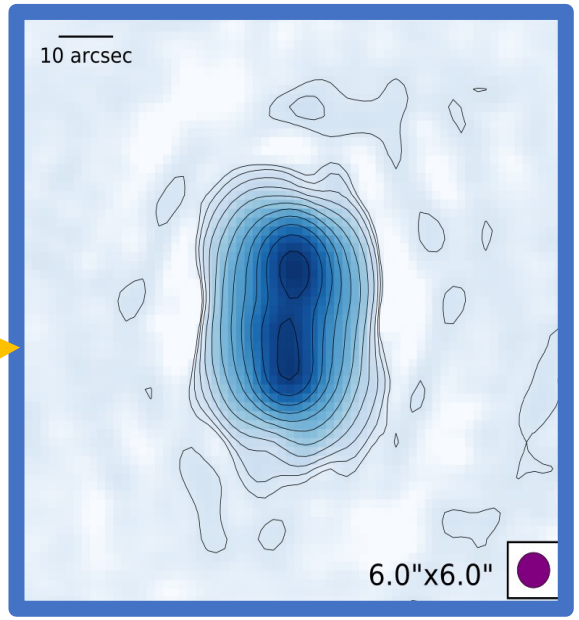
Credit: ASTRON

Email: Catherine.Hale@ed.ac.uk

Current Radio Facilities

Credit: Morabito et al. 2022, A&A, 658, A1

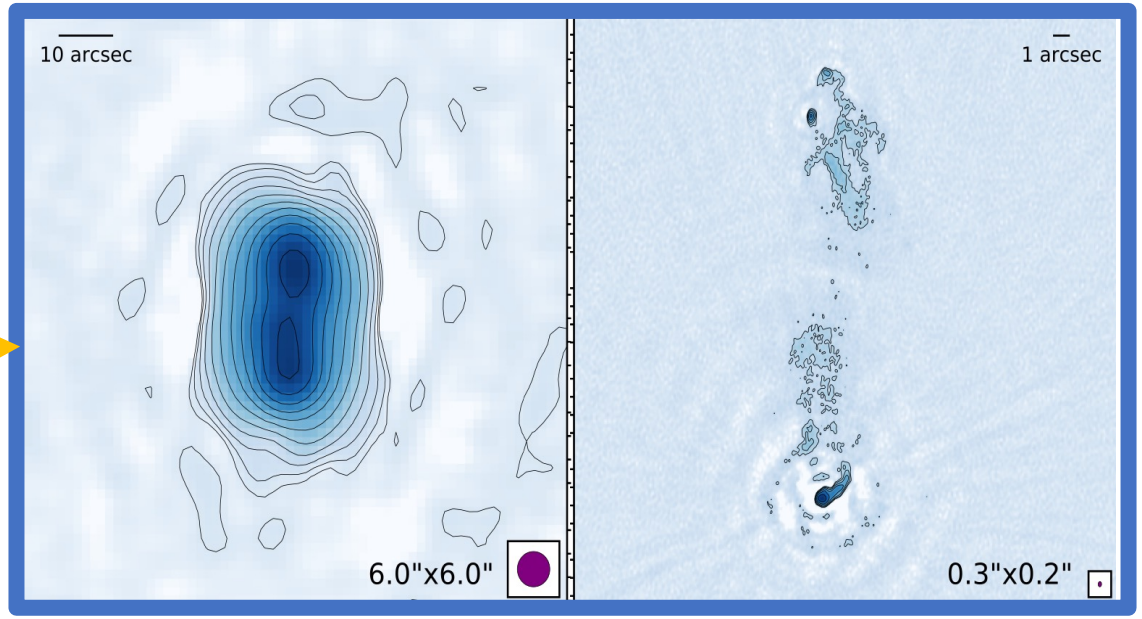
Credit: ASTRON



Email: Catherine.Hale@ed.ac.uk

Current Radio Facilities

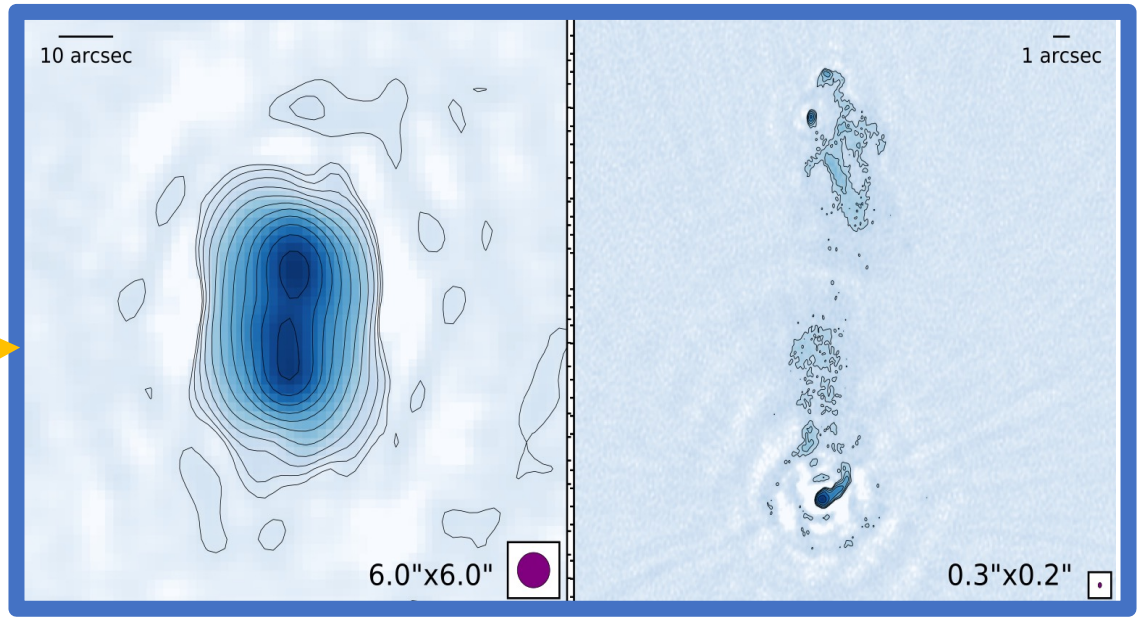
Credit: Morabito et al. 2022, A&A, 658, A1



Email: Catherine.Hale@ed.ac.uk

Current Radio Facilities

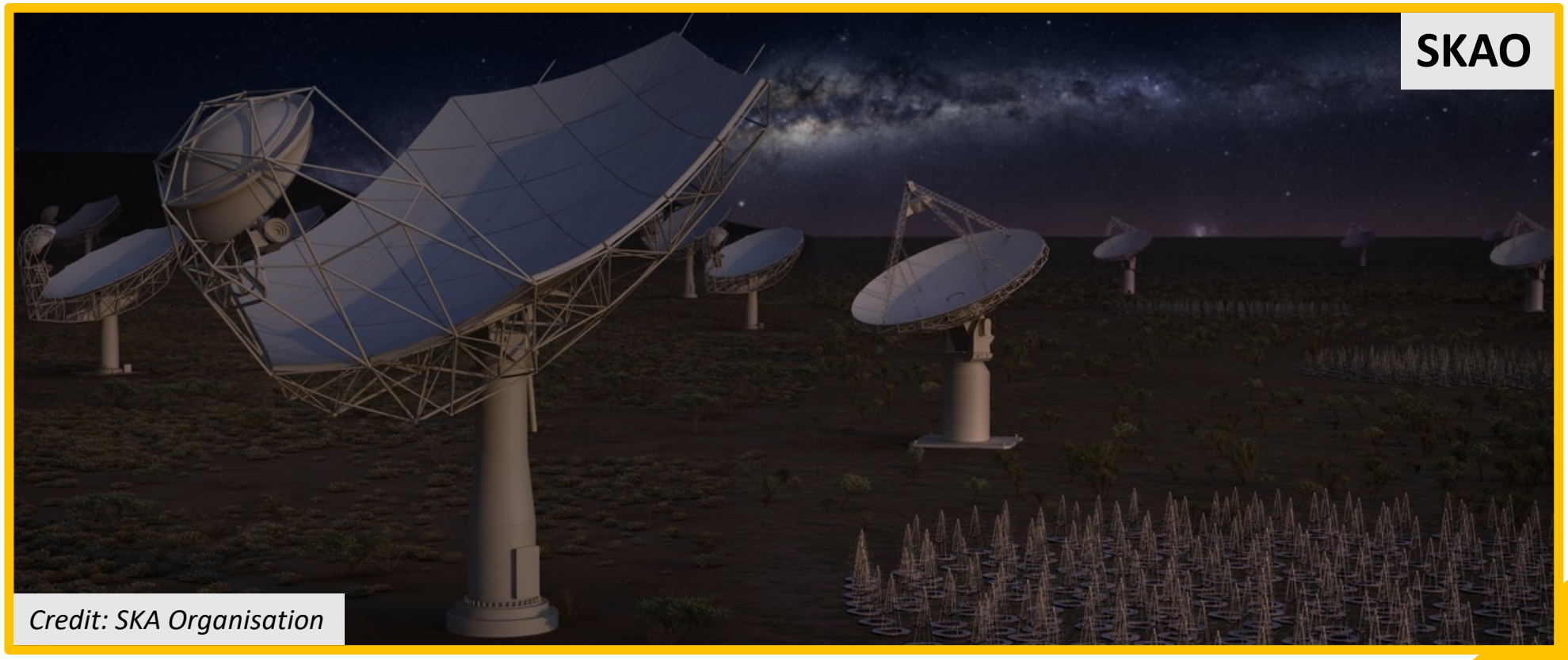
Credit: Morabito et al. 2022, A&A, 658, A1



Allow even deeper imaging
Easier comparison to multi-wavelength data

Email: Catherine.Hale@ed.ac.uk

SKA



Credit: SKA Organisation

Email: Catherine.Hale@ed.ac.uk

Summary

- Deep Extragalactic Surveys with e.g. MeerKAT, ASKAP, LOFAR are allowing us to probe to deeper and higher redshifts – leading to larger numbers of SFGs and faint AGN
- Combining with deep multi-wavelength data, we can trace SFG and AGN contribution to radio synchrotron background
- Tools such as stacking and P(D) allow us to go even below 5σ
- With SKAO precursors and the SKAO, this will revolutionise knowledge of faint extragalactic populations

Email: Catherine.Hale@ed.ac.uk