

# Exploring the resolved $\mu\text{Jy}$ extragalactic radio source population at high resolution with wide-field VLBI surveys- paving the way for SKA+VLBI.

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Mike Garrett Christopher Harrison et al**

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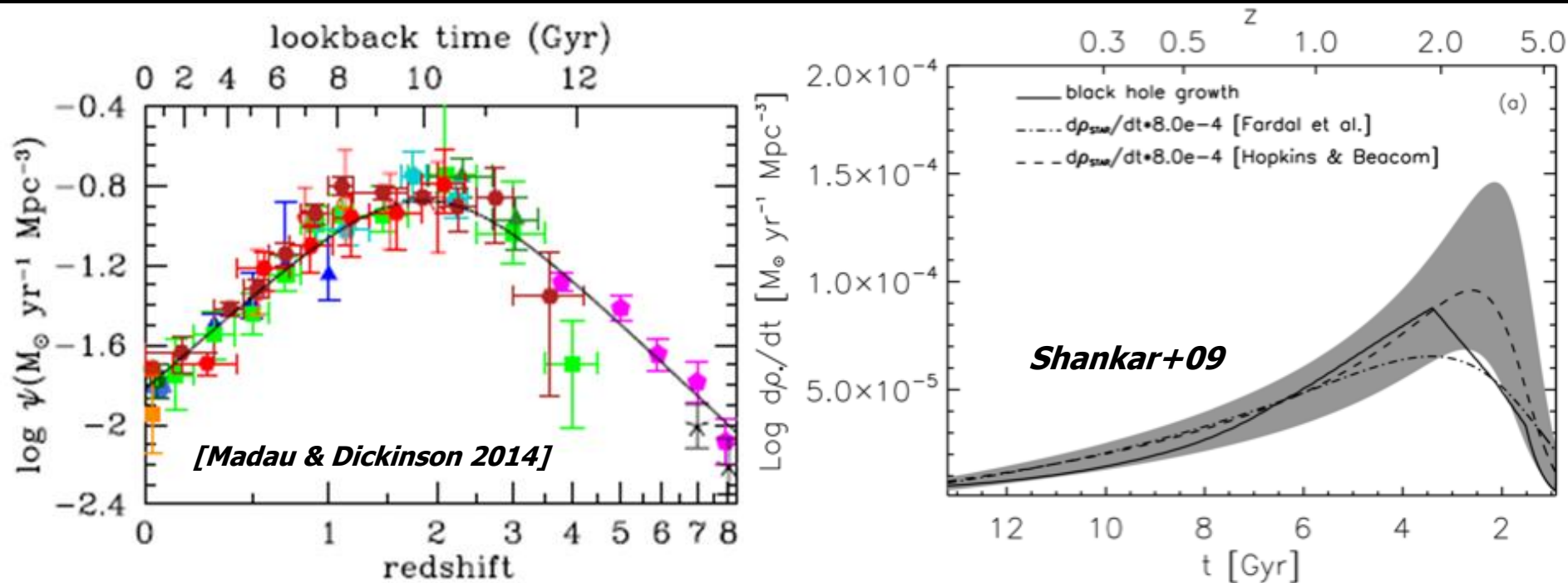
# Outline:

- Motivation: **why your AGN observations need a VLBI follow up?**
- Why VLBI?
- Wide-Field VLBI + Surveys
- Science with VLBI
- SKA+VLBI: The Future
- Key takeaways & conclusion

## ❖ Motivation

One Main goal for astrophysics: study the SF and galaxy evolution across cosmic time

SFR peaks at  $z \sim 1-2$ , with AGN accretion showing a similar trend: implying co-evolution = host-SMBH feedback

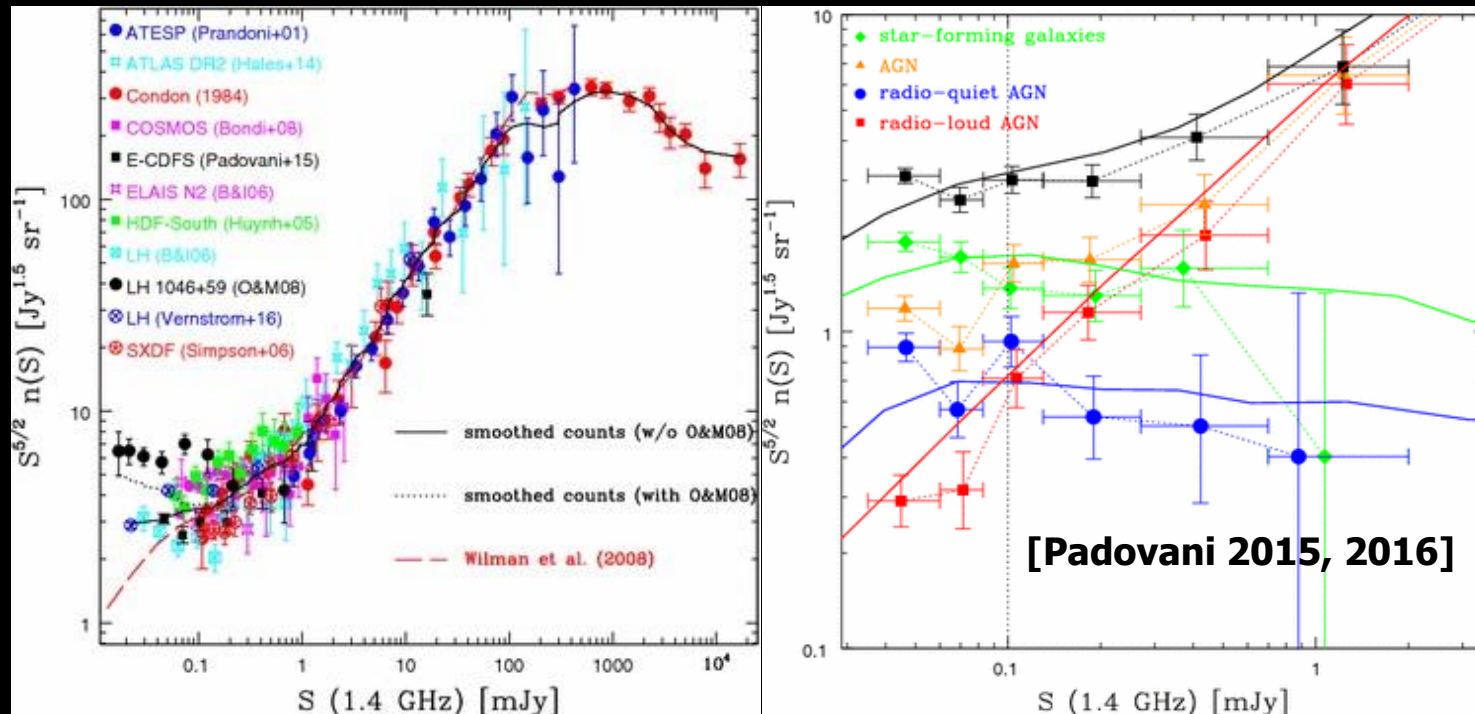


To understand feedback mechanism, for precise SFRs, we need to find all the AGN in our fields!

**Why VLBI?**



# Radio



- ❑ Radio measurements require no dust corrections/unbiased tracer for SF
- ❑ Radio: Upsurge of sources at sub-millijansky (at  $z > 0.1$ )
- ❑ Composed of AGNs & SFGs
- ❑ Obscured in X-rays, IR and optical

# Radio Morphology

- Can identify AGN via morphology, but most are unresolved at typical radio resolutions and  $\mu\text{Jy}$  sensitivities!

*Few sources <1%*

1.5155 GHz

*Many sources*

1.5155 GHz

VLA A-array  $\sim 1.5''$  resolution

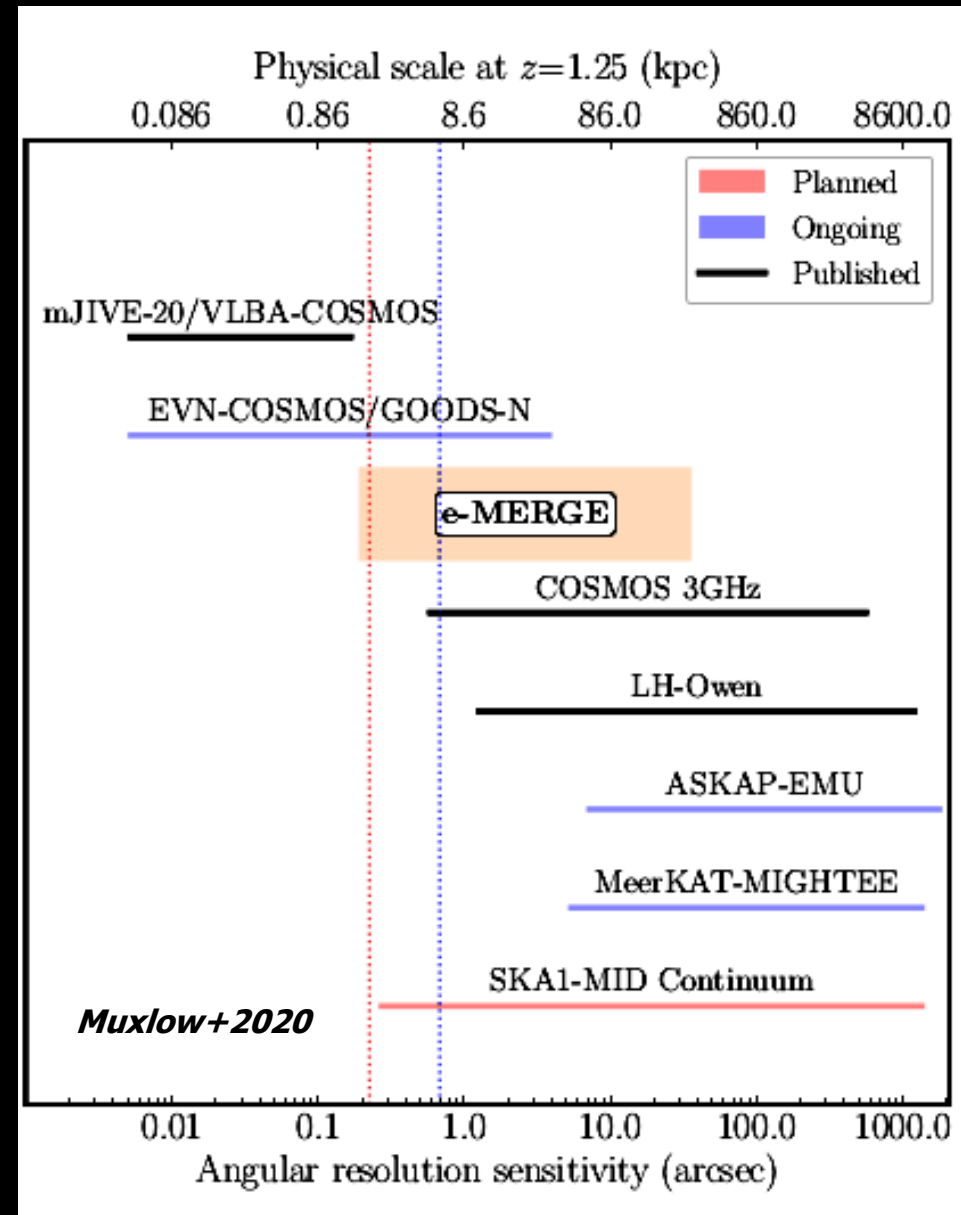
$\sim 22 \text{ mJy}$

$\sim 0.6 \text{ mJy}$

Credit: J.F. Radcliffe

## ❖ *So, Why VLBI?*

- **Interferometric (+VLBI) radio continuum surveys: High Angular Resolution and High Sensitivity**
- **VLBI provide ultra-high milliarcsecond (mas) angular resolutions =  $\sim$ parsec scales @  $z \sim 2$**
- **VLBI provides a powerful extinction-free tool to hunt for 'elusive' AGN and spatially resolve AGN & SF**



# Wide-field VLBI + Surveys

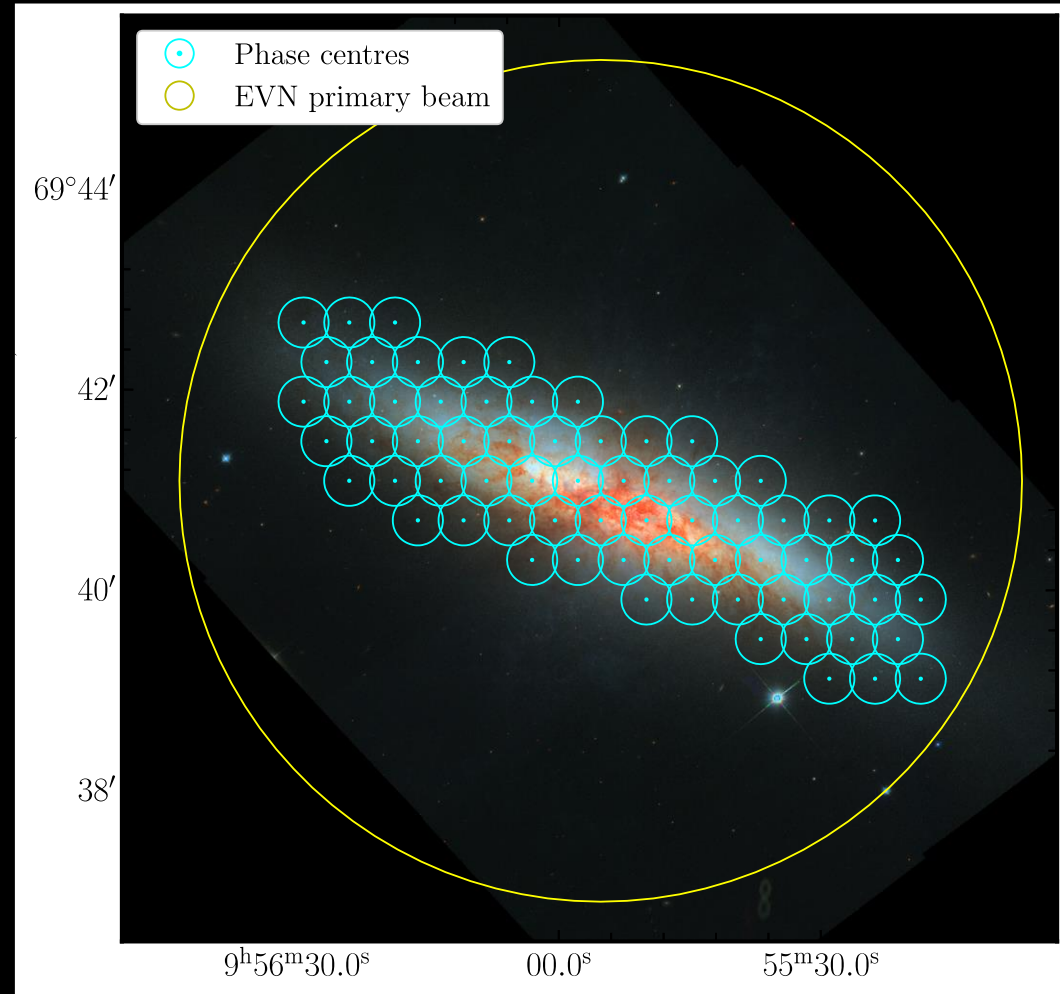




# ❖ Wide-Field VLBI: Multiple phase centre correlation

*[Morgan et al 2011, Deller et al. 2011, Keimpema et al. 2015]*

- **Correlate simultaneously on multiple positions across the PB**
- **Phase centres pre-selected to cover either area / sources of interest / known radio sources**
- **Results in lots of small (in FoV & Size) datasets – same calibration steps = easily parallelisable**



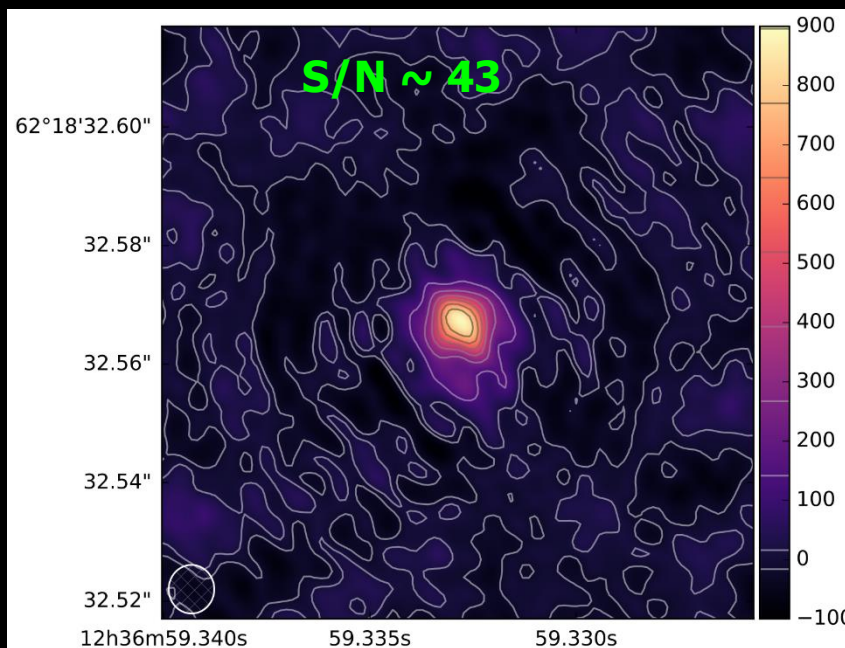
*Theoretical M82 system, Radcliffe2019 (thesis)*

## 2. Multi-Source self-calibration (MSSC)

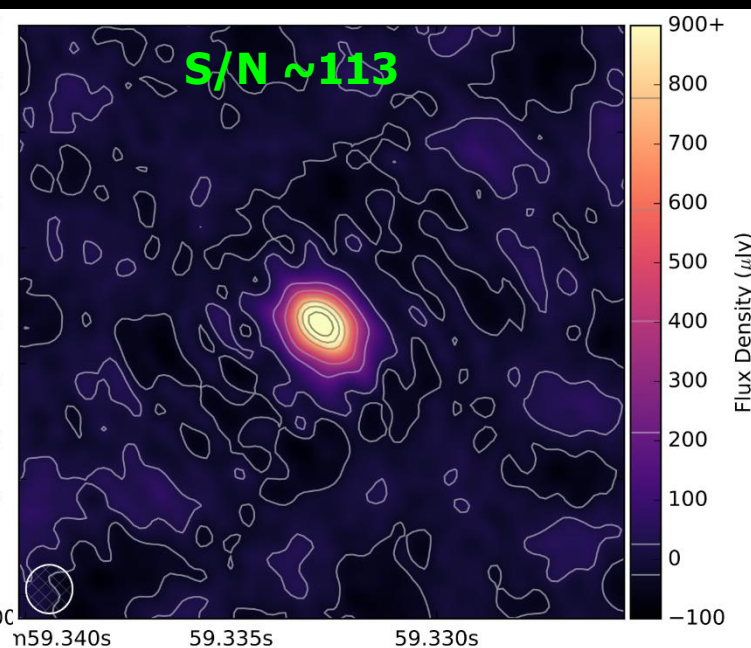
*Middelberg et al. 2013, Radcliffe et al. 2016*

- Ionospheric & atmospheric turbulence reduces image coherence in phase-referenced observations
- Absence of strong sources ( $\sim \mu\text{Jy}$  regimes) thus not suitable for self-calibration
- Use combined response of multiple sources across FoV (via  $uv$  stacking) to perform self-calibration

*Standard phase referencing*



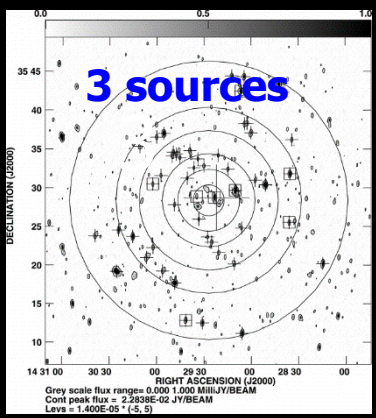
*MSSC*



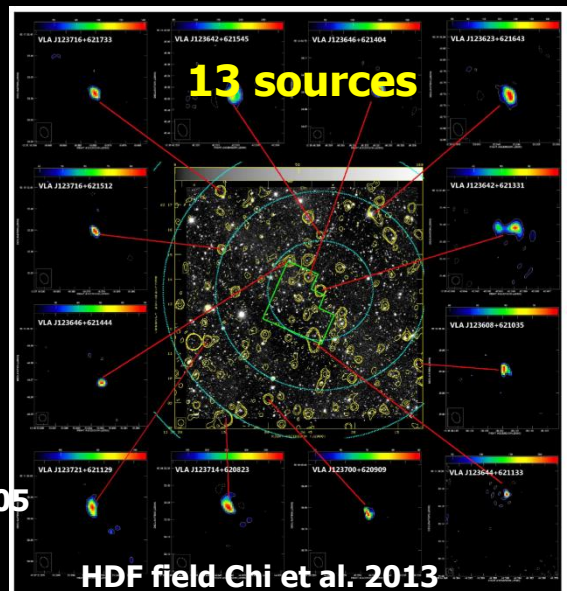
*Radcliffe+2016*



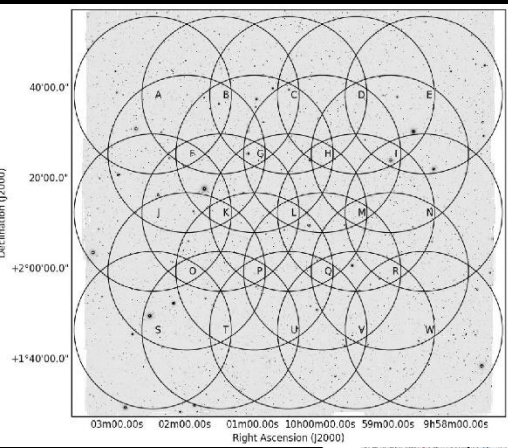
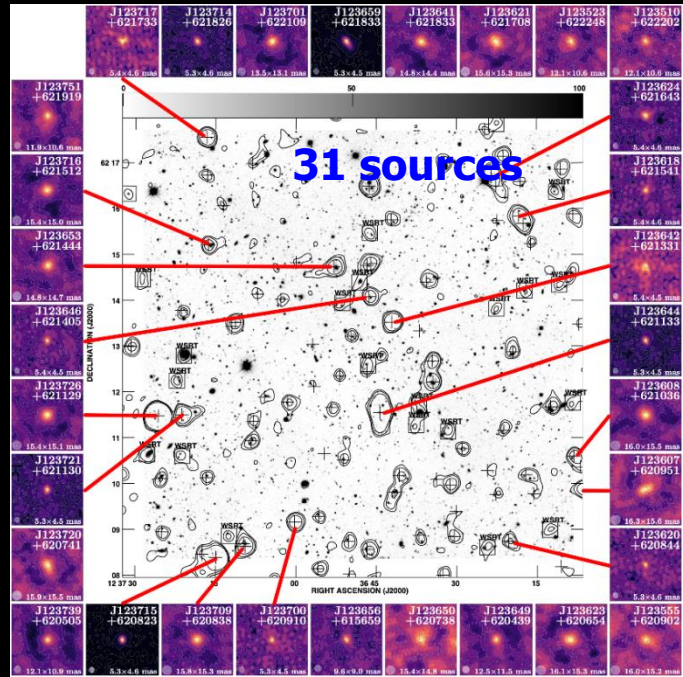
➤ Examples of Current Wide-Field VLBI Surveys:



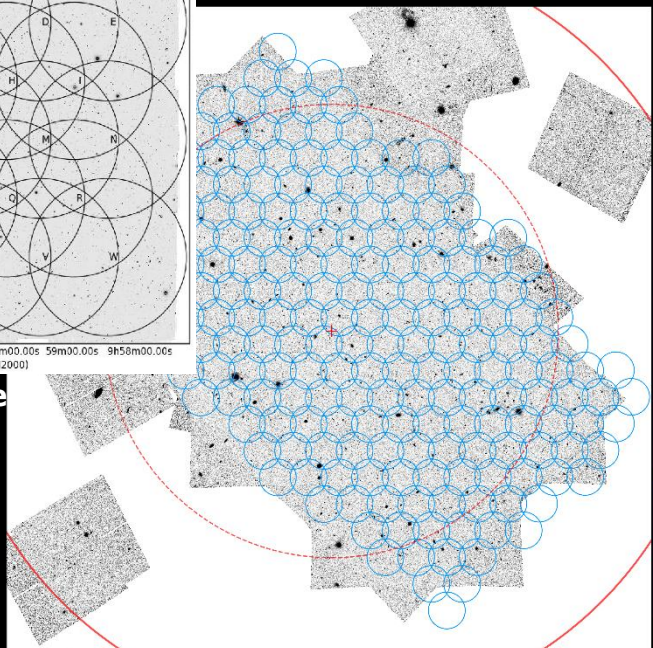
WSRT-Bootes field Garrett et al. 2005



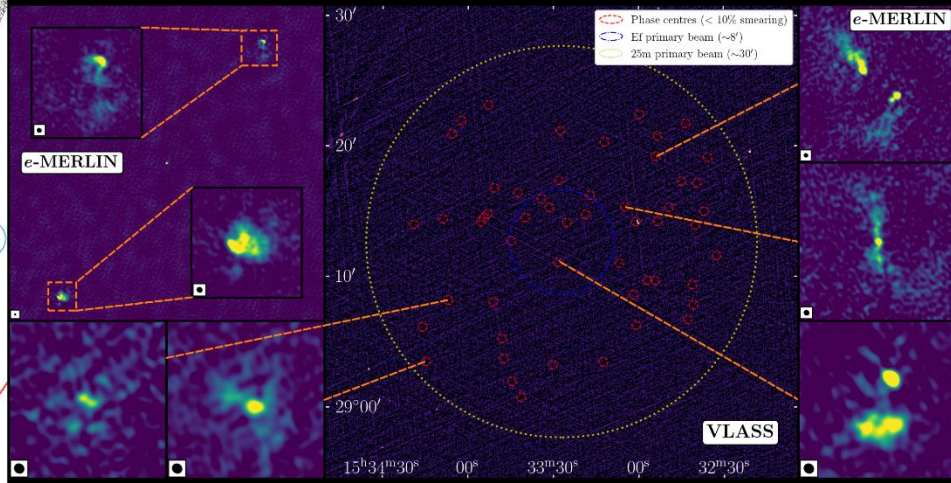
EVN-GOODS North Radcliffe et al. 2018



VLBA-COSMOS Herre 2017, 2018



VLBA-GOODS North, Deane+2024, Njeri+2024



SPARCS-N (EVN+eMERLIN) Njeri+2023



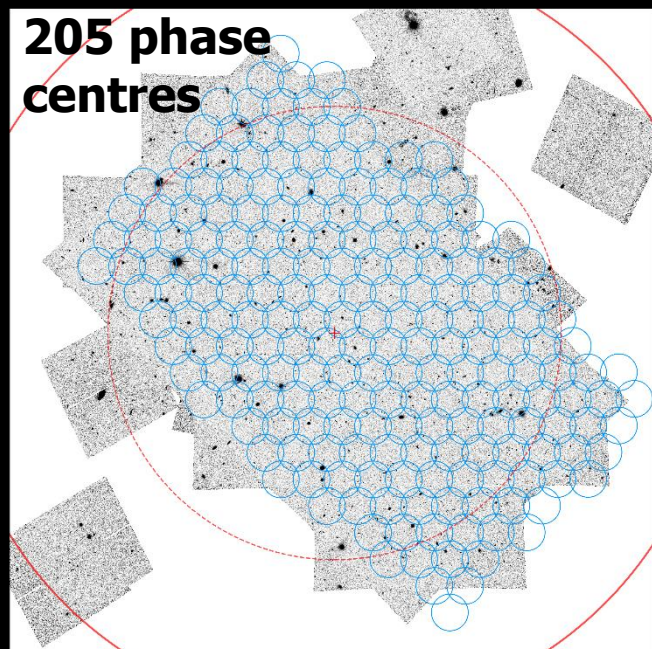
# ❖ Wide-Field EVN & VLBA GOODS-North 1.4 GHz Surveys

## VLBA 1.6 GHz GOODS-N Survey Deane+24, Njeri+24, Radcliffe+ in prep

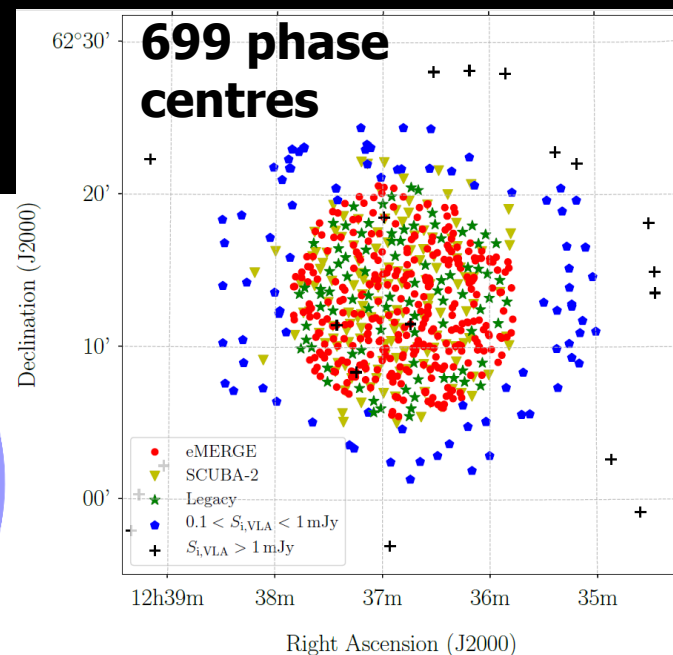
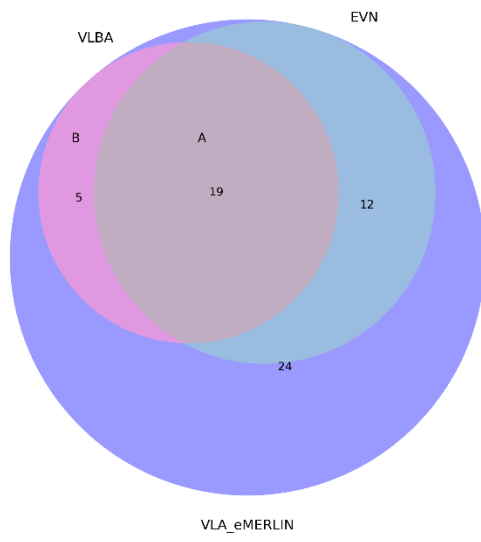
- ❑ 9' diameter centred on HDF
- ❑ r.m.s =  $\sim 10$   $\mu\text{Jy}/\text{beam}$
- ❑ resolution = 6 mas
- ❑ Contiguous coverage of CANDELS 205PC
- ❑ 24 sources at  $5.5\sigma$
- ❑ Unique extraction method using ancillary data

## EVN 1.5 GHz GOODS-N Survey Radcliffe+2018, 2021

- ❑ 15' diameter in area centred on HDF
- ❑ r.m.s =  $\sim 9$   $\mu\text{Jy}/\text{beam}$
- ❑ resolution = 5 mas
- ❑ Pre-selected targets 699PC
- ❑ 31 sources at  $7.0\sigma$

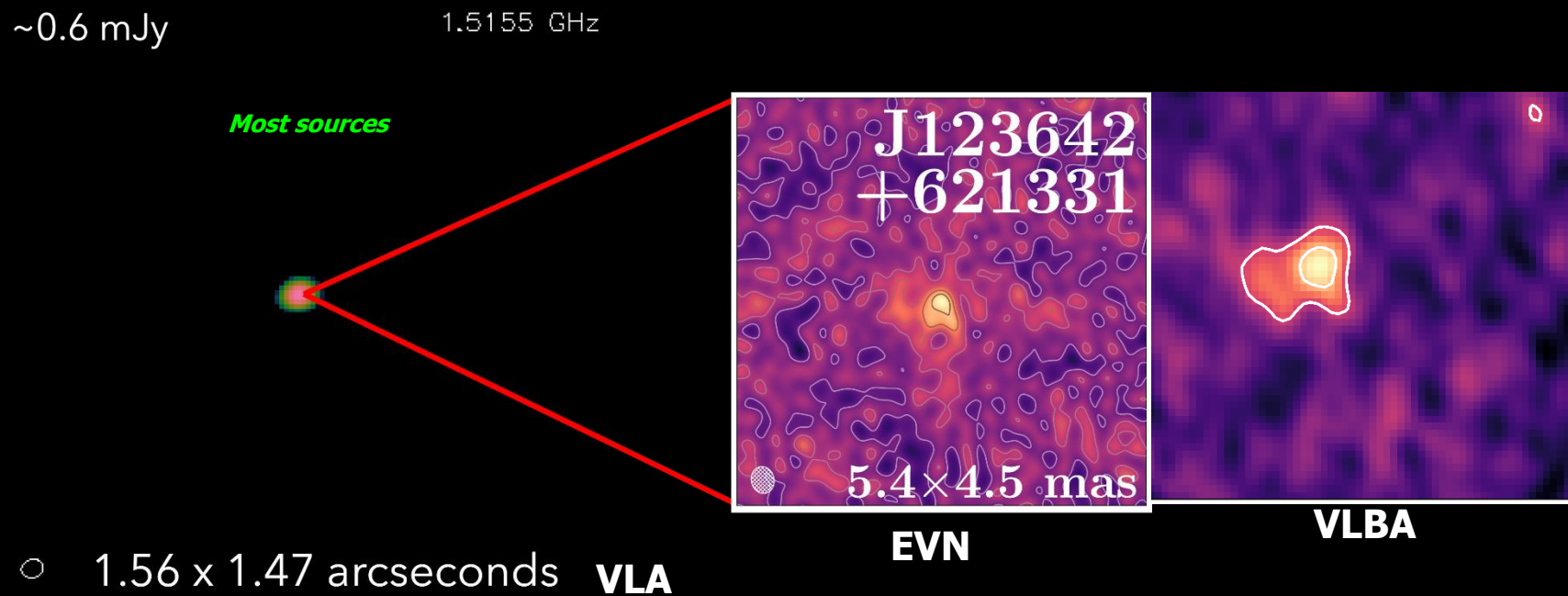
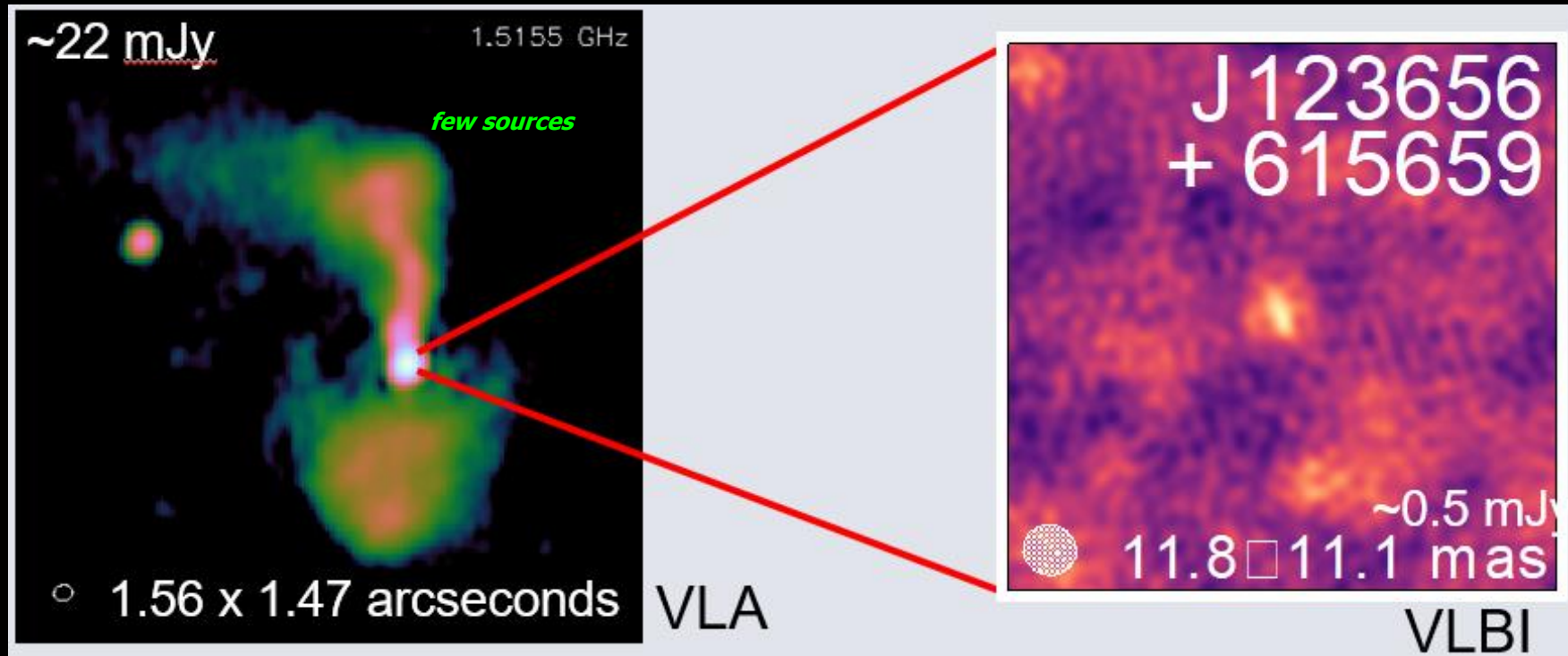


**$z = 0.5 - 4.4$**



# Science with VLBI

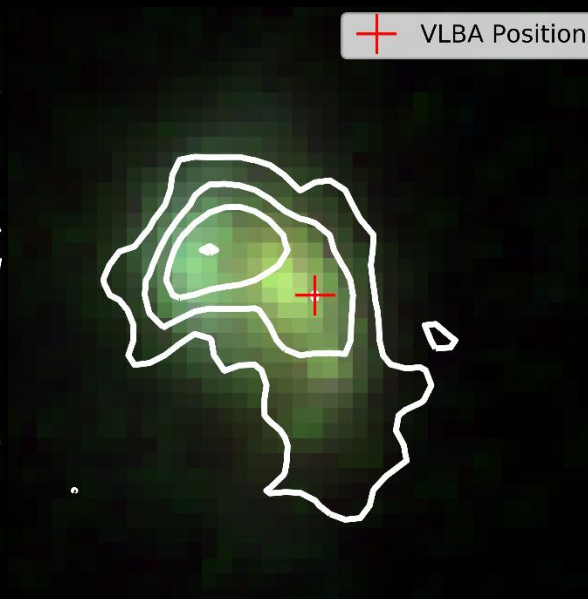




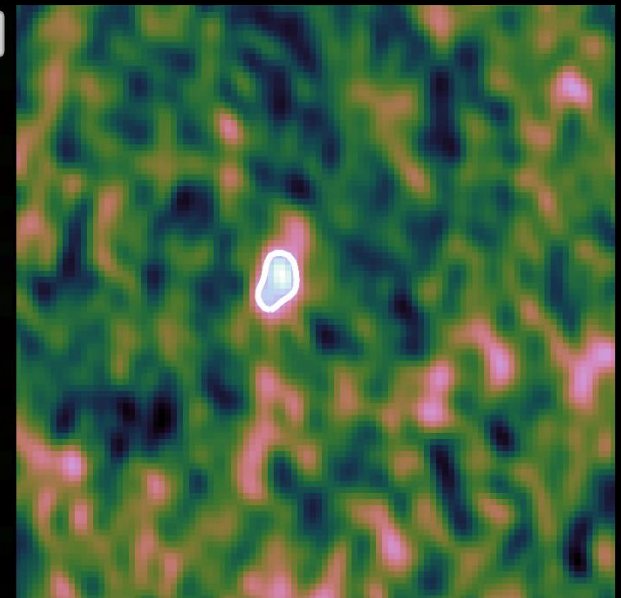
# Merging Galaxy Systems



JVLA



eMERLIN

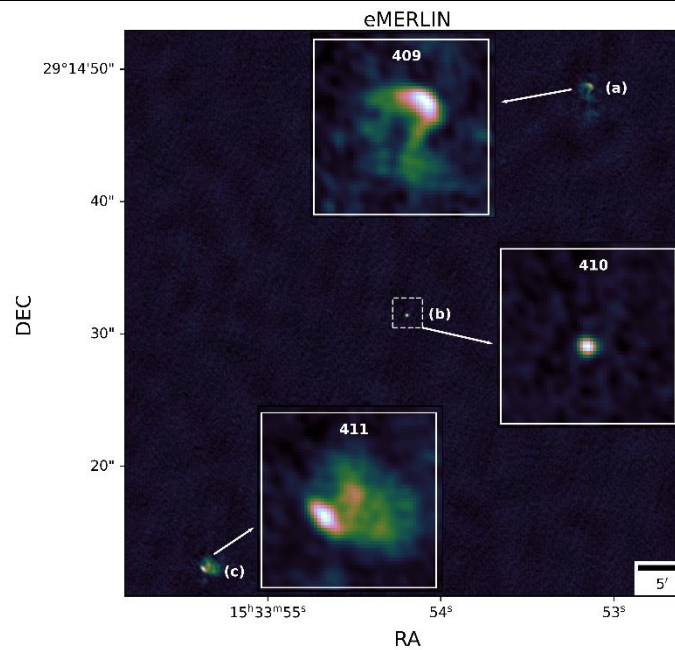
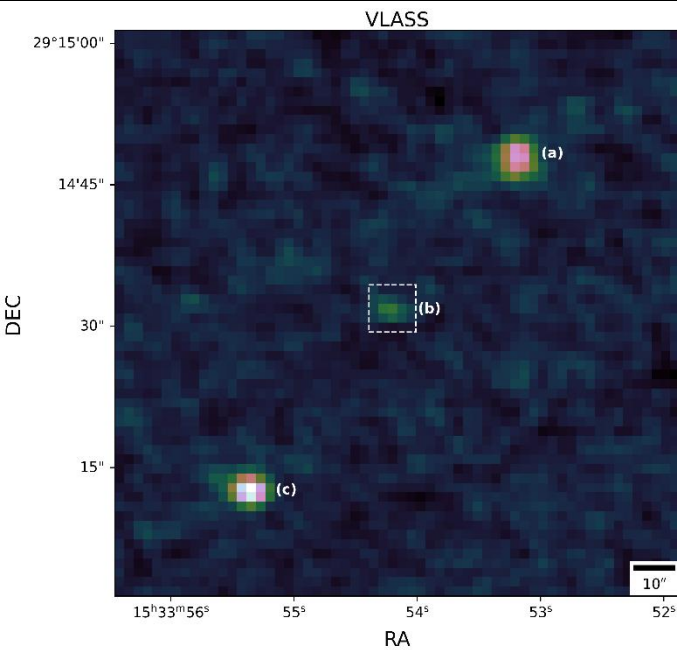


VLBA

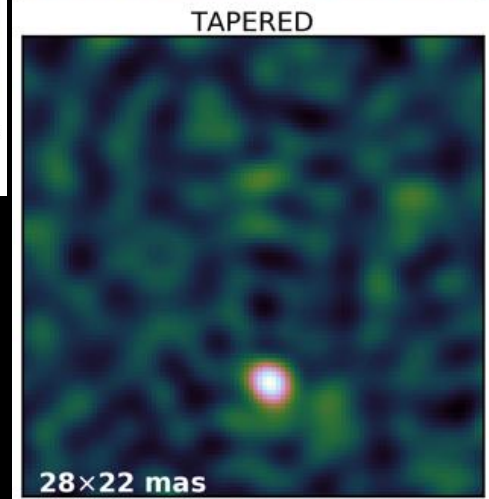
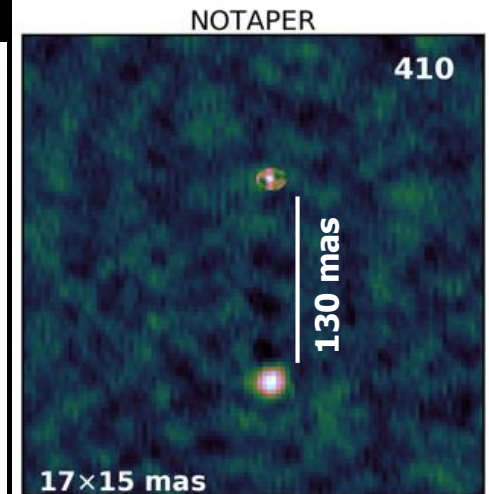
- $z \sim 1.224$       $T_B \sim 8.6 \times 10^6 \text{ K}$       $L_{1.5\text{GHz}} \sim 6.7 \times 10^{27} \text{ W/Hz}$
- VLBA S/N  $\sim 5.7$ : (source detected in ancillary data)
- VLBA position coincident with a second radio peak in eMERLIN
- Merging galaxy system: SF & AGN co-evolving system
- Merging galaxy systems: require VLBI



## ❖ Serendipitous discovery?



*Njeri+23*



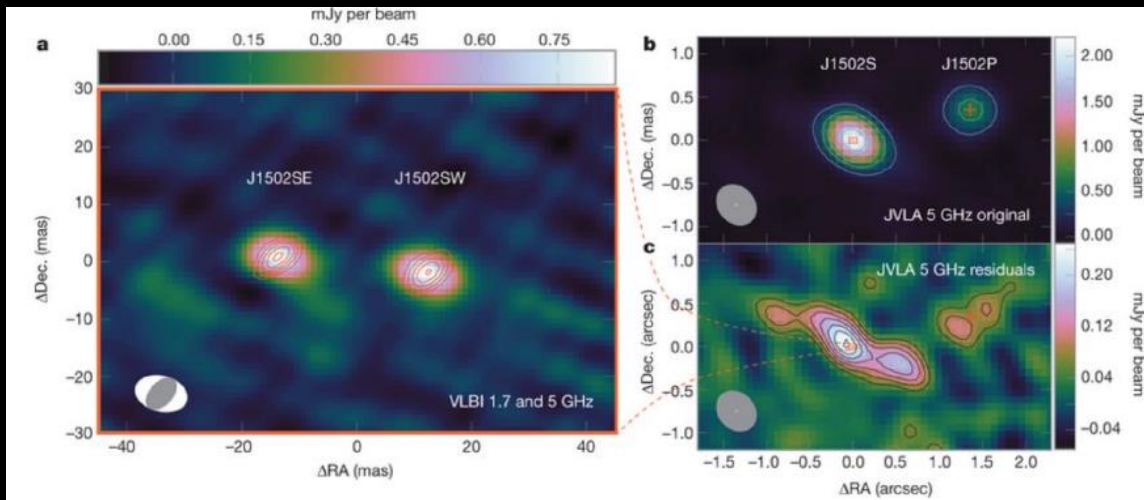
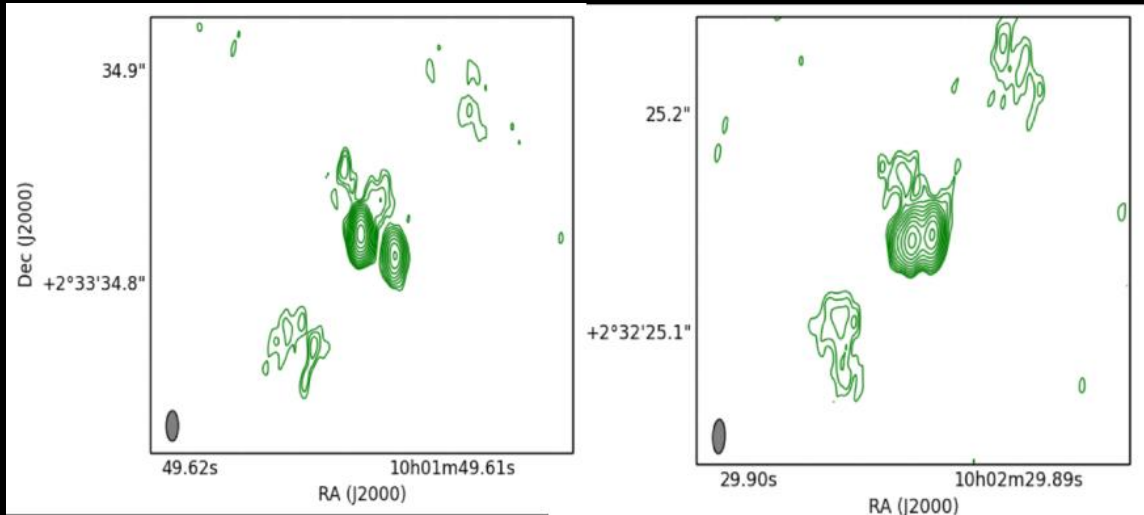
*Dual AGN/binary SMBH?*



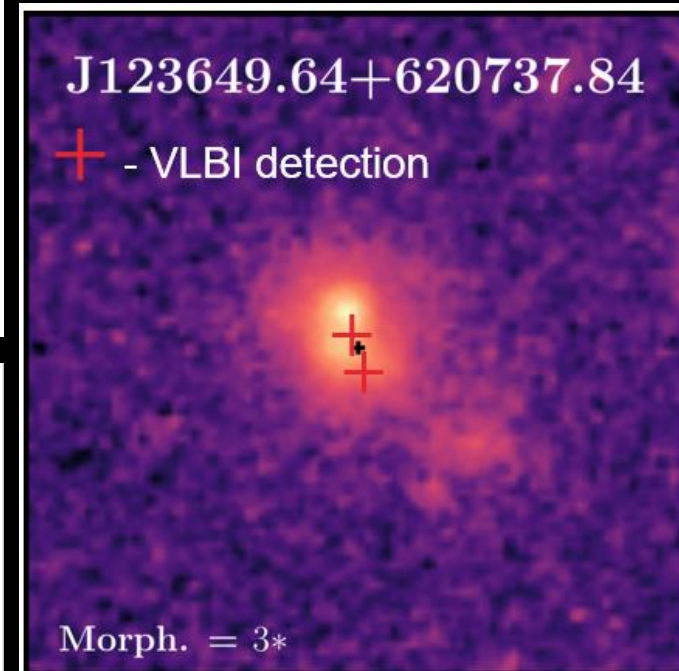
# Some binary SMBHs

17

*Herrera-Ruiz+17*

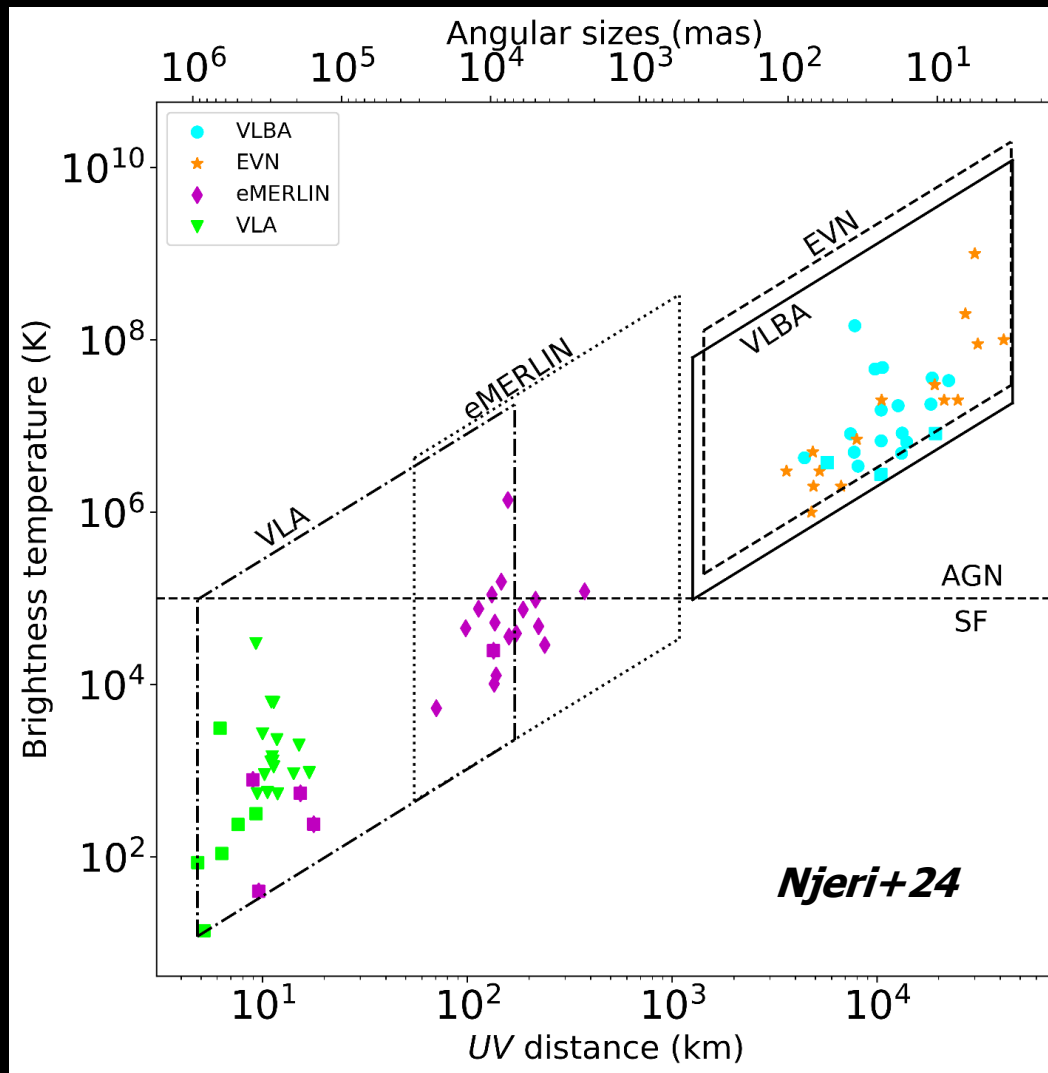


*Triple black hole system - Deane+14*



*Radcliffe+ in prep*

## ❖ Brightness Temperature



- ❖ VLBI resolves AGN that would otherwise remain unresolved in VLA/eMERLIN and thus mis-identified as SFGs

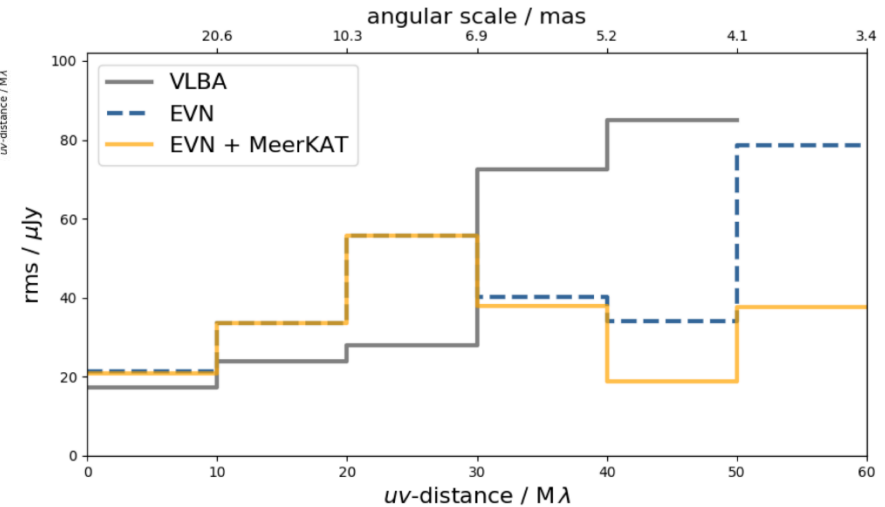
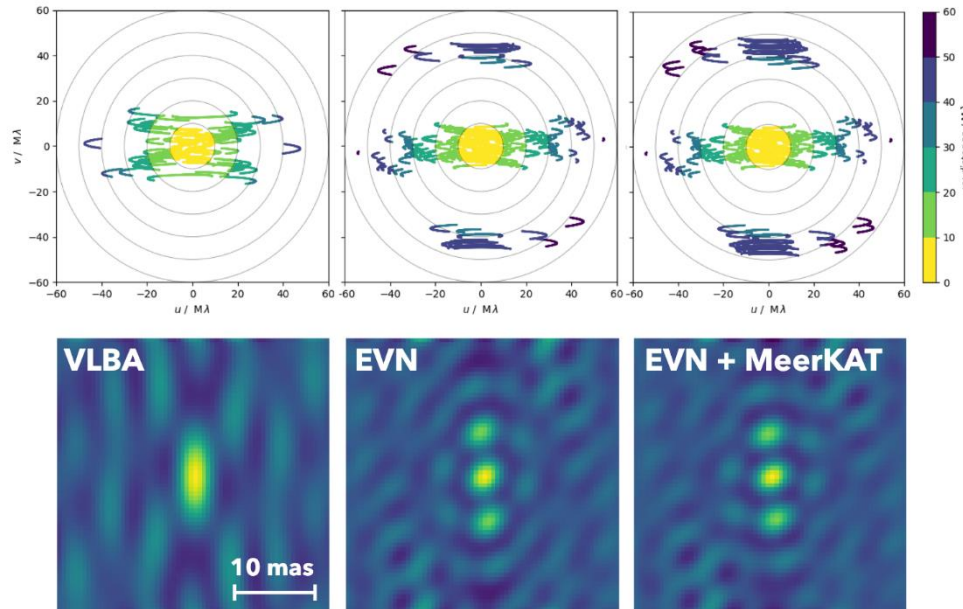
# SKA+VLBI: The Future



# ❖ MeerKAT+VLBI

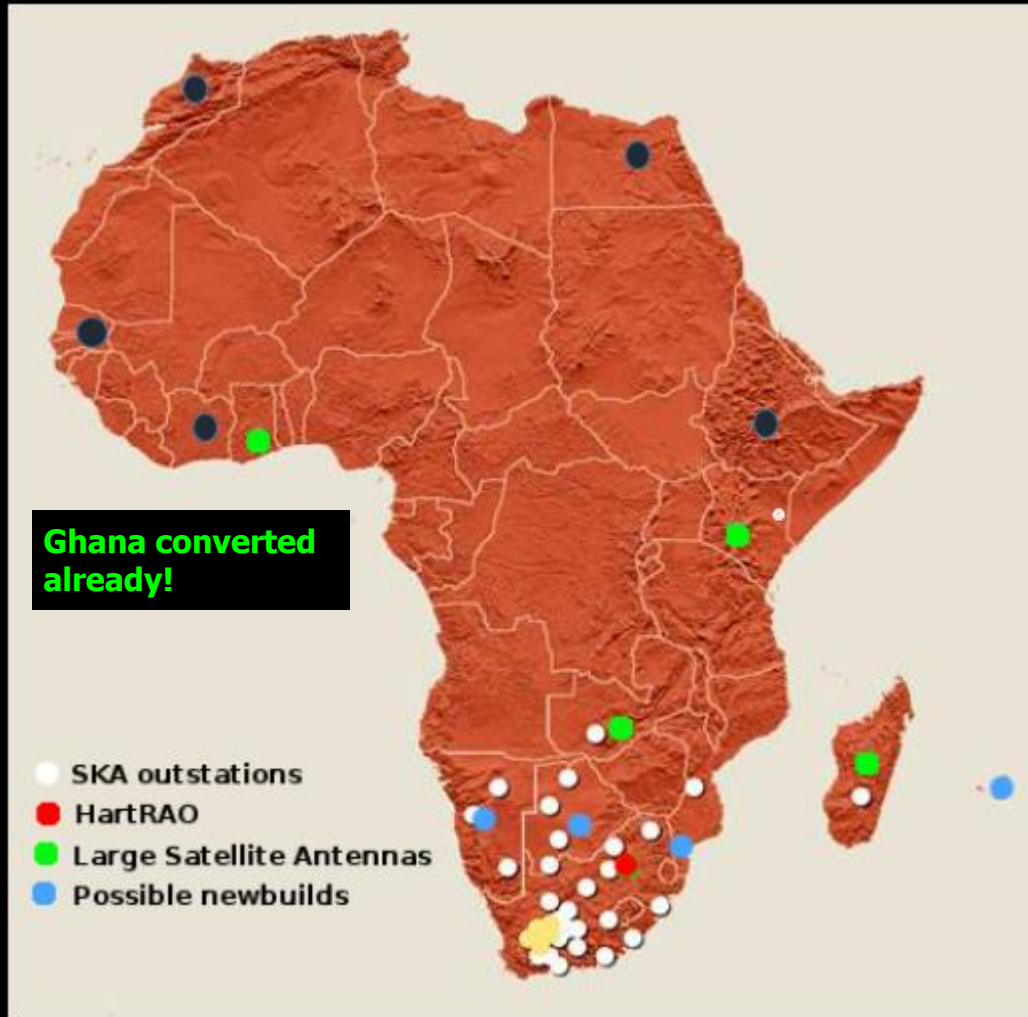
## The impact of MeerKAT to VLBI observations

*Deane 2017*



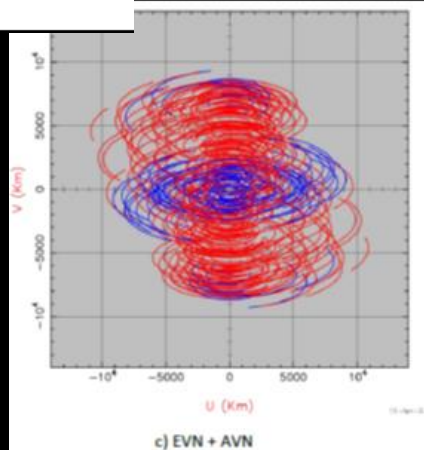
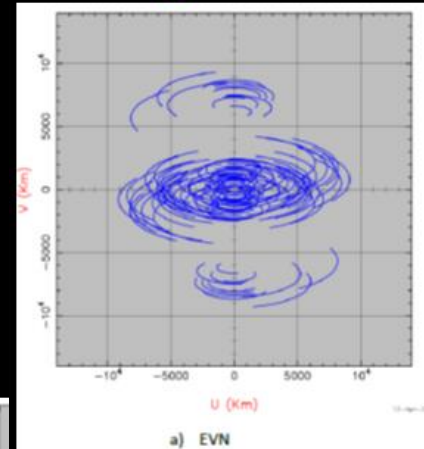
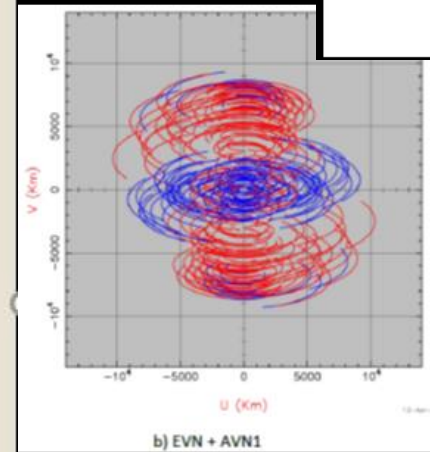
Simulated  
observations of  
XMM-LSS (-4.8  
deg),  $\Delta\nu = 128$   
MHz, 24 hr track

## SKA+VLBI... SKA+ African VLBI Network (AVN)



Ghana converted already!

Njeri (*MSc thesis*)



# **VLBI with MeerKAT:**

## **Science Case, Technical Description, and Potential Future Observing Modes Enroute to SKA-VLBI**

A White Paper by the MeerKAT-VLBI Working Group

### **Abstract**

The past decade has seen significant advances in cm-wave VLBI performance and capabilities, including wider instantaneous bandwidth, new stations, flexible software correlation, and data transfer rates sufficient to enable high-sensitivity e-VLBI. The future inclusion of MeerKAT into global VLBI networks would provide further enhancement, particularly the dramatic sensitivity boost to  $> 7000$  km baselines. This White Paper provides an overview of the significant contributions MeerKAT-VLBI could make to a wide range of Galactic and extragalactic scientific pursuits, including the MeerKAT Large Survey Projects. It also provides a top-level technical description of the MeerKAT backend and observing mode capabilities, as relevant to VLBI operations and science opportunities. Finally, it outlines possible future technical capabilities aimed at making dramatic enhancements to MeerKAT-VLBI scientific potential enroute toward SKA-VLBI.

## ❖ Key takeaways:

- ❑ **Wide-field VLBI surveys have plenty of science-in waiting/few workers e.g. GOODS-N, SPARCS-N, COSMOS, Lockman Hole (also ILT), UDS, mJIVE**
- ❑ **EVN+eMERLIN resolution space = SKA-2 and the ngVLA!**
- ❑ **Multi-resolution (multiple instruments) at low & high resolutions = SKA-2 dataset: imaging using multiple arrays (VLA-eMERLIN-VLBI): an SKA2-like dataset! Key technical verifications relevant for SKA-pathfinders/precursors!**
- ❑ **Many SKA-MID fields will not be able to identify all extragalactic AGN (esp. without radio excess e.g. Radcliffe+2021)**
- ❑ **Insufficient resolution, No FIR telescopes , WISE too shallow & ALMA small FoV**
- ❑ **VLBI vital role in Identifying AGN in distant fields ('SKA-sky').**



