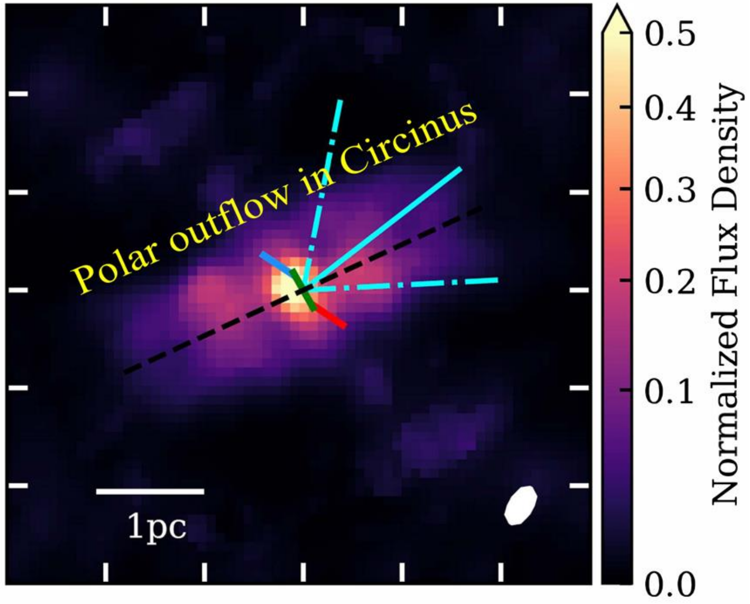
Exploring the innermost thermal outflows in nearby AGNs with the SKA1-mid

Dr. **Jun Yang**
Senior VLBI Support Scientist and Research Engineer
Onsala Space Observatory, Chalmers University of Technology, Sweden

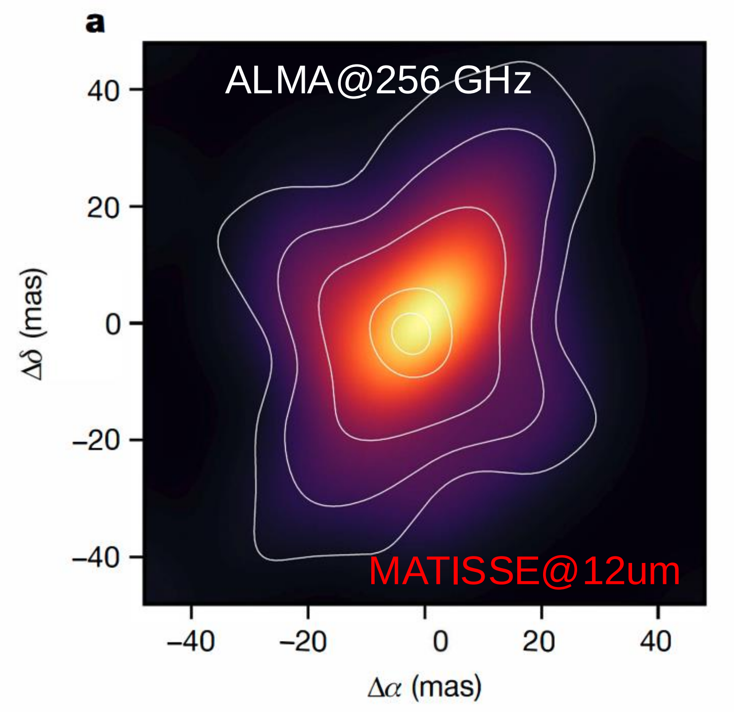
The 2nd National SKA Science Day Sweden, Gothenburg, 2024 Sep 10-11

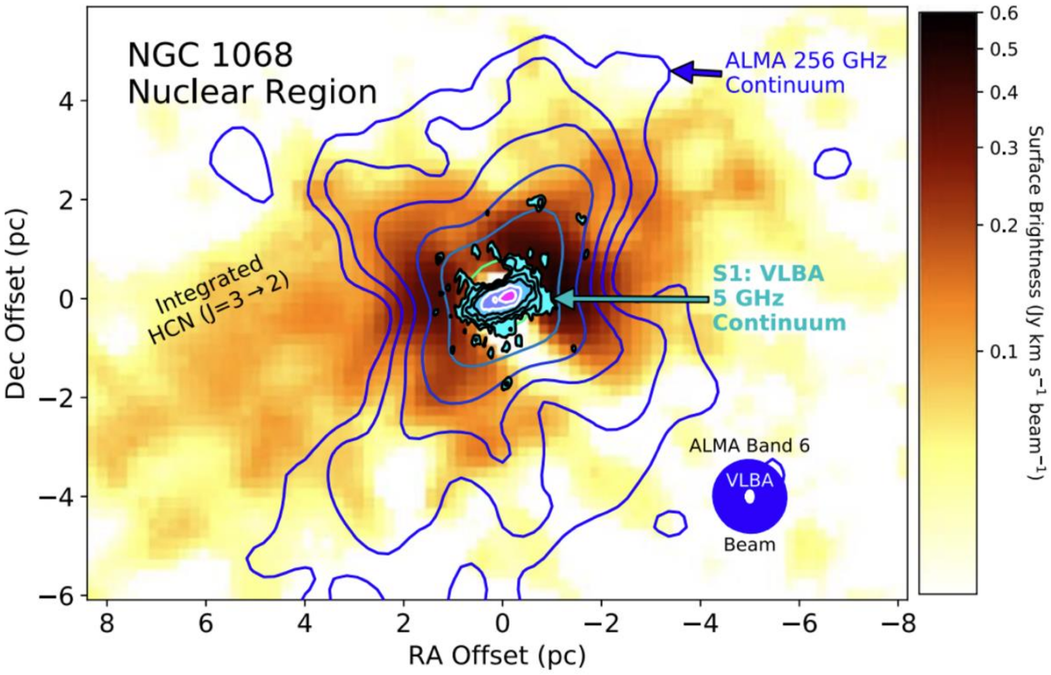
1. Introduction

- Polar outflows have free-free emission and are tightly connected with the (clumpy) torii with a temperature of <2000K.
- Key component to study AGN feedback and heavily accretion system.
- To date, it is clearly detected by VLT interferometer at 8-12 um in Circinus.
  - Nearly edge-on disk with PA ~ 45.
  - Polar outflow and radio jet: Marked in black dashed line.
  - Inner molecular masers: Marked as solid lines in blue, green and red according to their speed.
  - Optical ionization cone: Marked as cyan lines.
- Note that polar outflows on much smaller scales are frequently seen in young stellar objects (e.g. Anglada et al. 2018).



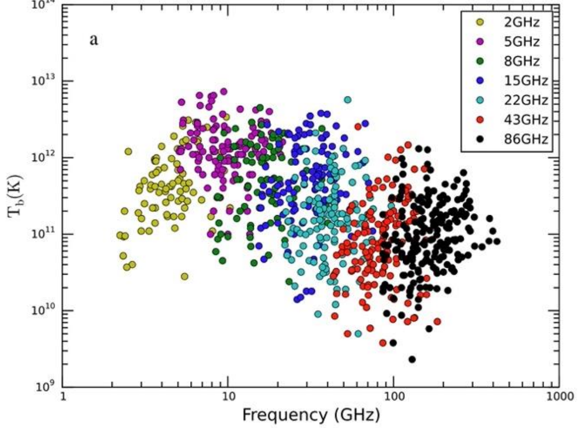
X-shaped wide-angle outflow in the pc-scale nuclear region of NGC 1068





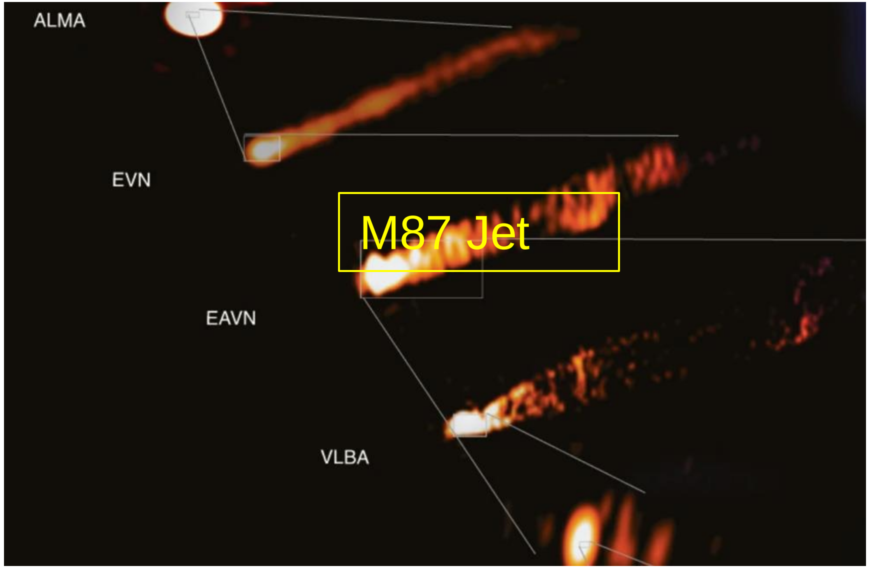
Left: Gámez Rosas et al. 2022. Right: Impellizzeri et al. 2019 and Gallimore et al. 2004

Differences from the jet bases



Jet bases in AGNs

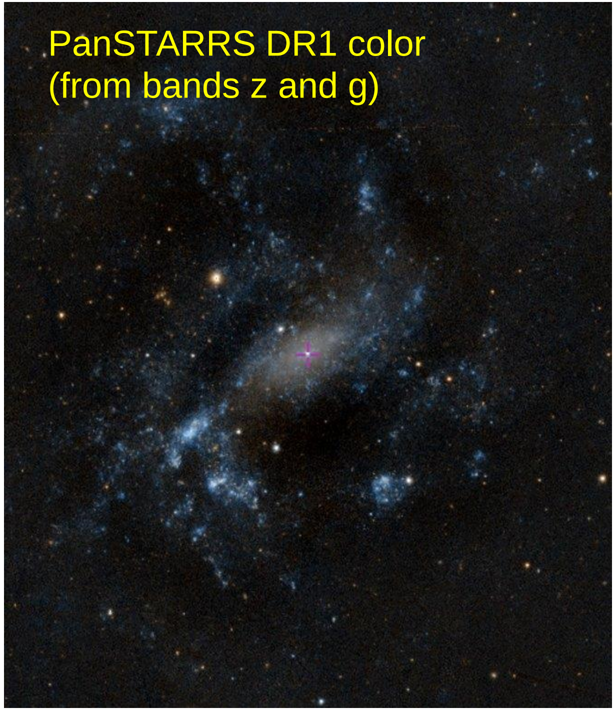
- Usually unresolved on pc scales, e.g. M87 jet (EHT collaboration).
- Flat or inverted radio spectrum at <~10 GHz.
- Non-thermal radio emission with Tb >~10^9 K (e.g. Fig. 4, Cheng et al. 2020).
- Strong variability.
- …



2. Detection of a polar outflow at cm wavelengths

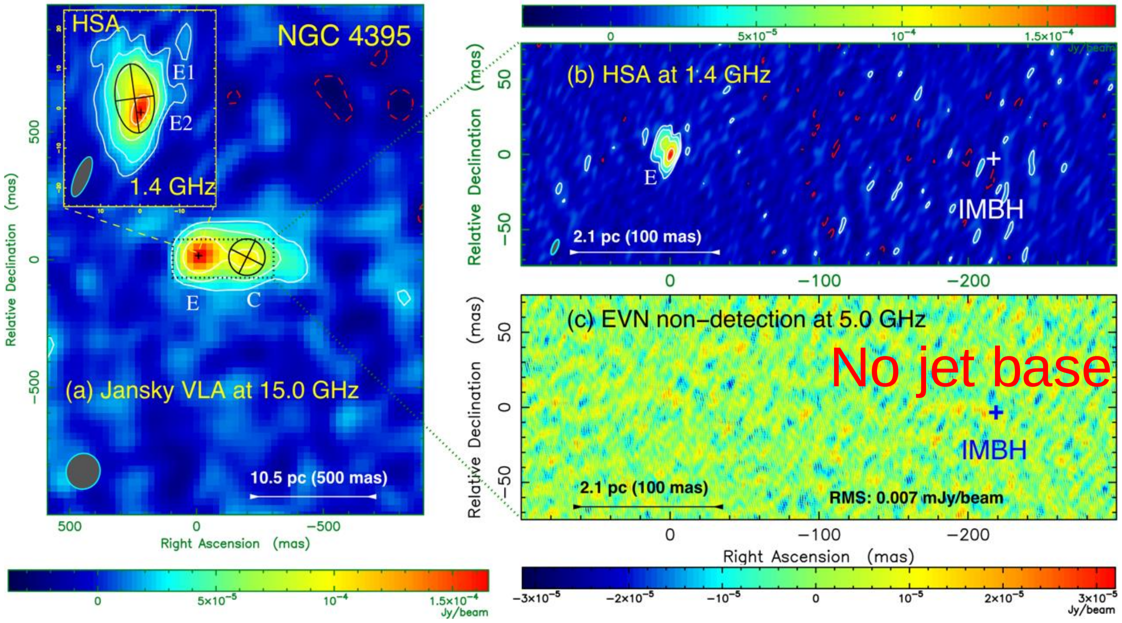
Nearby mini-AGN NGC 4395

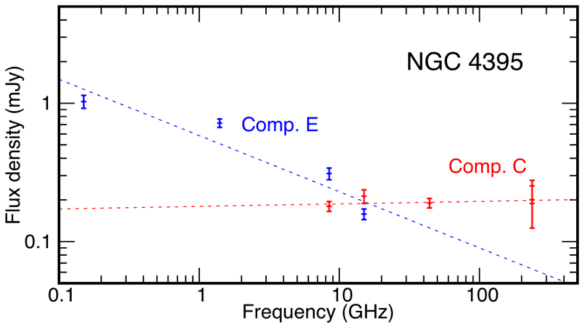
- A face-on dwarf galaxy at z=0.00106
  - Distance: 4.3 Mpc.
  - Map scale: 1 arcsec = 21 pc.
- AGN with the lowest black hole (BH) mass
  - **M_{BH} ~ 10^4 M_{sun}** from reverberation mapping (e.g. Woo et al. 2019, Gu et al. 2024).
  - Seyfert 1 galaxy with broad emission lines (e.g. Ho et al. 1995).
  - Bolometric Luminosity: $L_{bol}=10^{40\text{-}41}$ erg s^{-1} (Brum et al. 2019).
  - Bipolar O[III] outflow (Woo et al 2019).
  - Extremely weak star-formation activity in the nuclear region (e.g. Nandi et al. 2023).

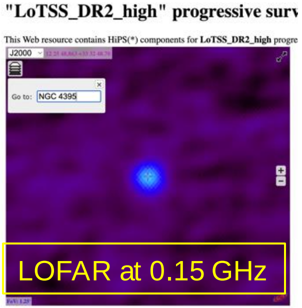


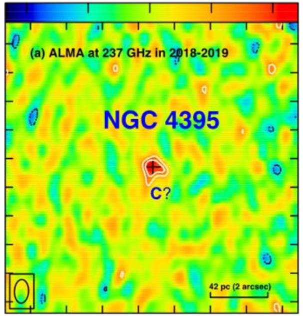
Revealing a pc-scale flat-spectrum radio nucleus in NGC 4395

E: Steep spectrum, compact on the VLA scales, detected only in the 1.4-GHz VLBI maps.
C: Near the optical centroid (+), flat spectrum, not detected in the VLBI maps.





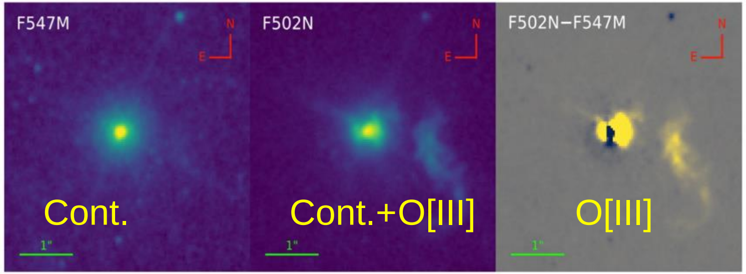


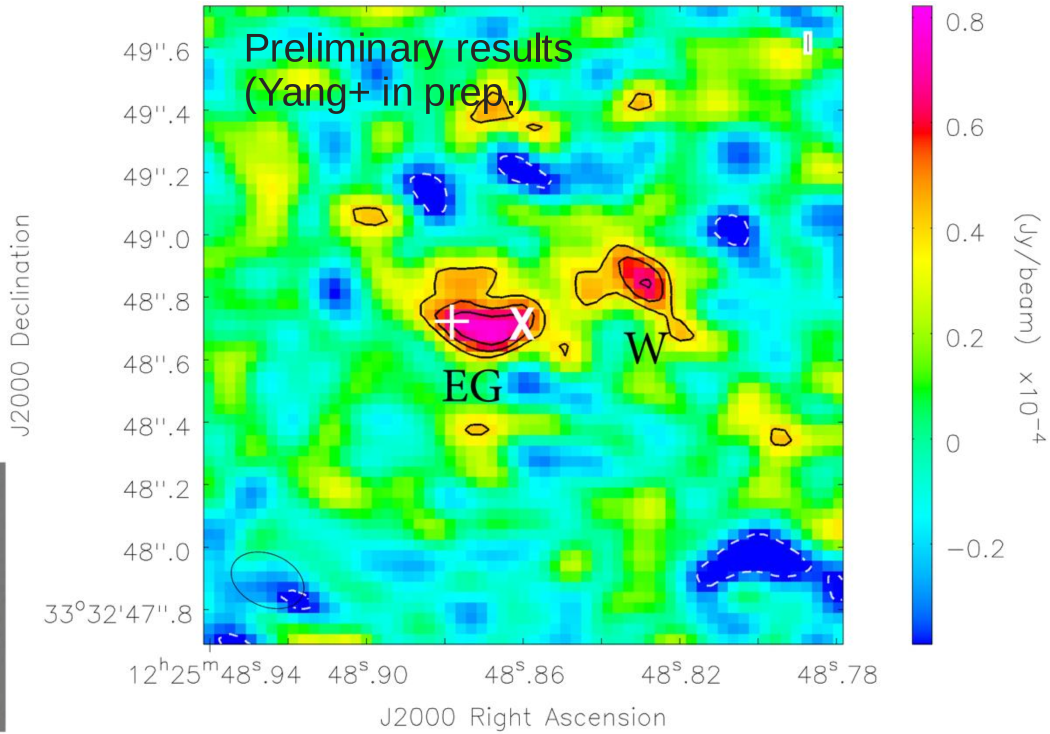


Reference: Yang et al. 2022

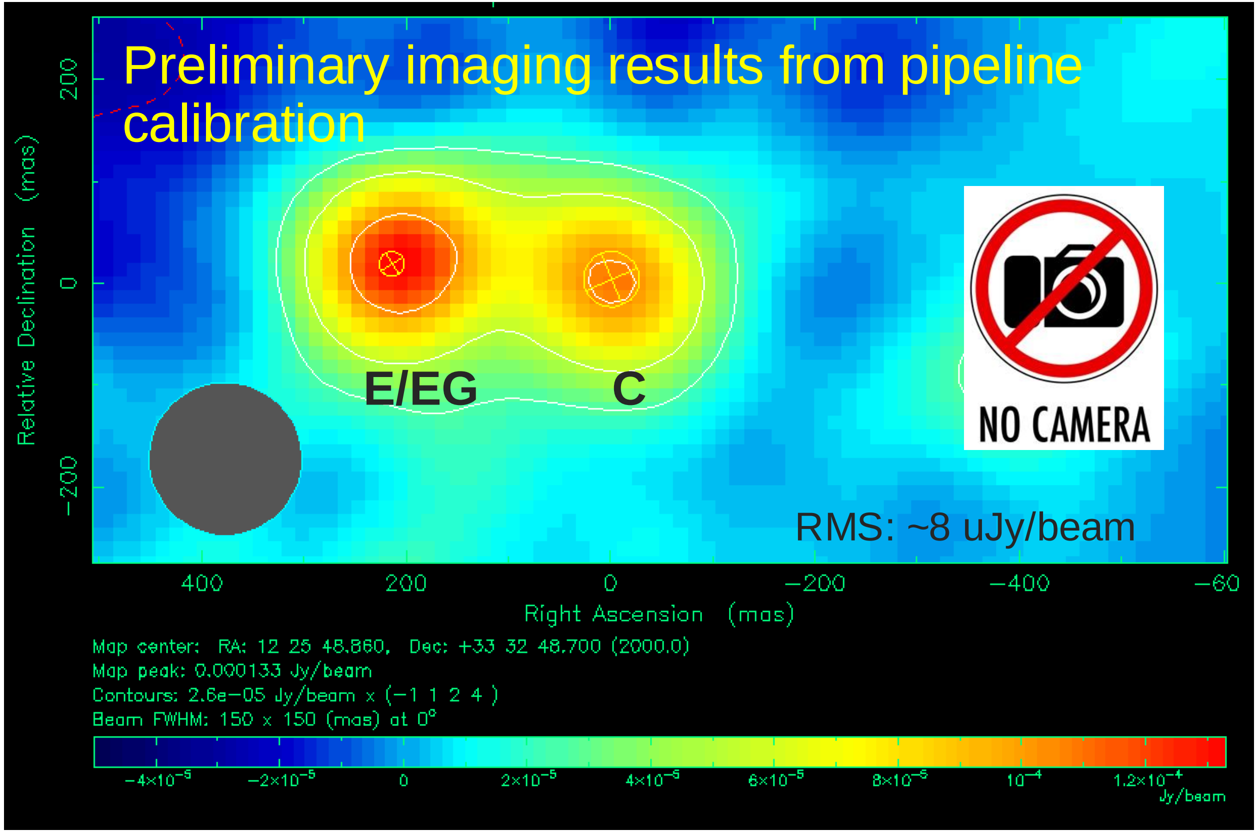
Detection of a polar outflow with the Jansky VLA at 43 GHz

- Revealing a two-sided structure
  - Radio component E (HSA): +
  - Optical centroid (Gaia position): X
  - Peak brightness: 85 uJy/beam (~50K).
  - Map RMS: 13 uJy/beam.
  - Contours: (-3, 3, 4, 5) x RMS.
- Components EG and W are consistent with the O[III] outflow direction revealed by HST observations (Woo et al. 2019).
- Component E: a terminal shock resulting from a polar outflow.





Deep e-MERLIN observations at 5 GHz



3. Revealing more polar outflows with the powerful SKA1-mid

Science goals

- Uncover weak AGN ejection activity in the unprecedented regime of L_R<~10^{38} erg s^{-1}.
- Study physical parameters (electron temperature, ionization fraction, mass loss rate, …) in the innermost nuclear regions with their low-frequency radio spectra.
- Probe AGN feedback in the nuclear regions and the co-evolution between galaxies and massive BHs.

Target sources

- Nearby (dwarf) galaxies and candidate AGNs.
- No hint of jet and star-forming activity.

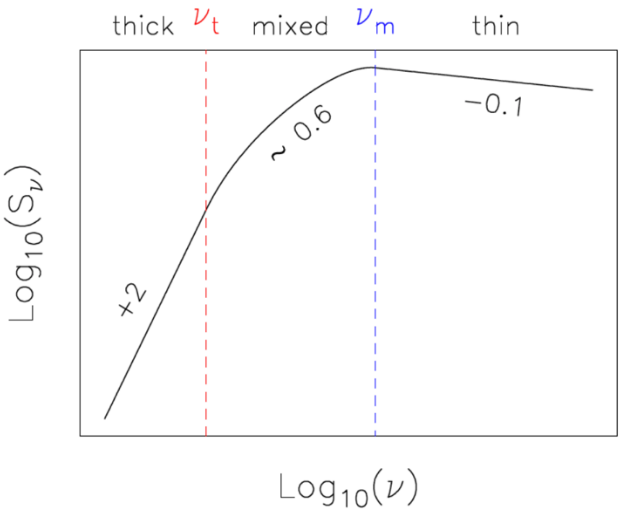


Figure 1. A theoretical radio spectrum derived by Reynolds (1986) for a typical thermal outflow. The two turn-over frequencies ν_t and ν_m represent the characteristic frequencies from purely optically thick to purely optically thin regimes.

SKA1-mid image sensitivity and resolution

Nominal frequency	110 MHz	300 MHz	770 MHz	1.4 GHz	6.7 GHz	12.5 GHz
Range [GHz]	0.05-0.35	0.05-0.35	0.35-1.05	0.95-1.76	4.6-8.5	8.3-15.4
Telescope	Low	Low	Mid	Mid	Mid	Mid
FoV [arcmin]	327	120	109	60	12.5	6.7
Max. resolution [arcsec]	9.7	3.5	0.7	0.3	0.06	0.03
Max. bandwidth [MHz]	300	300	700	810	3900	2 x 2500
Cont. rms, 1hr [μJy/beam] [a]	26	14	4.4	2	1.3	1.2
Line rms, 1hr [μJy/beam] [b]	1850	800	300	140	90	85
Resolution range for cont. & line rms [arcsec] [c]	12-600	6-300	1-145	0.6-78	0.13-17	0.07-9
Channel width (uniform resolution across max. bandwidth) [kHz]	5.4	5.4	13.4	13.4	80.6	80.6
Narrowest bandwidth, zoom mode [MHz]	3.9	3.9	3.1	3.1	3.1	3.1
Finest zoom channel width [Hz]	226	226	210	210	210	210

a. Continuum sensitivity at nominal frequency, assuming fractional bandwidth of $\Delta\nu/\nu = 0.3$

b. Line sensitivity at nominal frequency, assuming fractional bandwidth per channel of $\Delta\nu/\nu = 10^{-4}$ ($>10^{-6}$ will be possible]

c. The sensitivity numbers apply to the range of beam sizes listed

For more details refer to the document "Anticipated SKA1 Science Performance" (SKA-TEL-SKO-0000818 available on astronomers.skatelescope.org and at arxiv.org/abs/1912.12699)

4. Summary and outlook

- Our deep radio observations reveal unprecedented faint ejection activity in NGC 4395. It might be interpreted as a rarely-seen thermal polar outflow and a non-thermal terminal shock (Yang et al. in prep.).
- SKA1-mid is an ideal array to uncover a new population of faint radio AGNs with thermal polar outflows at cm wavelengths in the nuclear regions of nearby (dwarf) galaxies.

AVANCEZ

1829

CHALMERS

UNIVERSITY OF TECHNOLOGY