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CONAHCYT
CONSEJO NACIONAL DE HUMANIDADES CIENCIAS Y TECNOLOGÍAS

The deepest VLA radio surveys in the GOODS-N and CEERS fields

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Outline

- Why do we need deep, high-resolution extragalactic radio surveys?

- A census of the deep radio sky with the VLA

  3 and 10GHz surveys of the GOODS-N and CEERS fields

- Paving the way for the ngVLA

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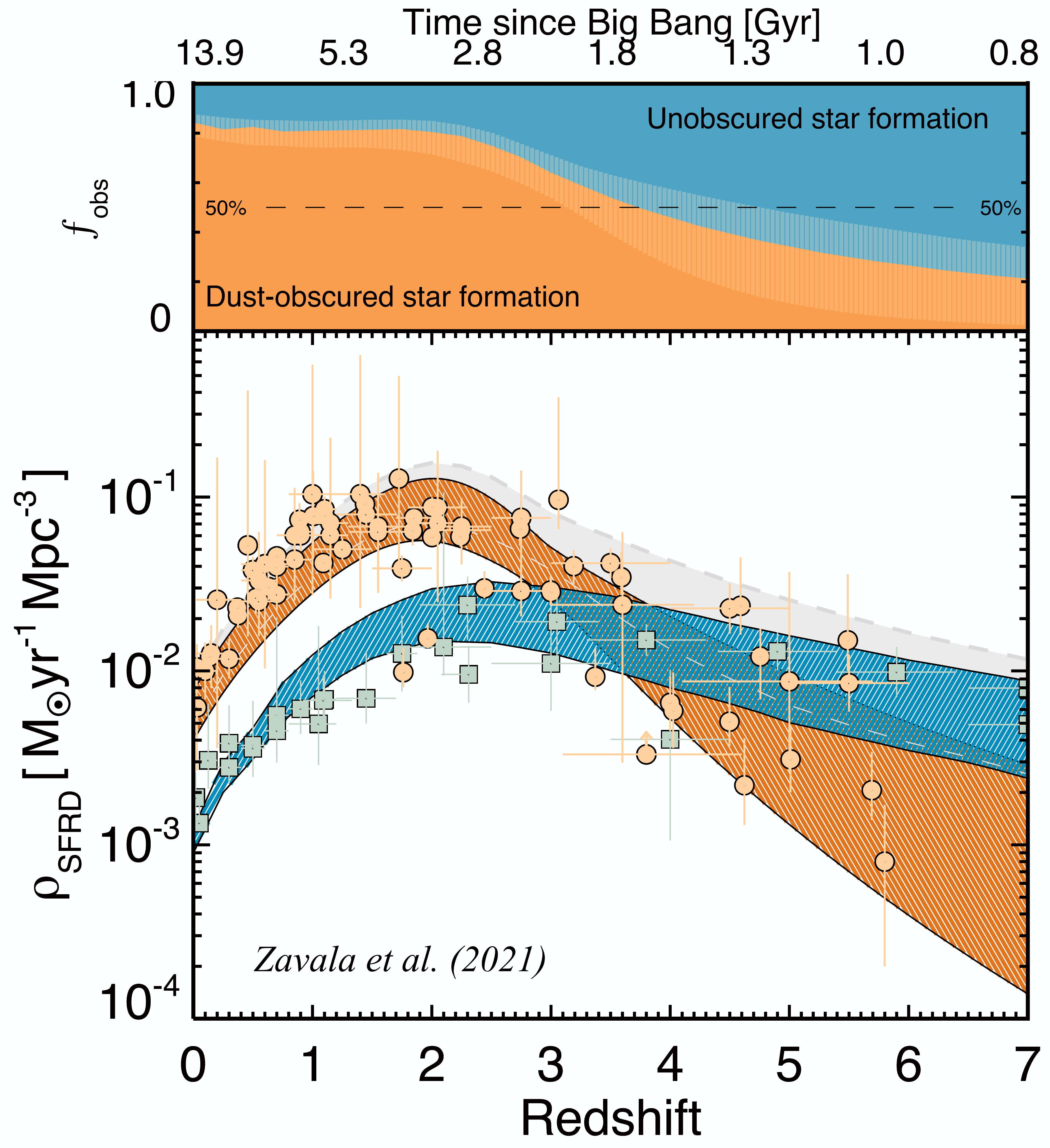
Key facts about deep radio continuum surveys

Deep radio continuum surveys are key to trace dust-obscured star formation and AGN across cosmic time.



Most star formation in galaxies remains obscured by dust out to $z \approx 4$.

↓

Deep observations with radio/sub-mm interferometers

Mauch et al. (2020)

Larger primary beam (FoV) in the radio regime!

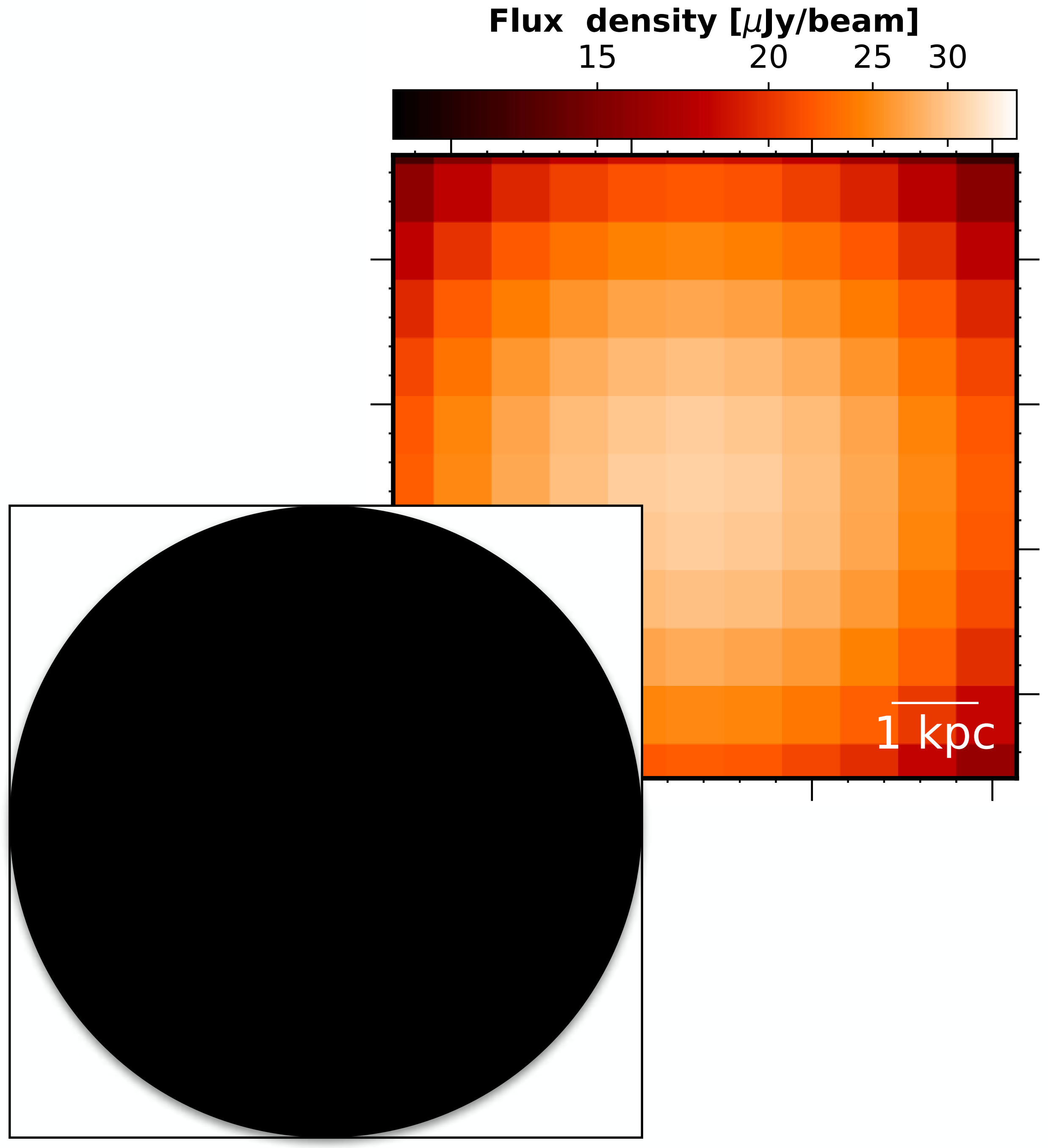
Richards 2000, Schinnerer et al. 2010, Owen 2018, Smolčić et al. 2017, Heywood et al. 2021 …

Key facts about deep radio continuum surveys

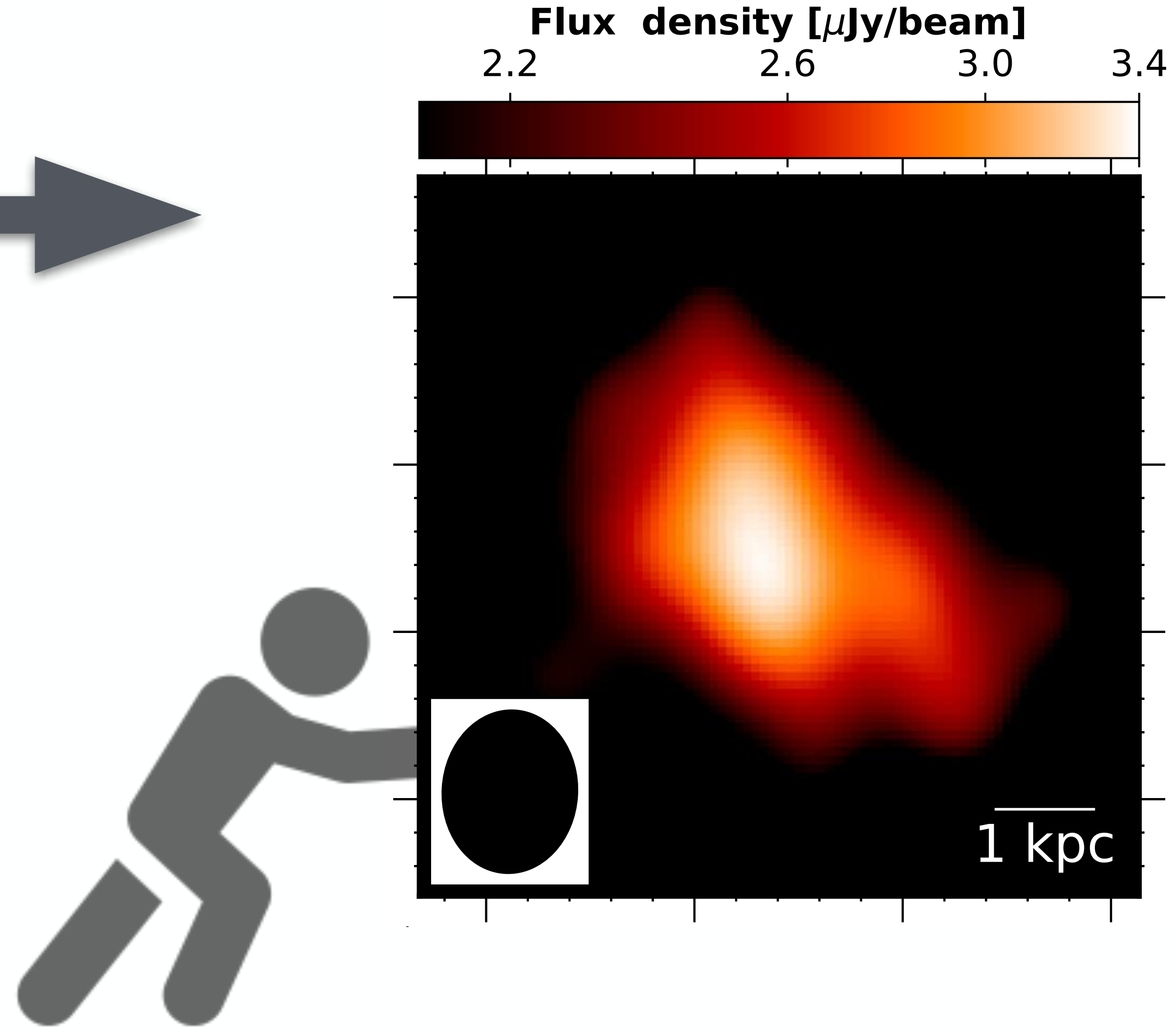
However, most deep radio continuum surveys have angular resolutions > 1arcsec.

A $z \approx 1.2$ star-forming disk "observed" with a 1.0, 0.2, and 0.05 arcsec resolution at 10GHz.

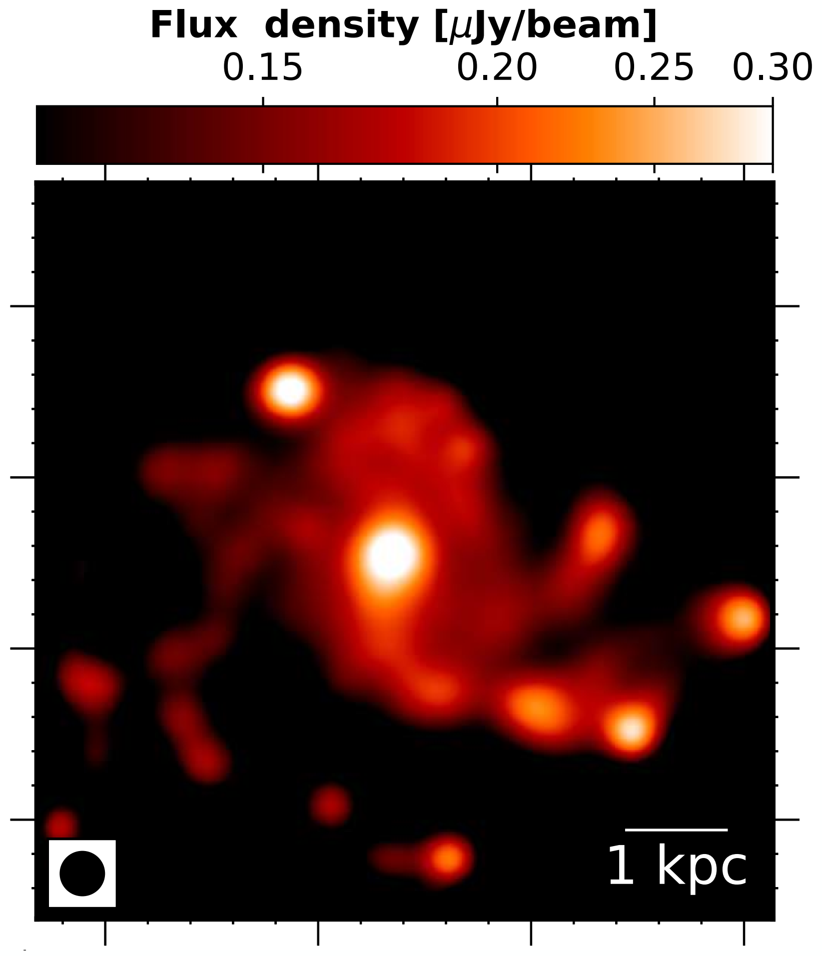
What we mostly see with current facilities:



The best we can get with current facilities:



What SKA/ngVLA will see:



To carry out spatially resolved analysis of radio-detected, high-z, star-forming galaxies, we need to push the resolution/sensitivity limits of current facilities.

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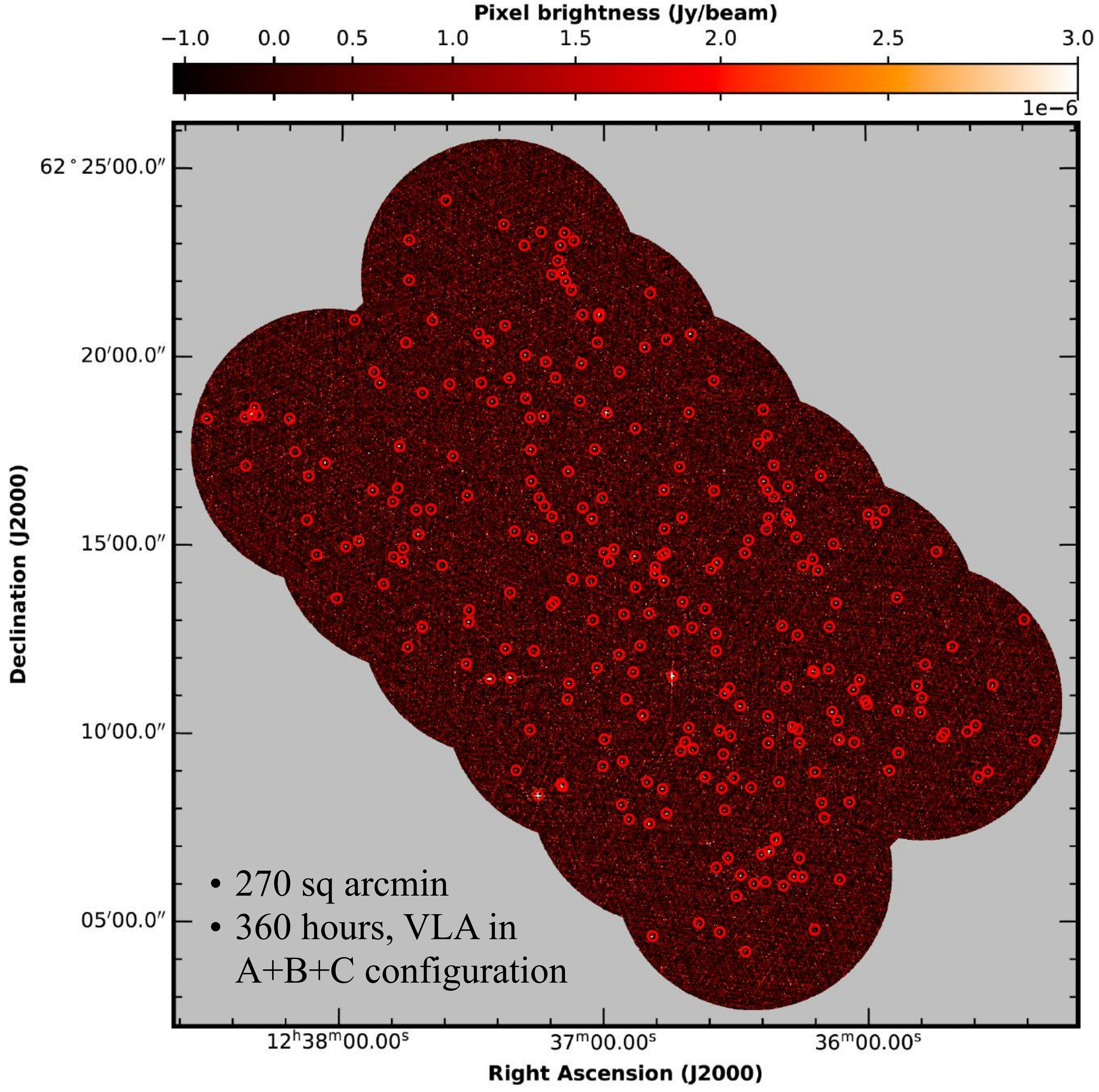
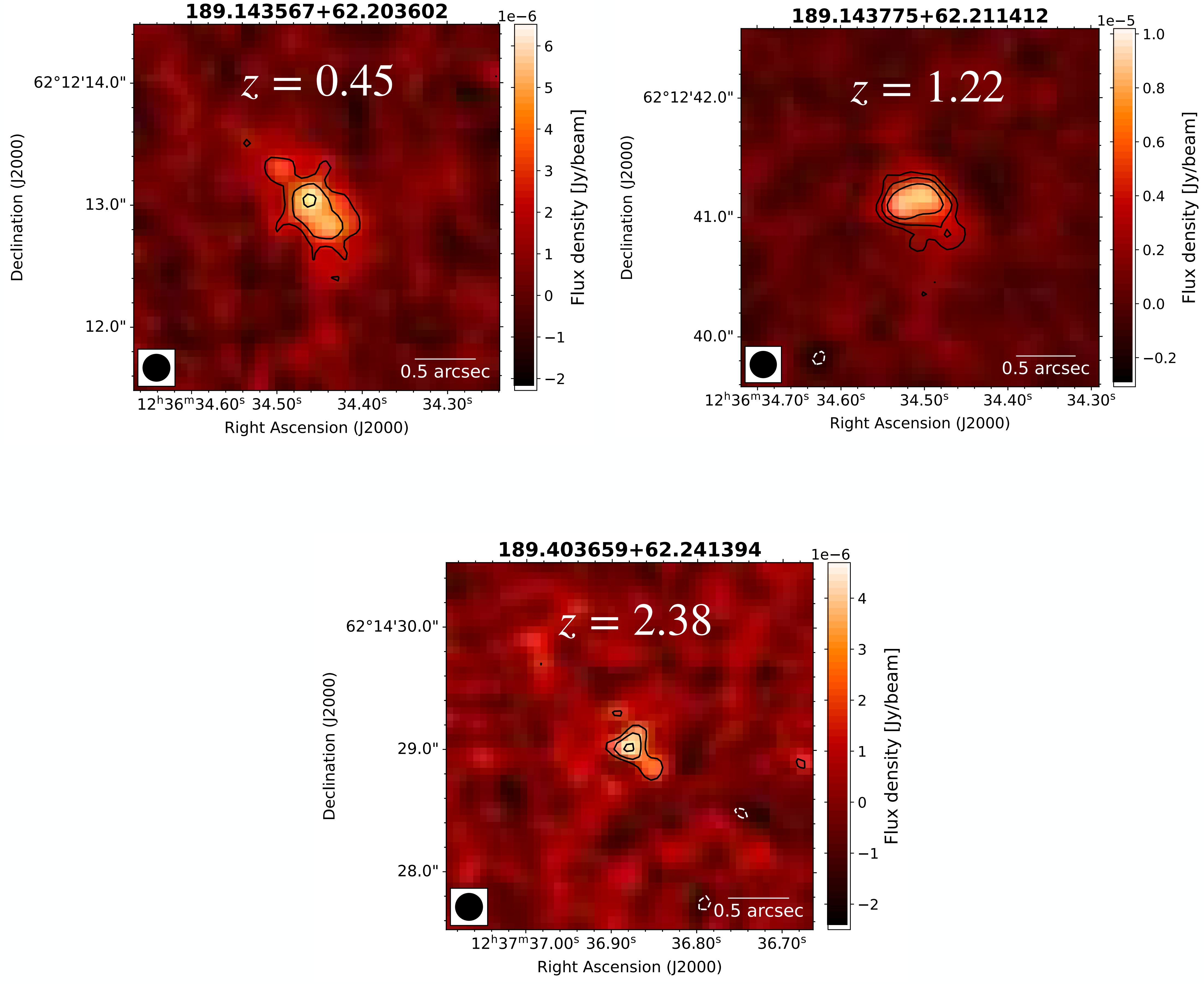
A deep 10GHz survey of GOODS-N

The first high-resolution, high-frequency observational campaign to fully map an extragalactic deep field.

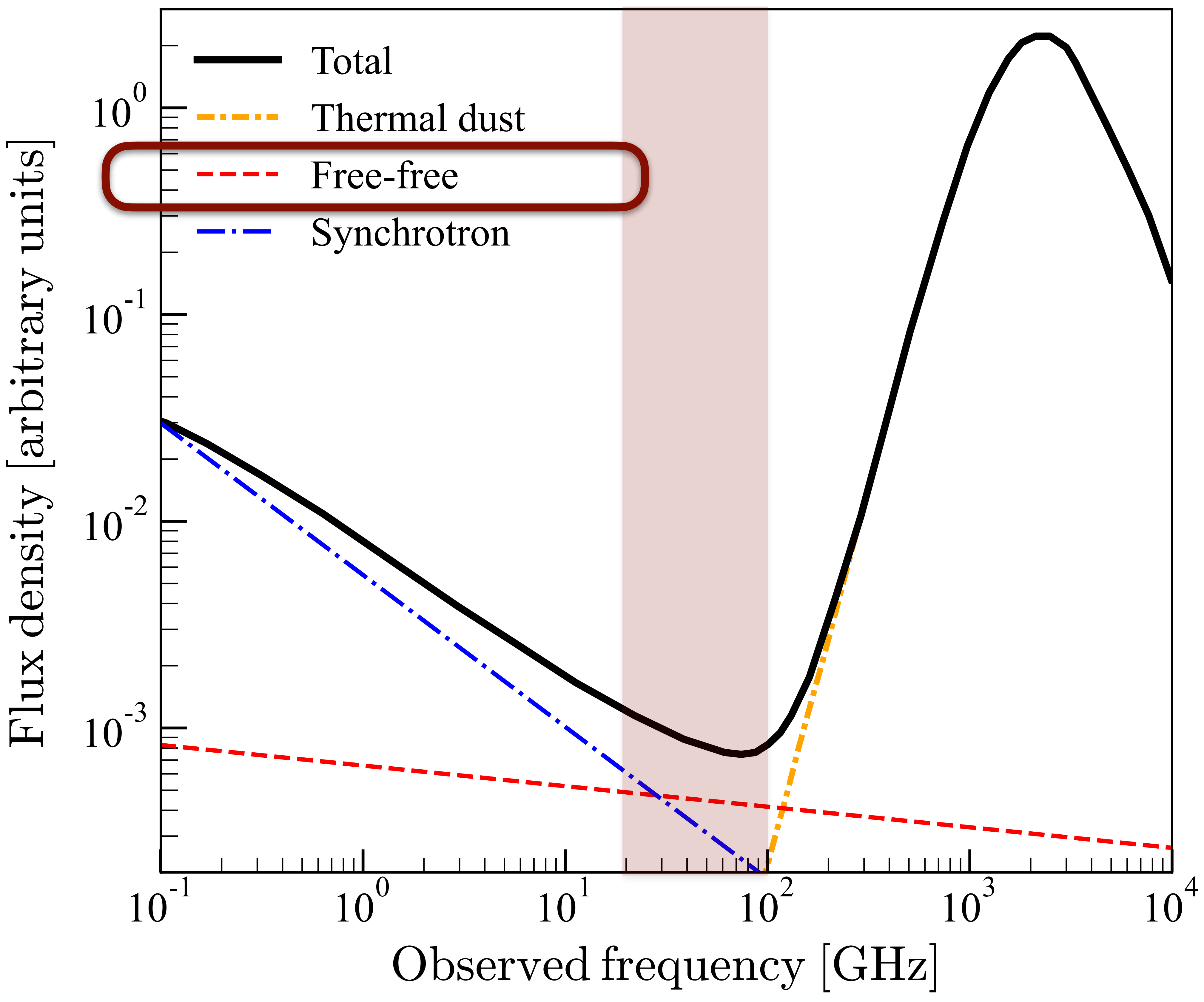


Jiménez-Andrade et al. (2024)



256 radio sources detected with SNR ≥ 5 at $0.5 \lesssim z \lesssim 6$

Why should we focus on high-frequency radio observations?



- At high radio frequencies, the ionizing photon rate is directly proportional to the thermal spectral luminosity:

$$Q(H^0) \propto L^T$$

—> better tracer of current star formation in galaxies.

- 10GHz observations are dominated by free-free emission from star-forming galaxies at $z > 1$.

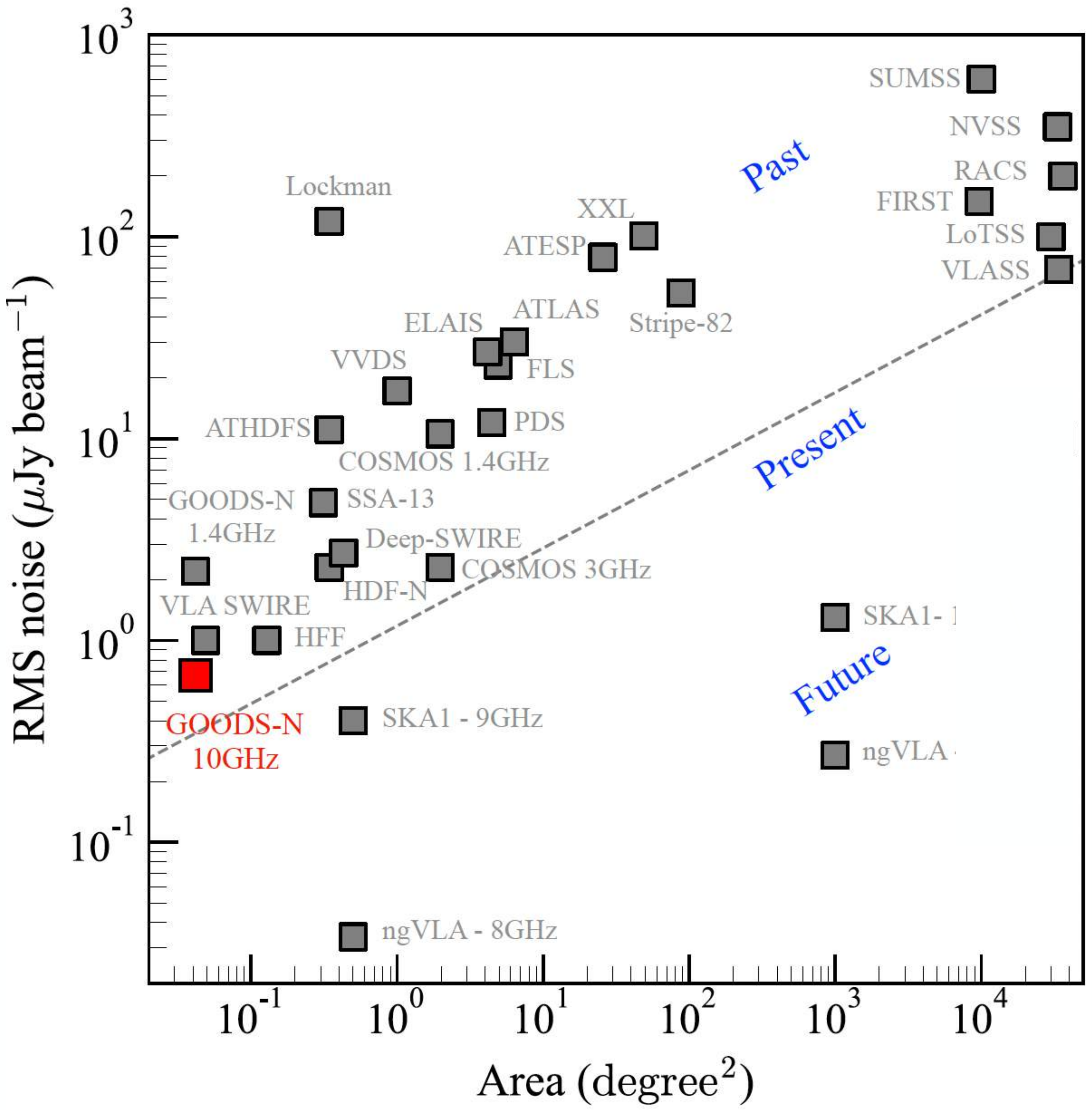
- Observations at high frequencies yield higher angular resolution imaging: PSF $\propto \nu^{-1}$.

Condon et al. 1992, Murphy et al. 2012, 2018, 2021 …

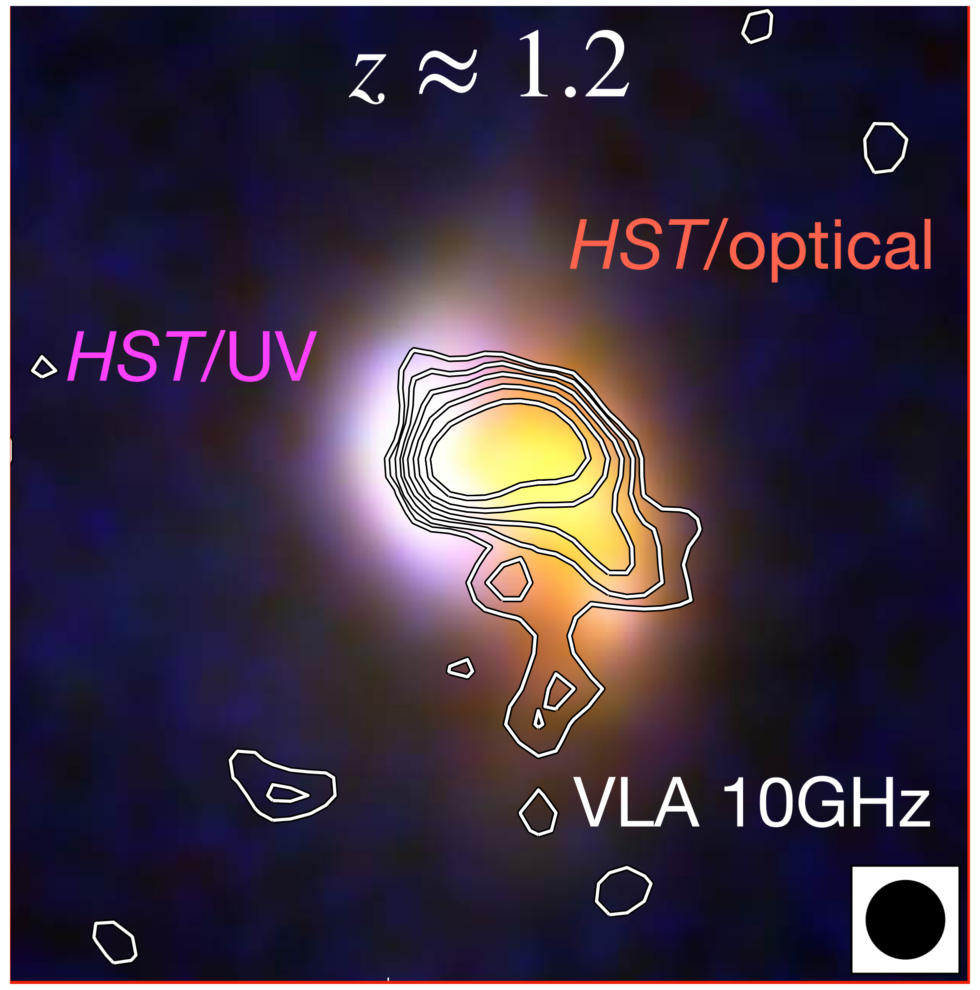
A deep 10GHz survey of GOODS-N

Noise rms ≈ 670 nJy beam^{-1}

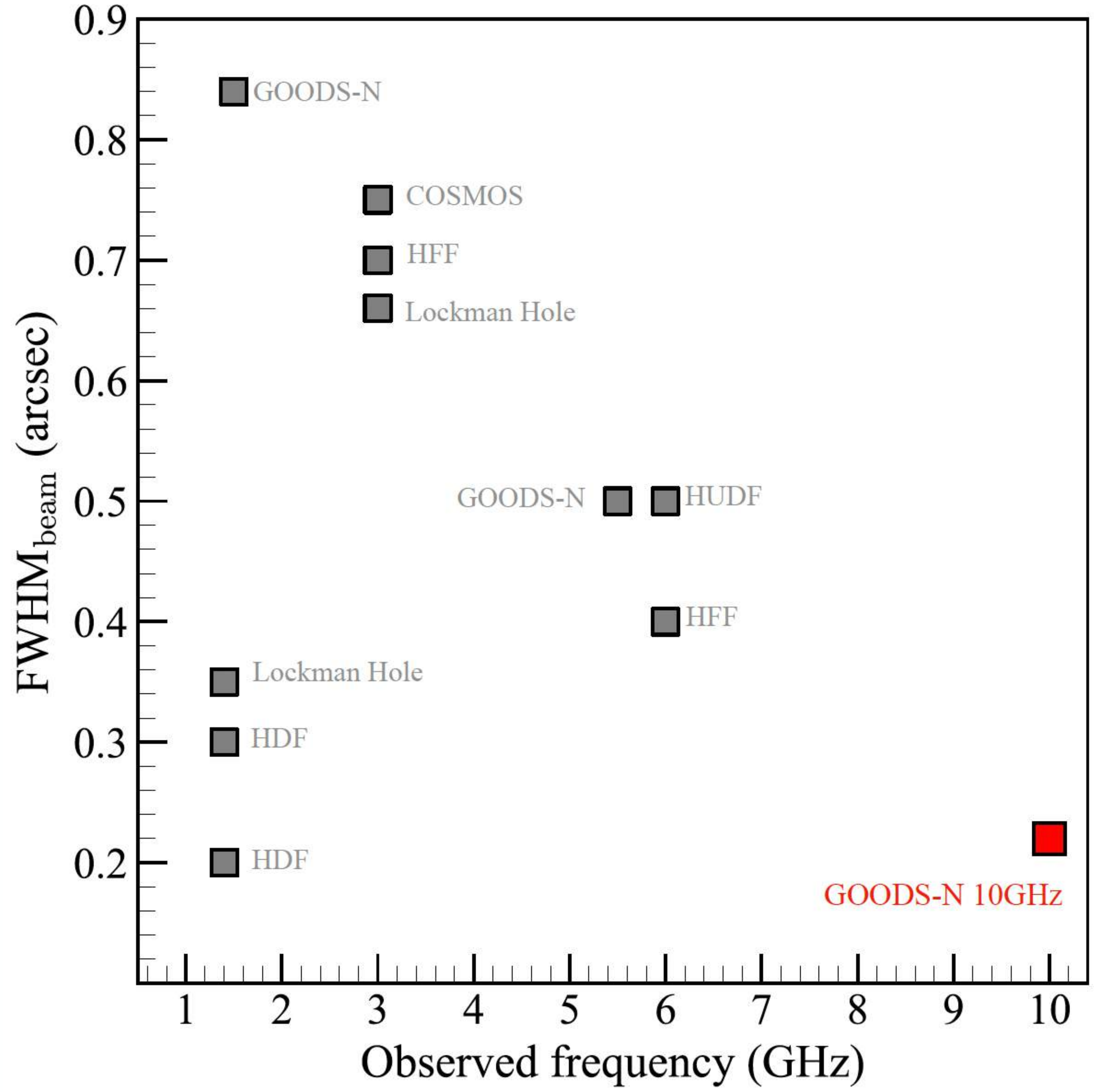
Maximum spatial resolution:
$\mathrm{FWHM_{beam}} = 0.22$ arcsec (> 1.9 kpc at all z)



Jiménez-Andrade et al. (2024)



10GHz-detected galaxy at $z = 1.2$ with
SFR = 500 $M_{\odot}$ yr^{-1}



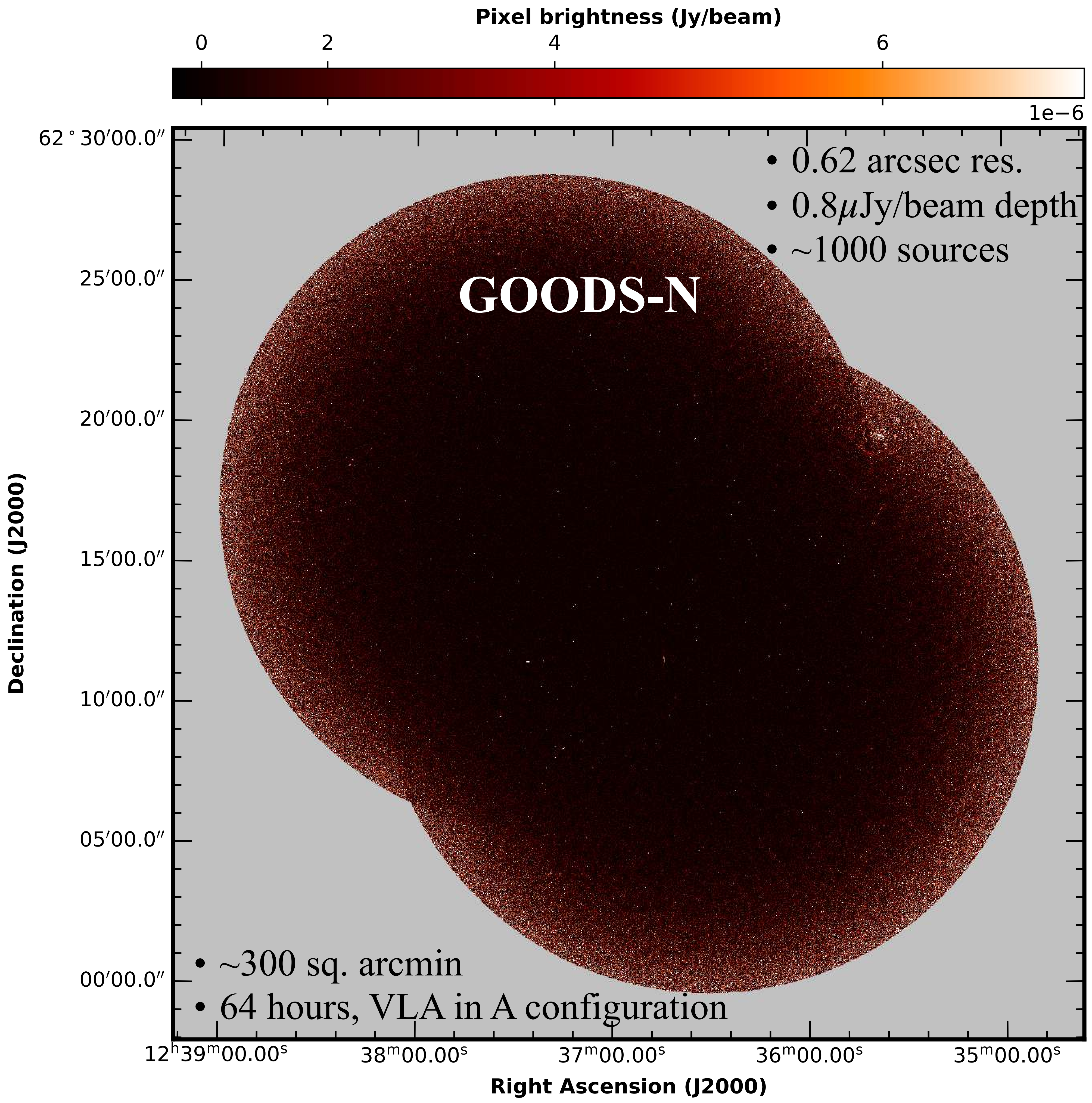
Jiménez-Andrade et al. (2024)

One of the sharpest and deepest extragalactic radio surveys to date.

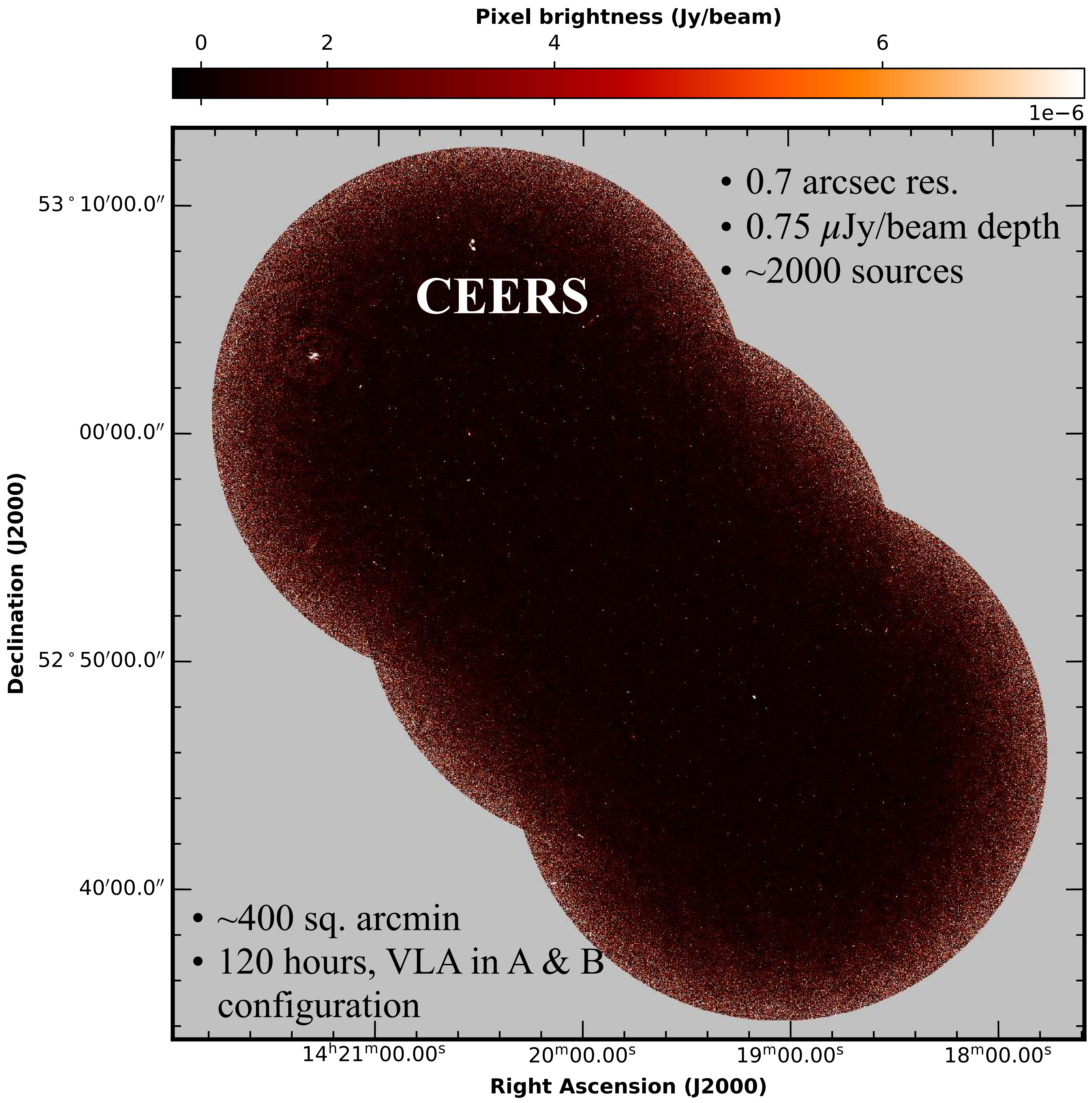
Deep 3GHz surveys of GOODS-N and CEERS

We have also produced deep 3GHz mosaics of the GOODS-N and CEERS fields.

Why 3GHz? More sensitive to high-z radio sources. Sub-arcsec angular resolution with the VLA.



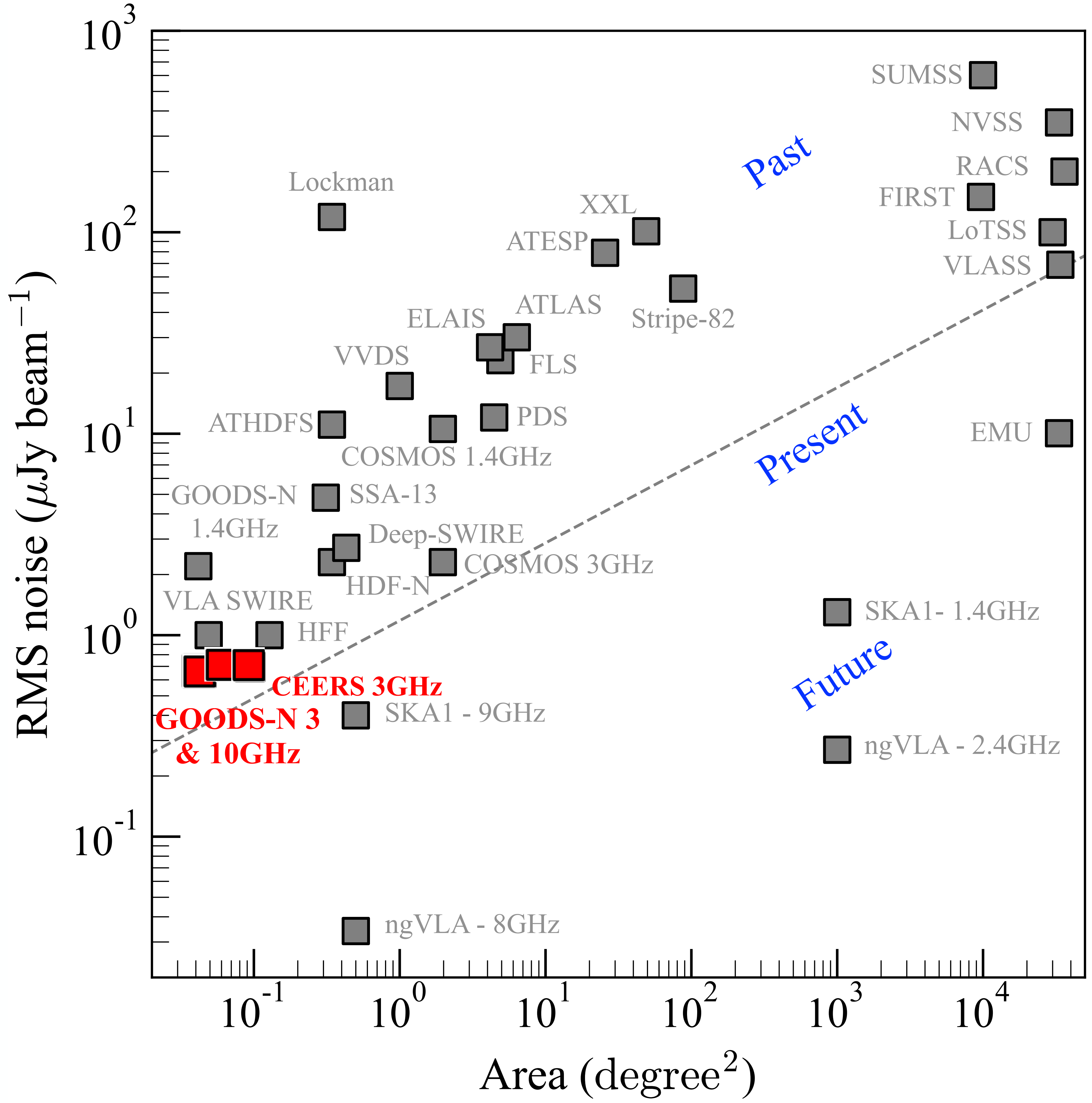
Jiménez-Andrade et al. (in prep.)

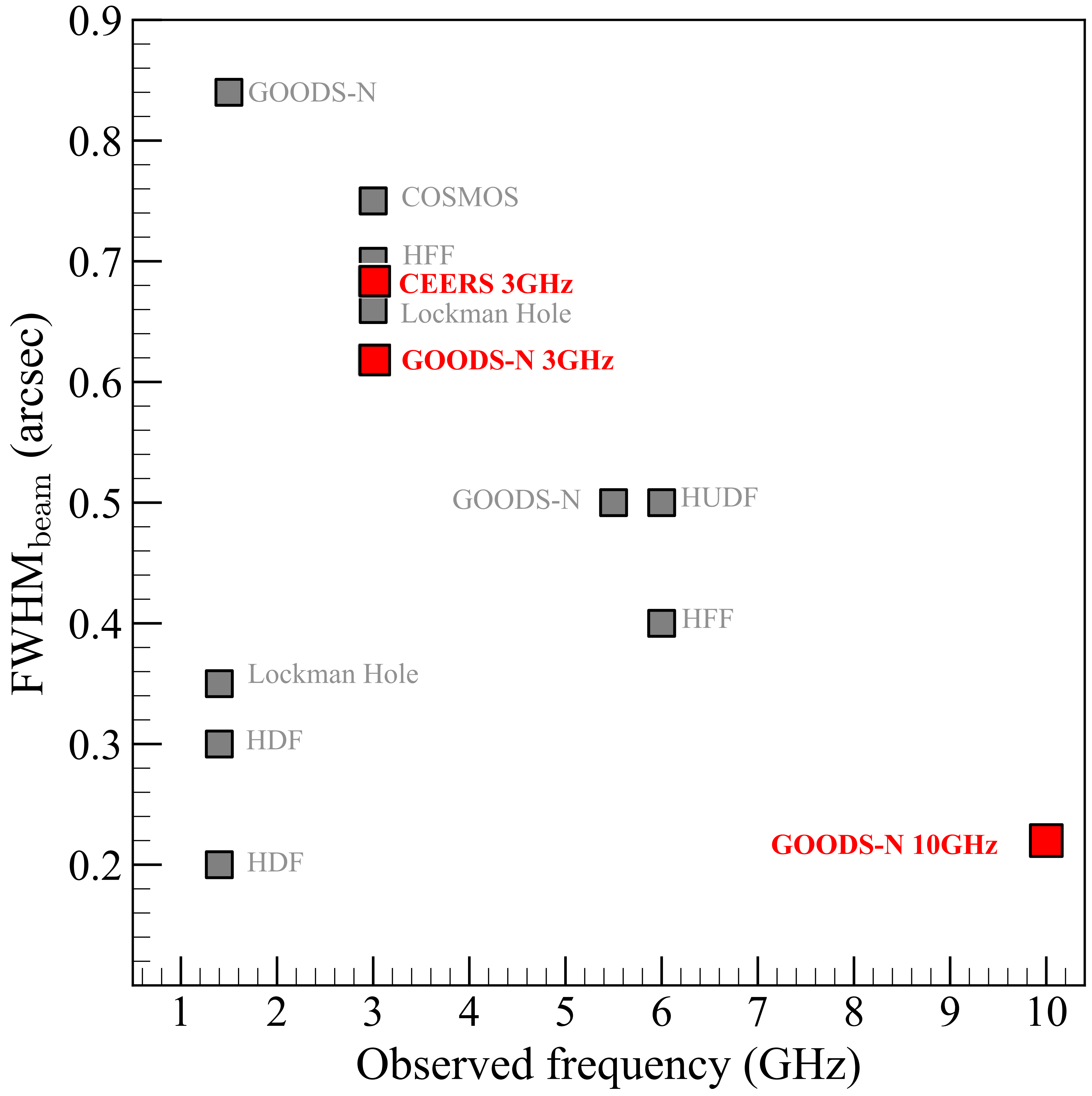


Jiménez-Andrade et al. (in prep.)

Deep 3GHz surveys of GOODS-N and CEERS

The 3GHz surveys of the GOODS-N and CEERS fields (red squares): among the deepest, sub-arcsec resolution radio images ever obtained.

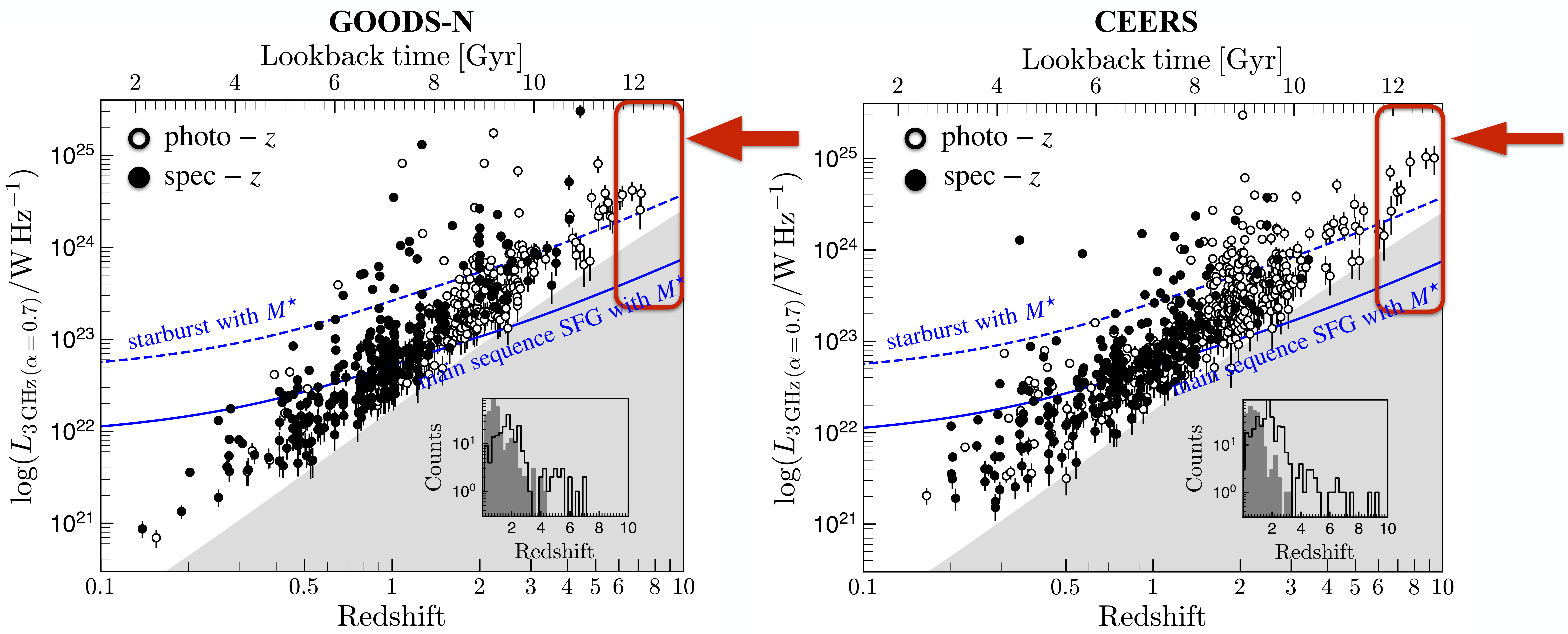




Jiménez-Andrade et al. (in prep.)

High-redshift radio sources in CEERS and GOODS-N

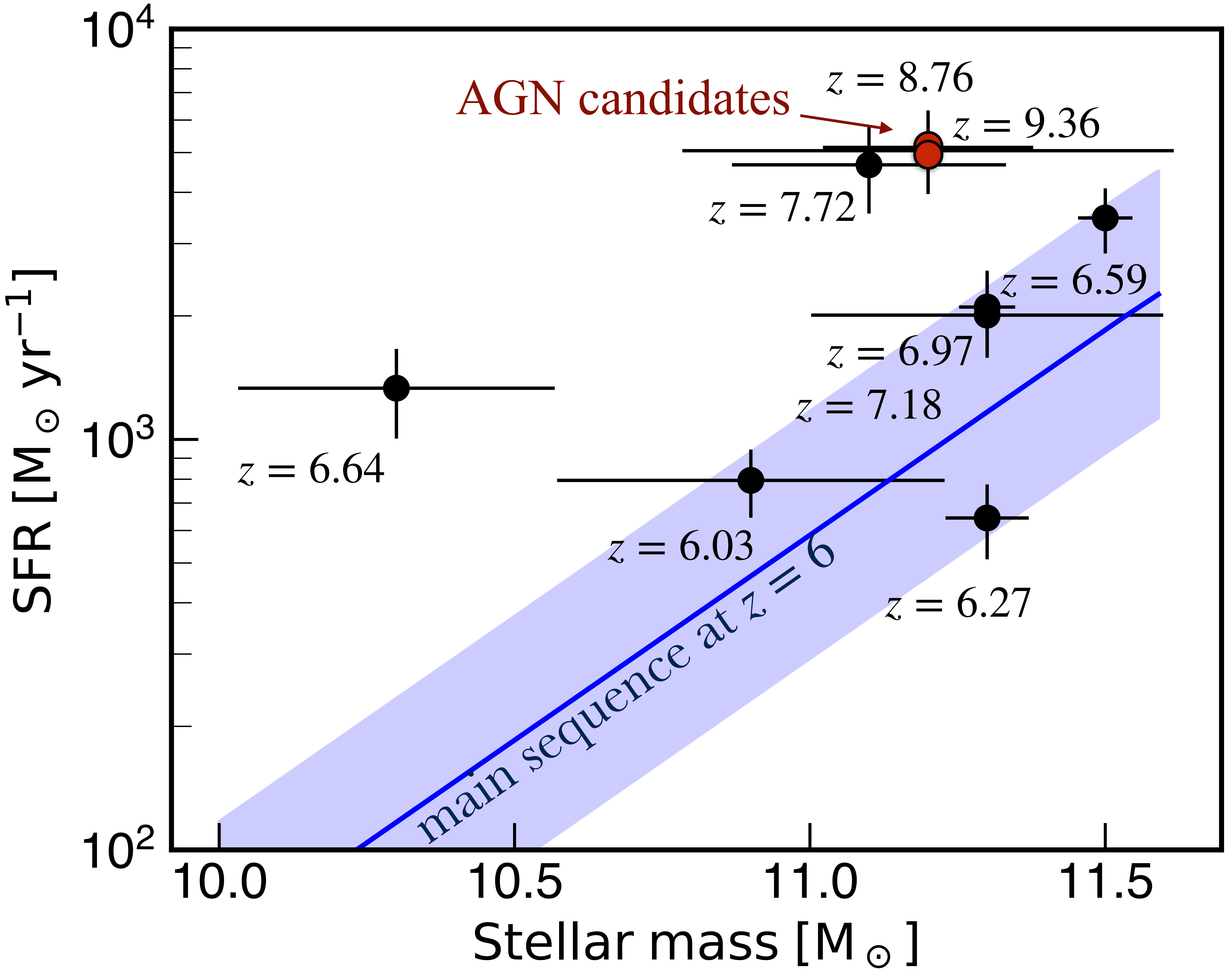
With sub-μJy level sensitivities at 3GHz, we are able to detect main sequence galaxies with $M^{\star}$ out to $z \approx 2.5$.



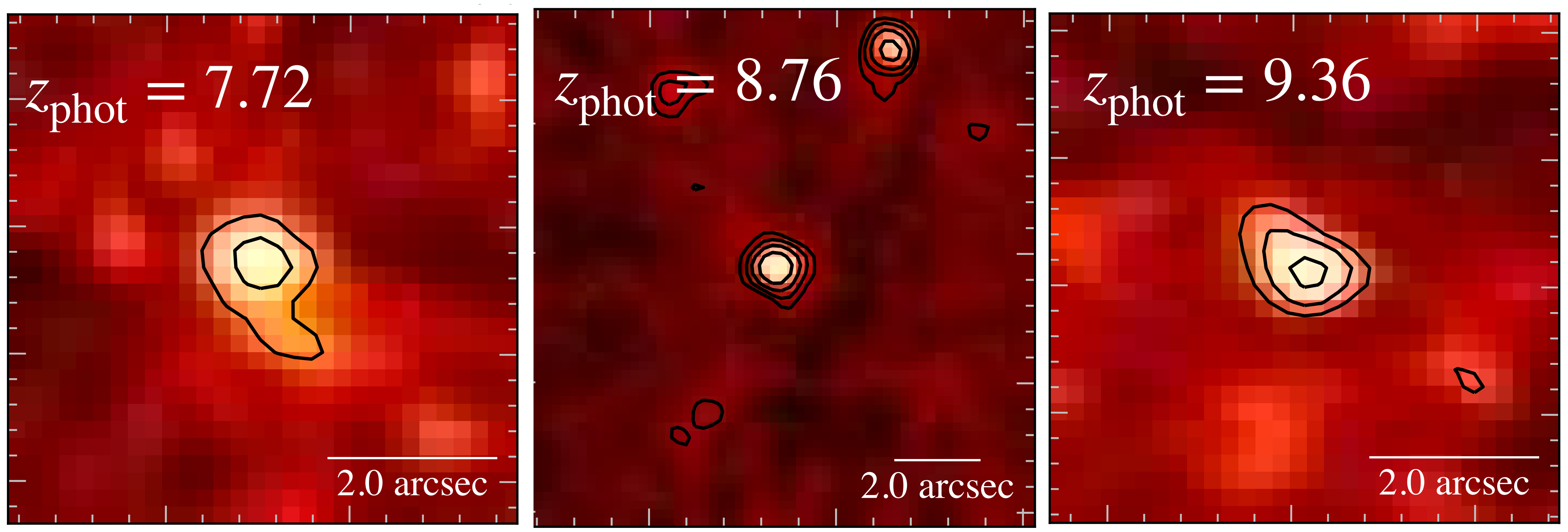
We are detecting galaxies with **photometric redshifts has high as** ≈ 9.4!?
Using Kodra et al. (2023)

High-redshift radio sources in CEERS and GOODS-N

Radio selected sources in CEERS with $z_{phot} > 6$



The most distant galaxy candidates in our radio sample



AGN candidates; X-ray detected
Nandra et al. (2015)

Confirmed X-ray detected AGN: UHZ1 (z=10.07; Bogdan+2024; Goulding+2023) and GHZ9 (z=10.145; Kovacs+2024; Napolitano+2024).

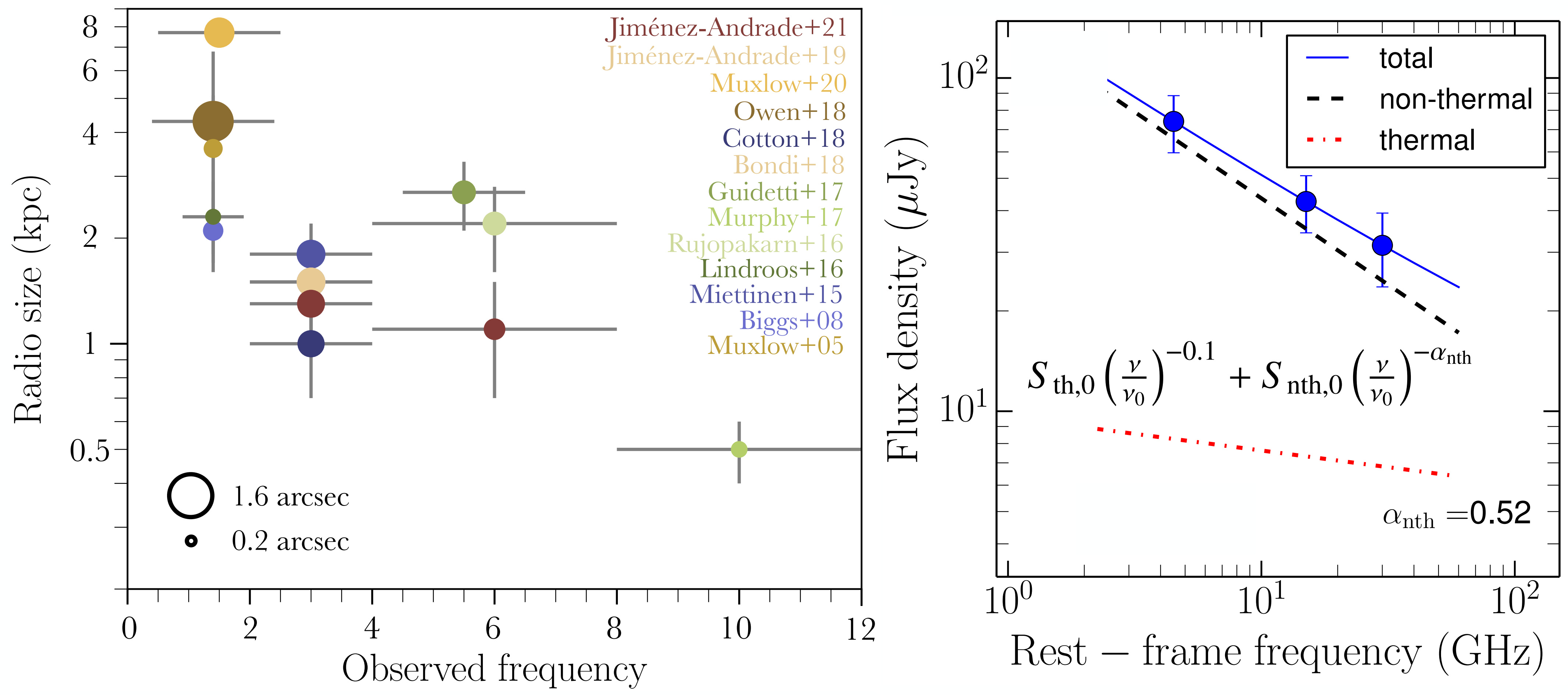
Are these the most distant radio loud AGN ever detected?

Or, are these low-redshift interlopers (as in Zavala et al. 2022, Fujimoto et al. 2023)?

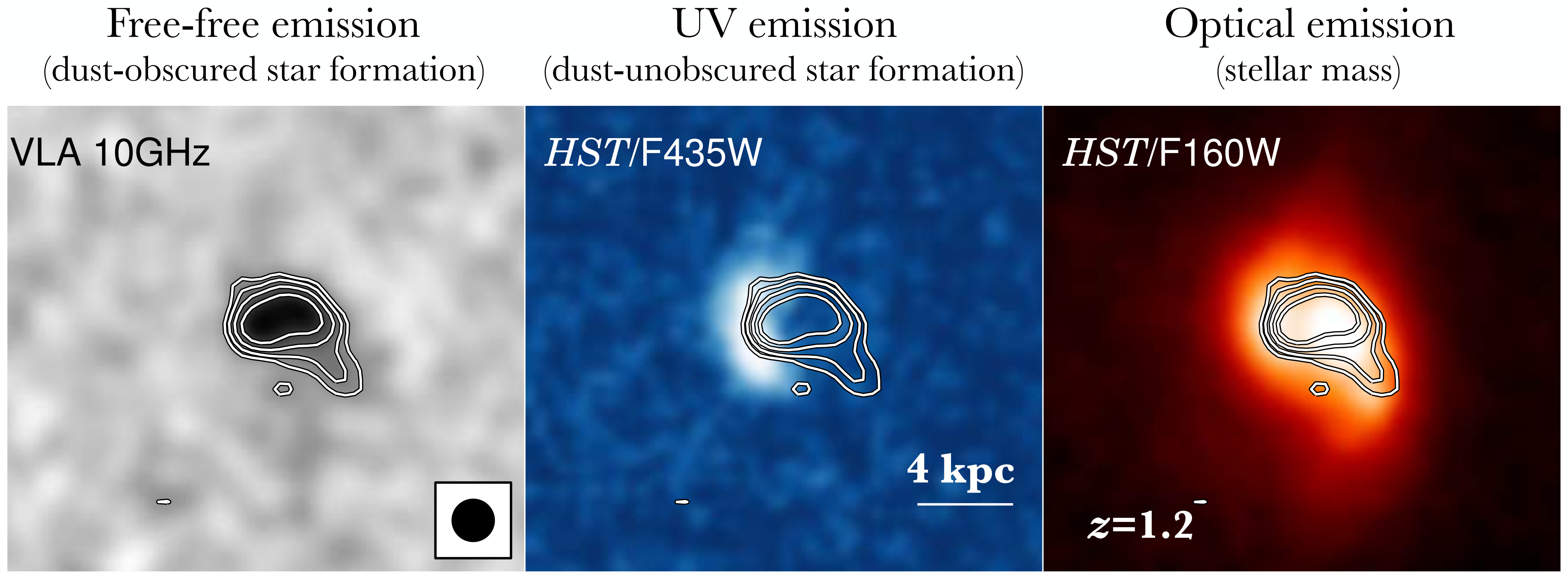
Ongoing projects with the GOODS-N and CEERS radio surveys

a) Benchmarking radio continuum as a SF tracer at high-z

(morphological k-correction in radio, radio SEDs, comparison with other tracers from *JWST* data)



b) Exploring how star formation shapes galaxies thought cosmic time



c) Follow-up of $z > 6$ radio sources

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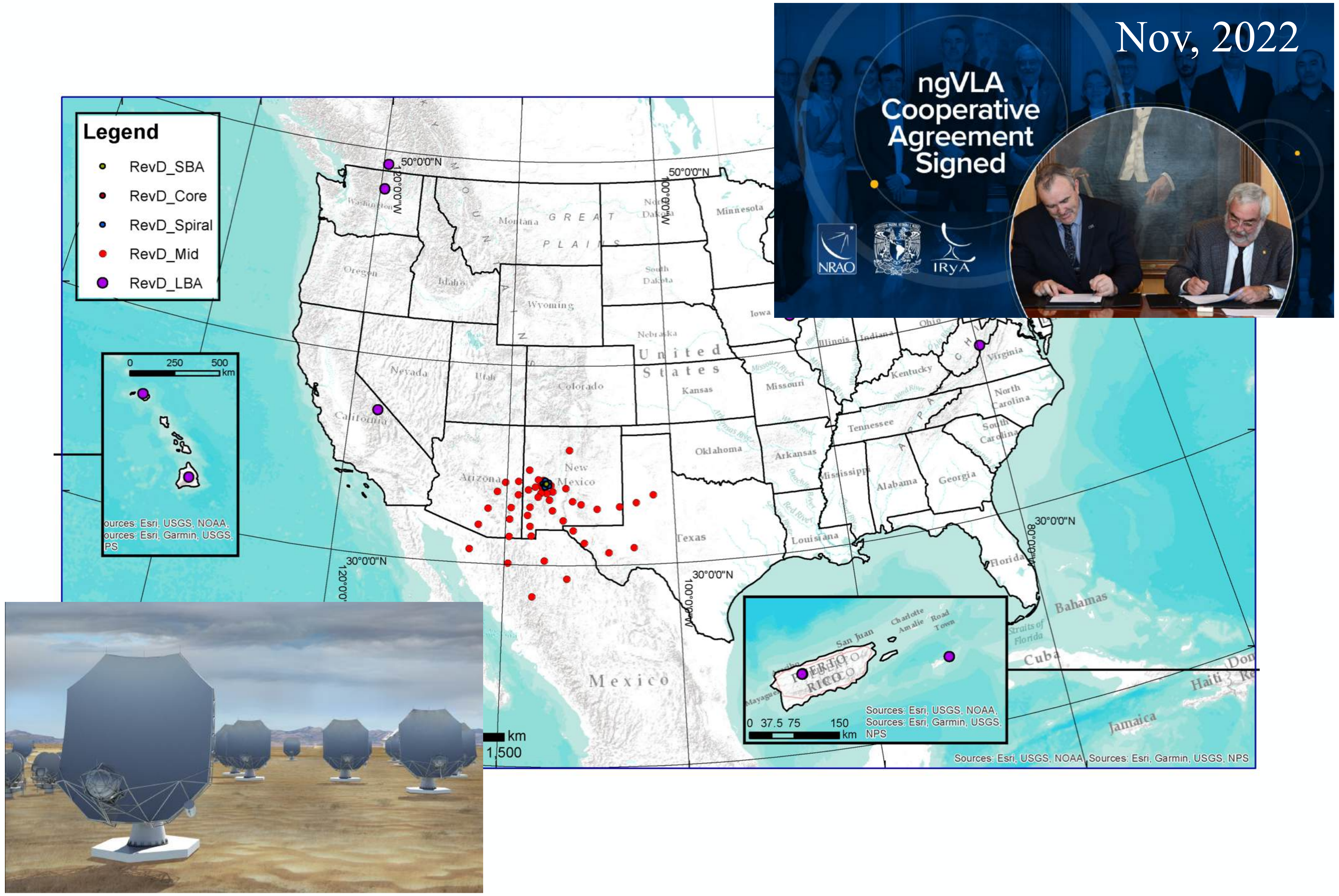
The ngVLA

A transformative new facility that will replace the VLA and VLBA to tackle a new Scientific Frontier: **ultra-sensitive imaging of thermal line and continuum emission at milli-arcsec scales.**

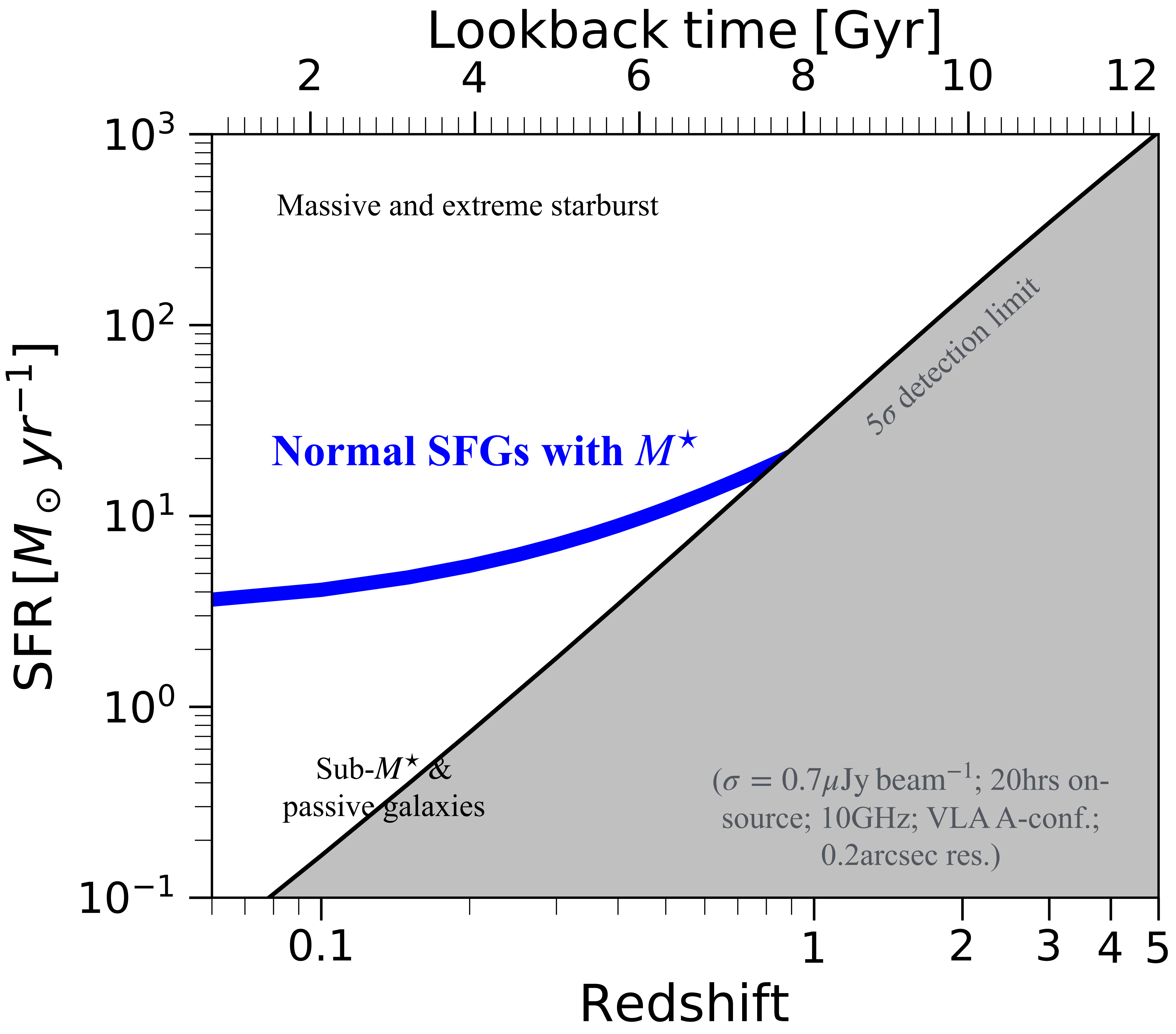
ngVLA Concept:

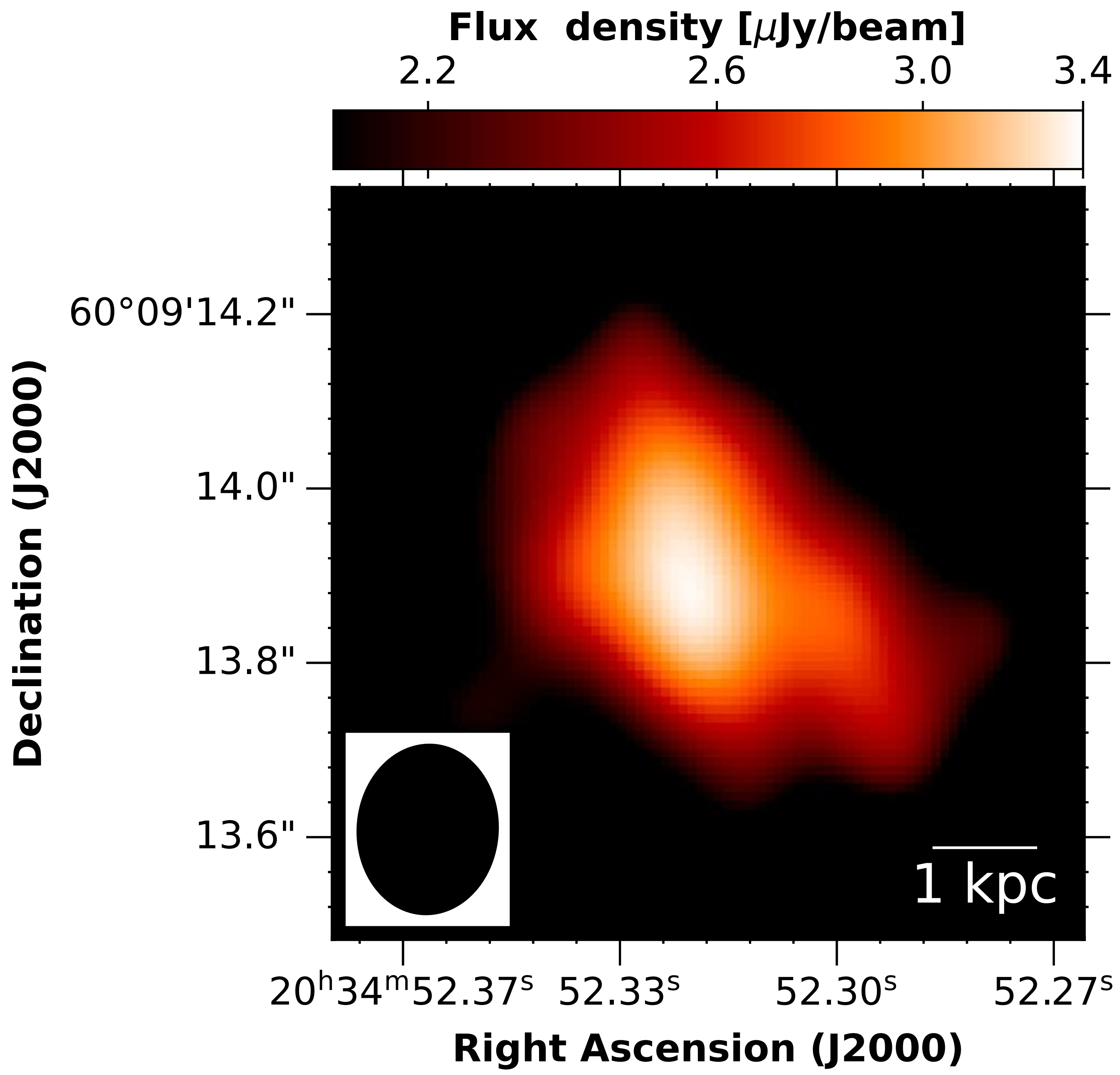
- 10x the sensitivity and resolution of the JVLA/ALMA
- 1.2 - 116 GHz Frequency Coverage
- 244 x 18m + 19 x 6m offset Gregorian Antennas
- Centered at VLA site and concentrated in SW US and North of Mexico.



Deep radio surveys with an ngVLA

Selection function imposed by the sensitivity of existing VLA imaging at 10GHz in GOODS-N.



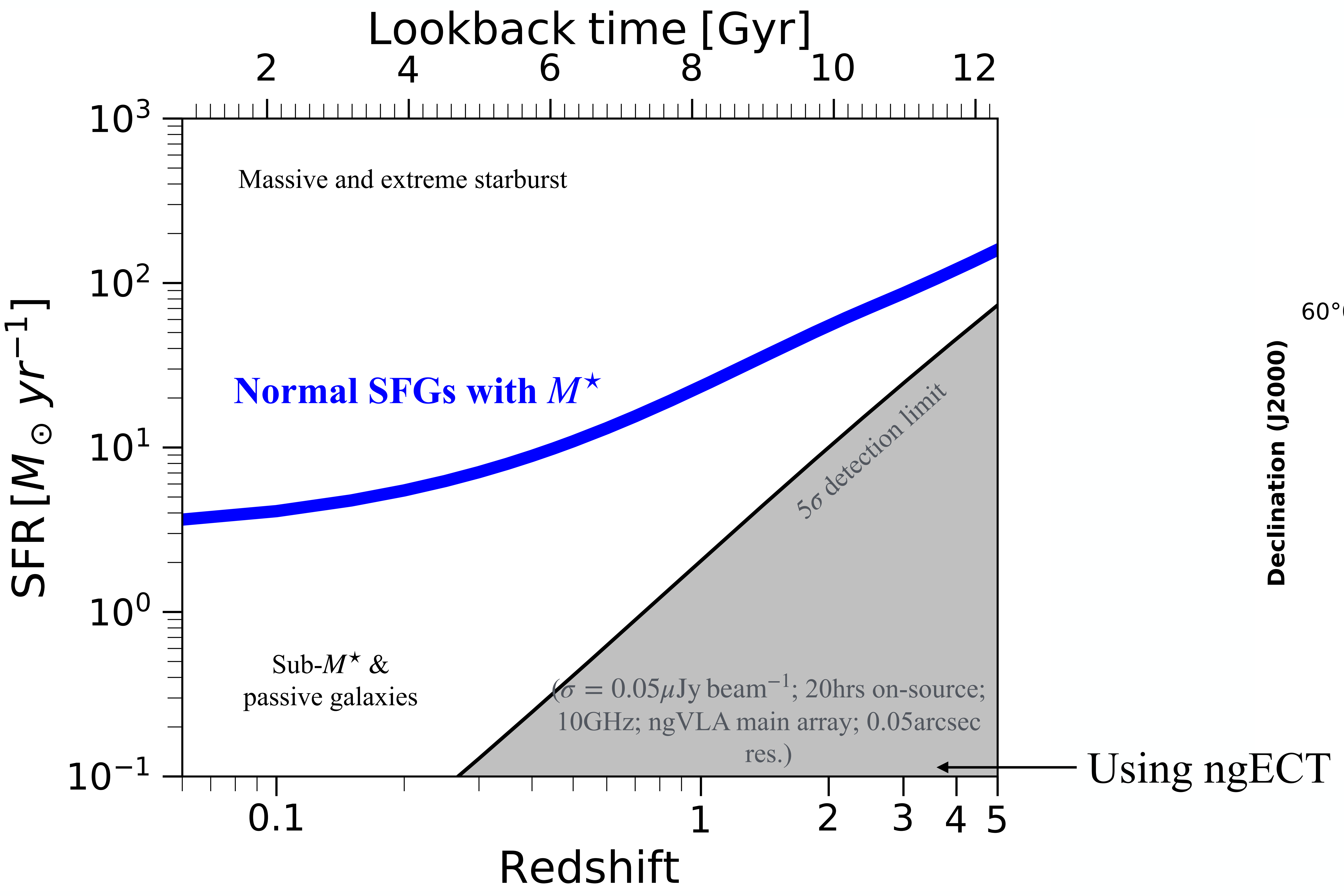


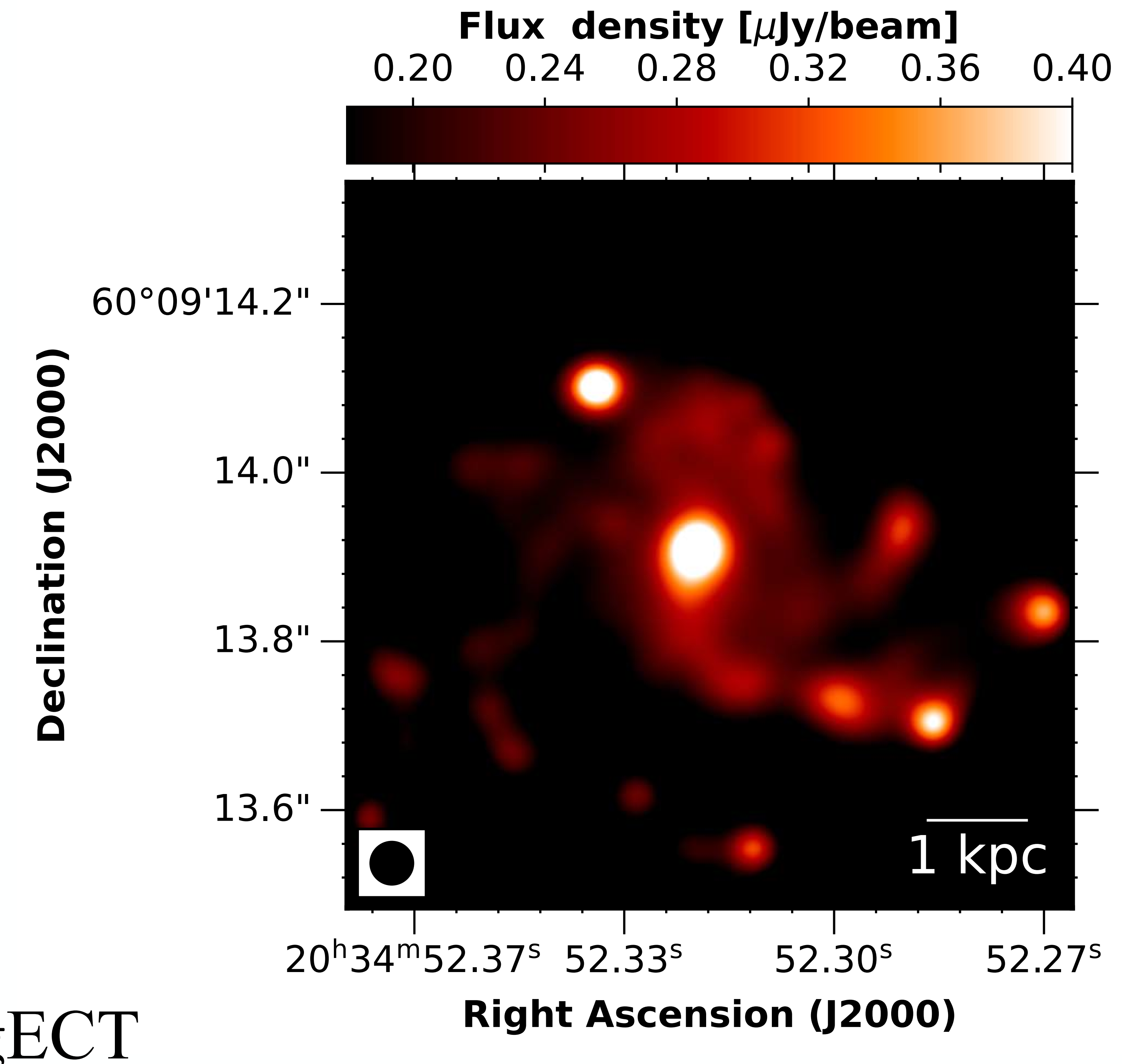
$z = 1.2$ with SFR $= 500\ M_\odot\ \mathrm{yr}^{-1}$

With 20hrs of on-source integration time with the VLA at 10GHz, we can detect main-sequence SFGs with $M^\star$out to $z \approx 1$.

Deep radio surveys with an ngVLA

ngVLA will produce maps of star formation of high-redshift SFGs at a level of detail that, to date, is only possible for galaxies in the local Universe.





$z = 1.2$ with SFR $= 500\ M_\odot\ \mathrm{yr}^{-1}$

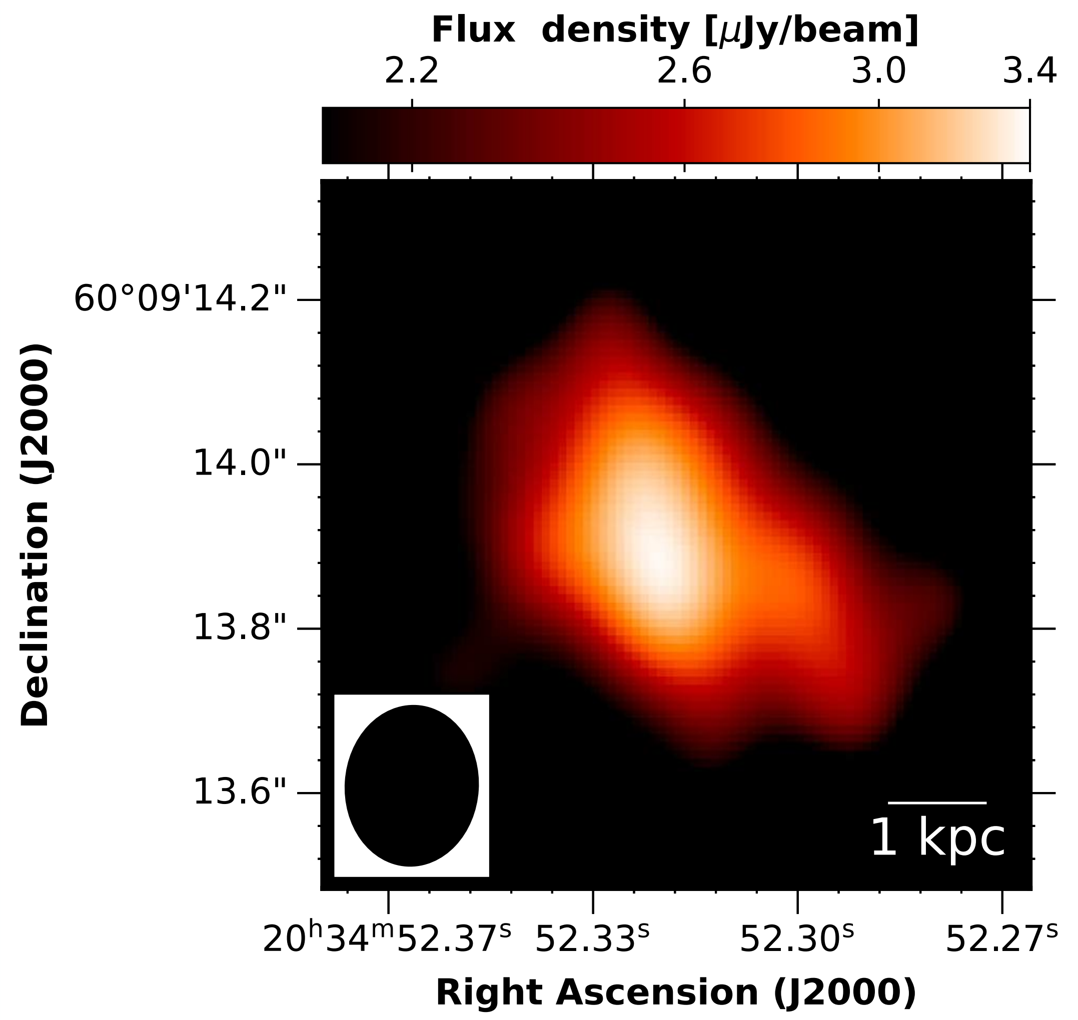
With 20hrs of on-source integration time with the ngVLA at 10GHz, we will detect main-sequence SFGs with $M^\star$ out to $z \gtrsim 5$.

We have been pushing the resolution and sensitivity limits of the VLA to obtain some of the deepest and sharpest radio continuum images ever obtained.

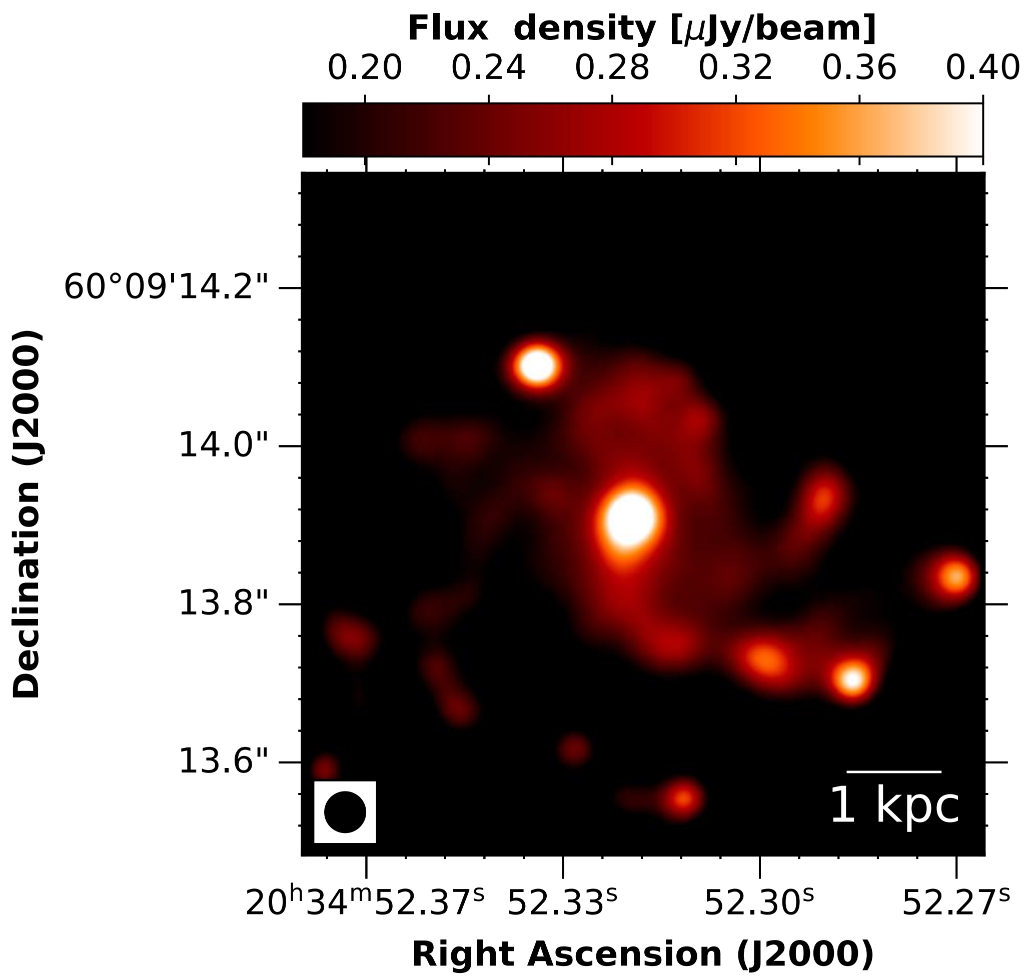
GOODS-N (3 & 10GHz) CEERS (3GHz)

All with sub-uJy sensitivities at sub-arcsecond resolutions —> potential $z \approx 6 - 9.5$ detections, paving the way for the ngVLA

Deep24



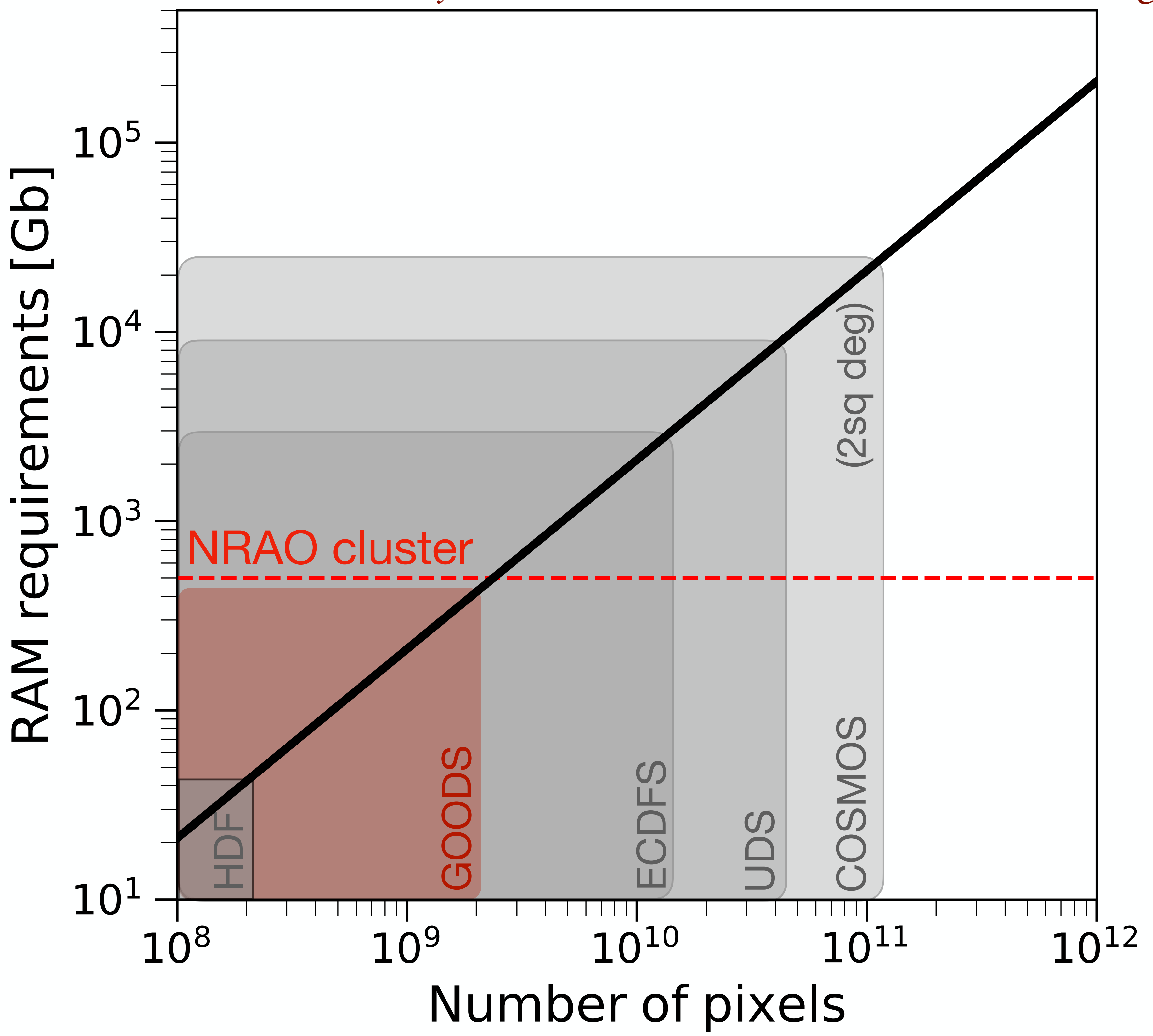
Deep33?…



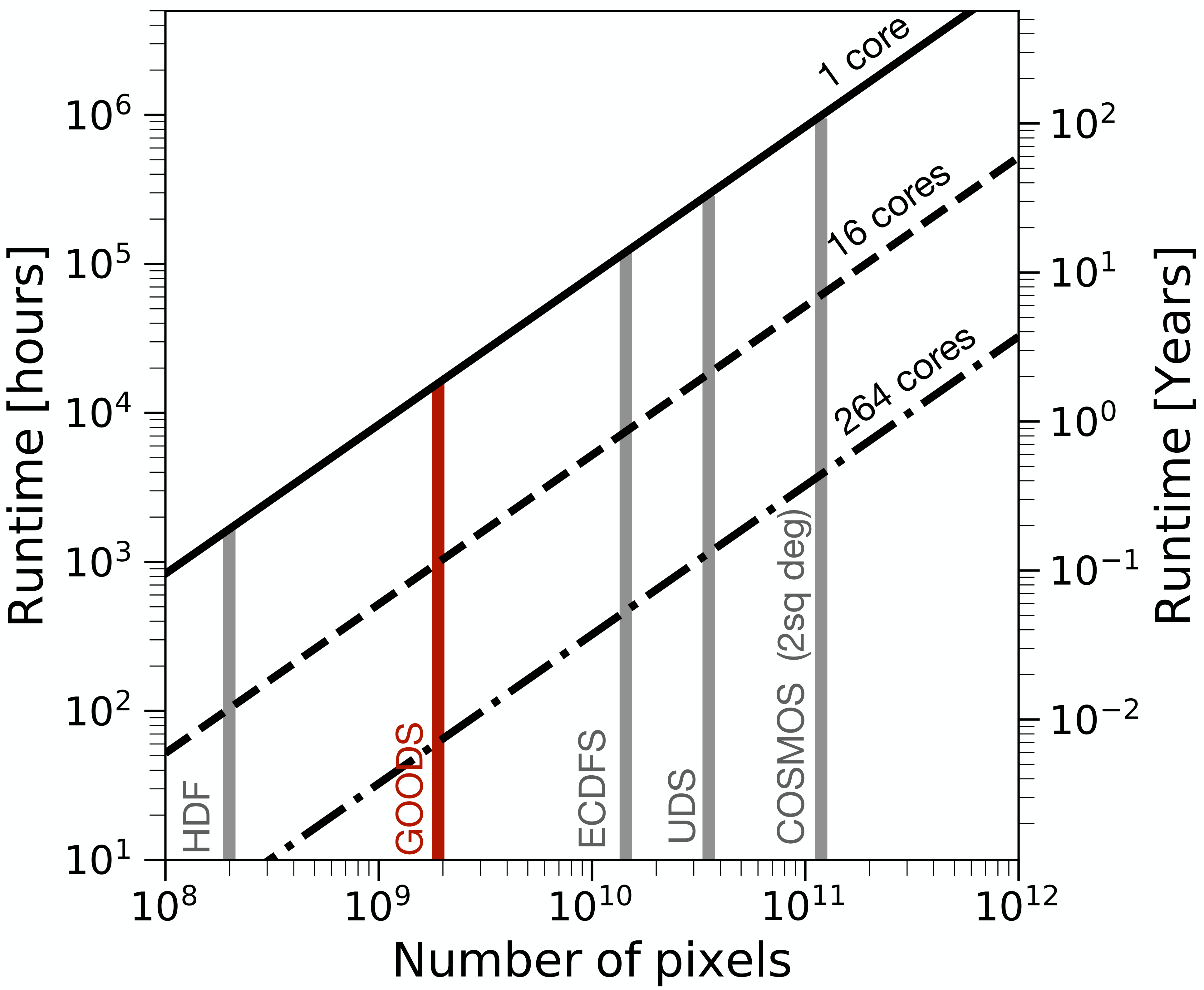
RAM and runtime needed to get a joint mosaic —with current NRAO resources— with AWprojection + MTMFS + multi-scale cleaning.

Assuming a 0.015 arcsec/pixel scale for an ngVLA-like 0.05 arcsec resolution.

$\mathrm{RAM} \propto 5.5 \times (N_x N_y) \times \mathrm{nterms}_{\mathrm{MTMFS}} \times \mathrm{nscales}_{\mathrm{cleaning}} + \mathrm{CF}$



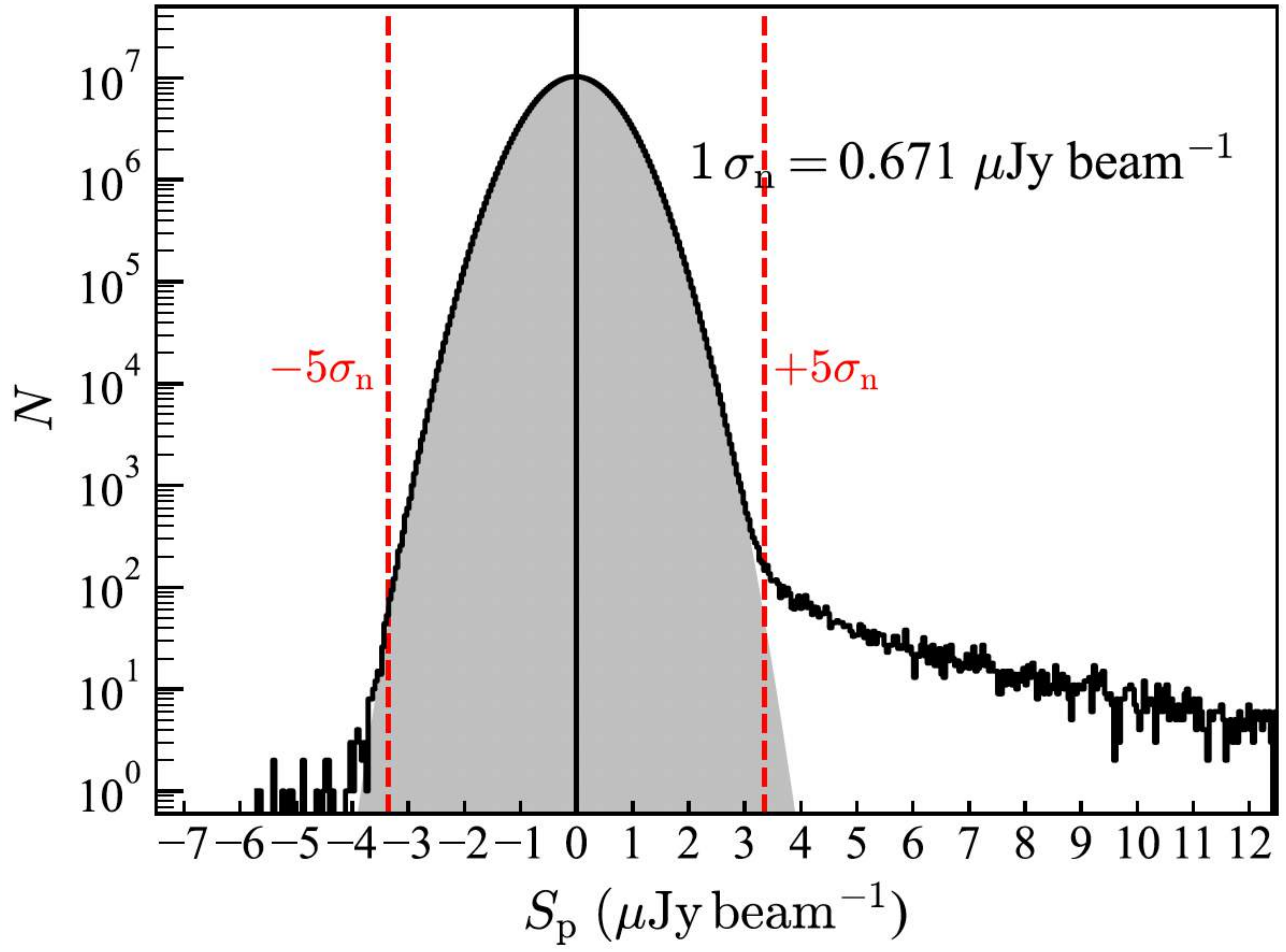
$\mathrm{Runtime} \propto (N_x N_y)$

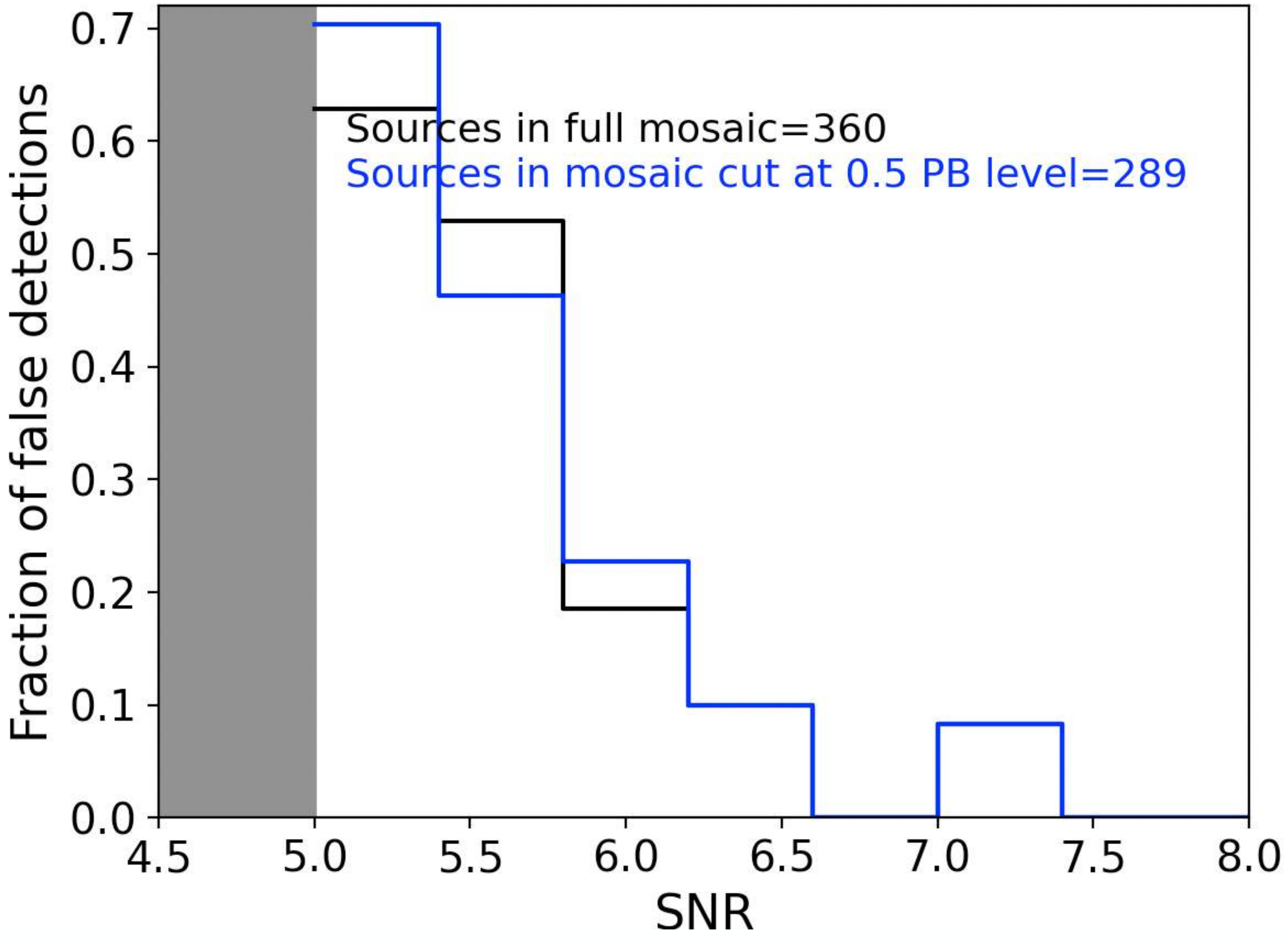


To reduce size-of-computing, ngVLA will require *"parallel processing at a relatively massive scale"* *(Bhatnagar et al., 2021)* + GPU.

Do we really want sub-arcsec resolution in deep, blind radio surveys?

We are finding a high fraction of spurious sources (~30%) in our full resolution 10GHz mosaic (0.22 arcsec).

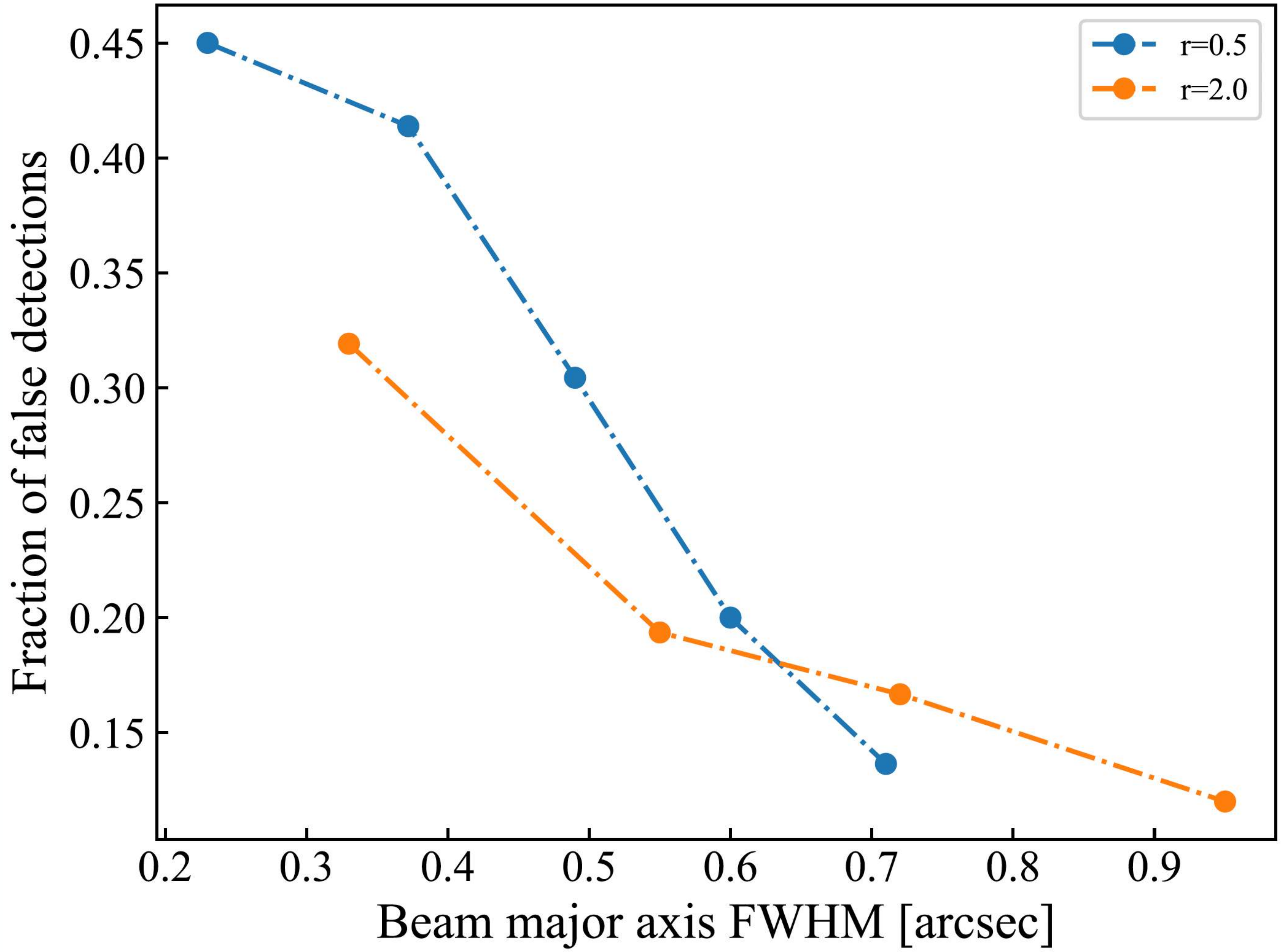




Even though the noise amplitude distribution is well-described by a Gaussian function and these spurious sources are not related to artifacts/sidelobes.

Do we really want sub-arcsec resolution in deep, blind radio surveys?

After extensive tests, we find that the fraction of spurious sources is well-correlated with the beam size.



On the contrary, the fraction of spurious sources DOES NOT strongly depend on:

- observed frequency
- source extraction algorithms (PyBDSF and Blobcat)
- imaging software (CASA and WSclean)
- pixel scale
- imaging algorithms (with/without MTMFS & wproj)

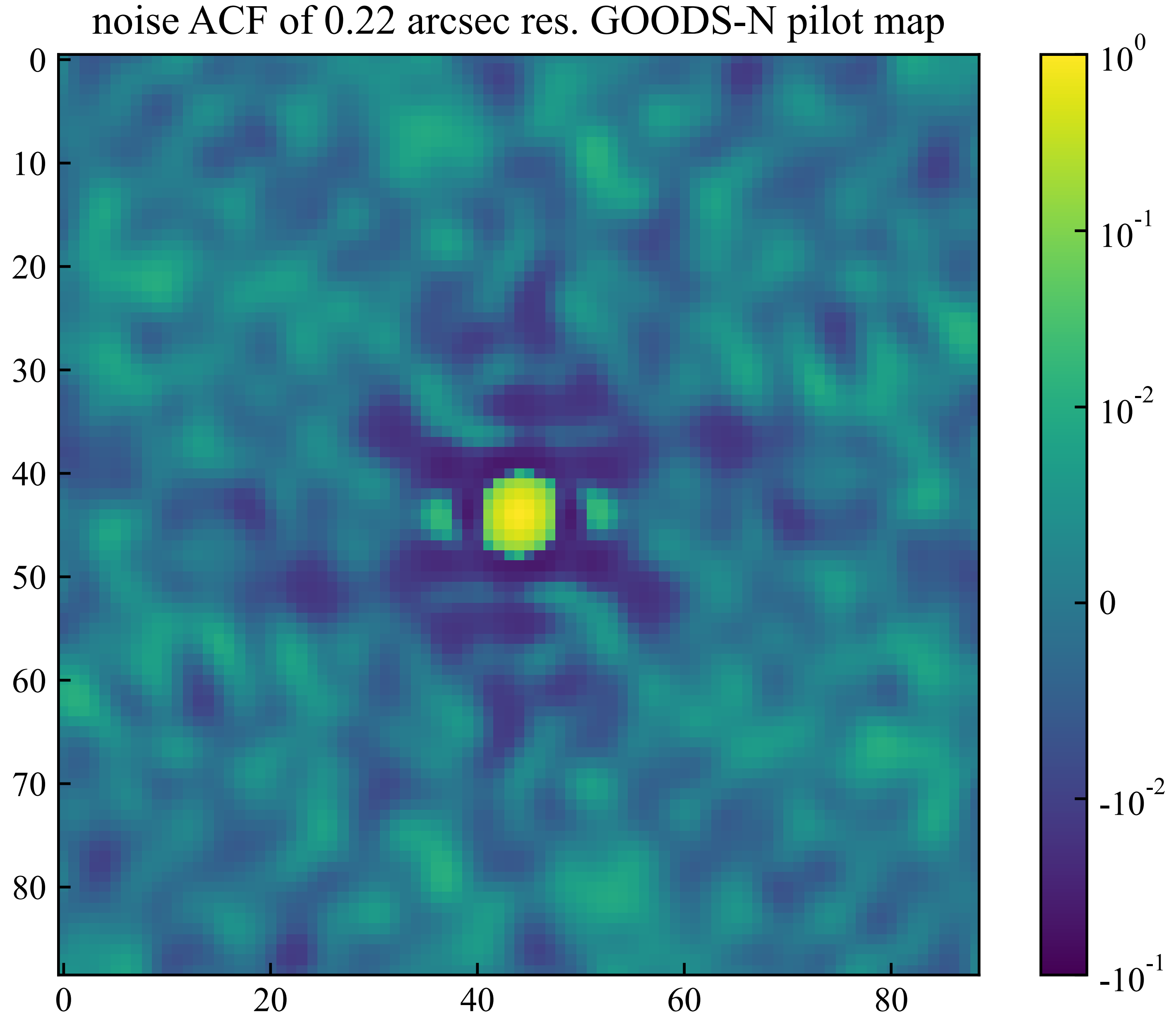
The higher the resolution, the higher the number of spurious sources.

Do we really want sub-arcsec resolution in deep, blind radio surveys?

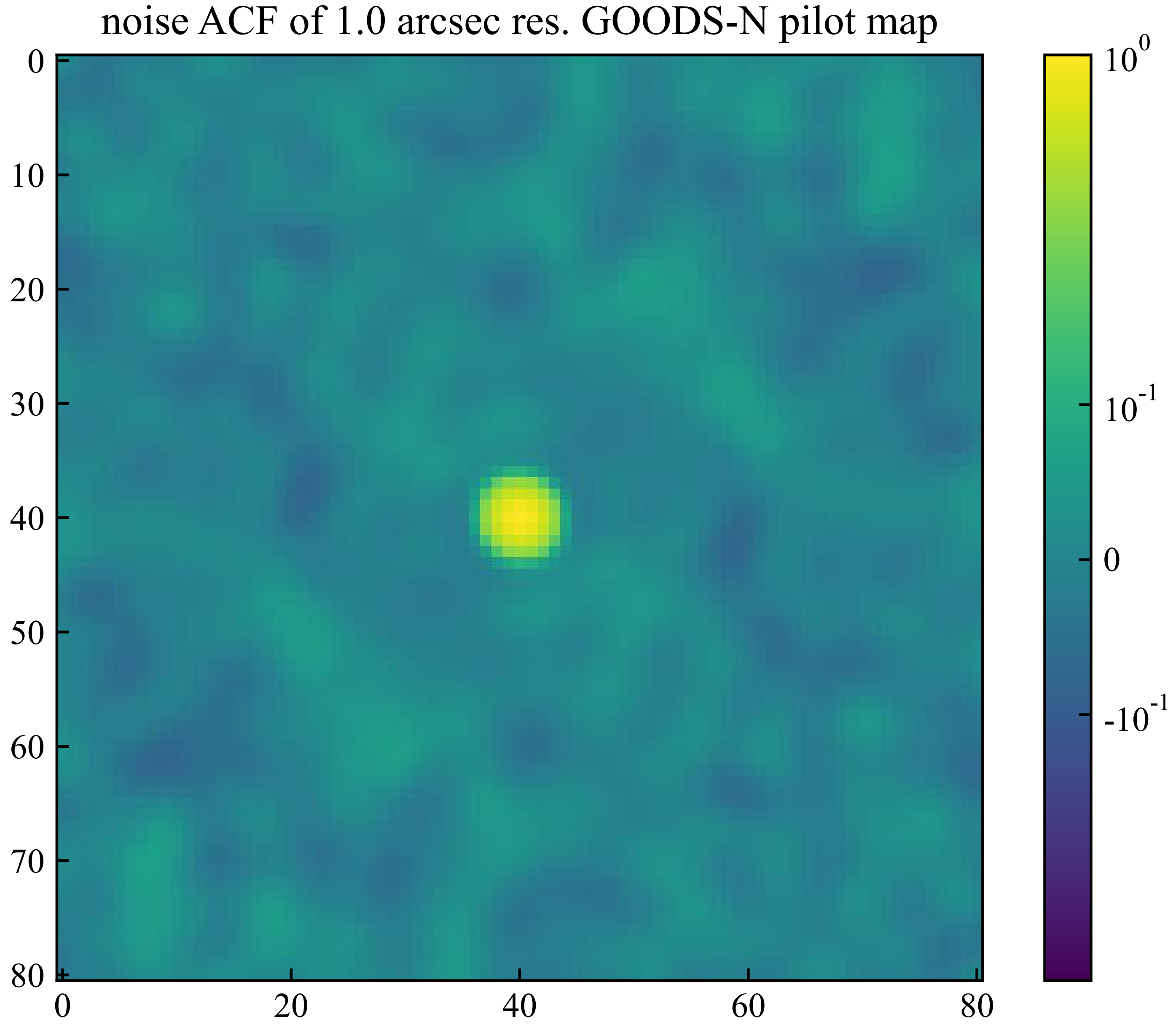
The **higher resolution means more scarce uv-coverage** and may have strong negative/positive sidelobe —> negative sources

Thanks to Takafumi Tsukui et al. (2023, https://doi.org/10.1117/1.JATIS.9.1.018001)!

0.22 arcsec



1.0 arcsec



Alternatives

- Increasing the SNR detection threshold
- Detection in the UV plane?
- Detection in lower resolution maps (as done in our GOODS-N mosaic)
- Other?

If this is happing with an angular resolution of "only" 0.22 arcsec, what could we expect for ngVLA/SKA-like resolutions?