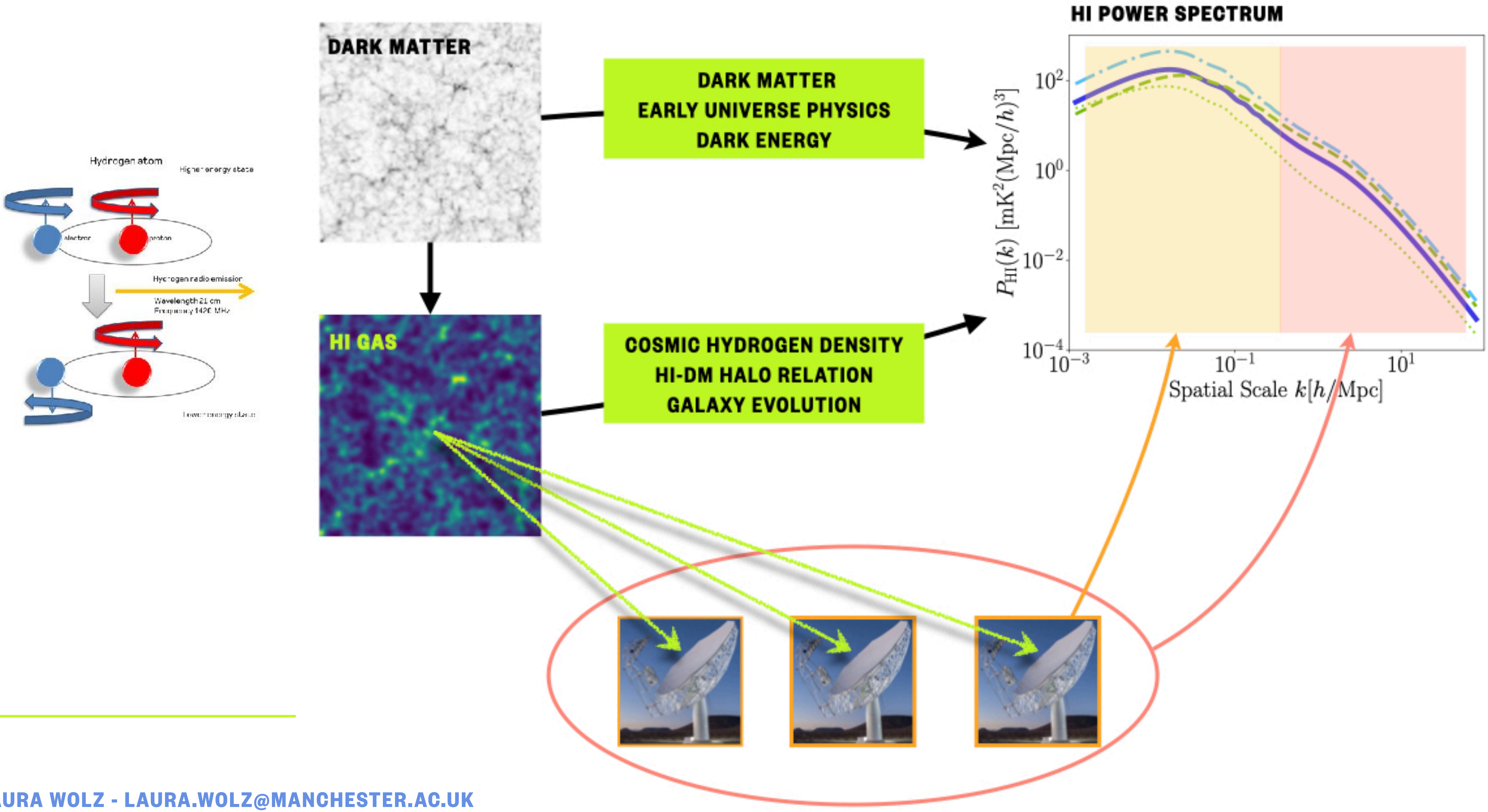
Dr Laura Wolz
UKRI Future Leader Fellow / Reader
University of Manchester

UK Research and Innovation

JODRELL BANK
CENTRE FOR ASTROPHYSICS

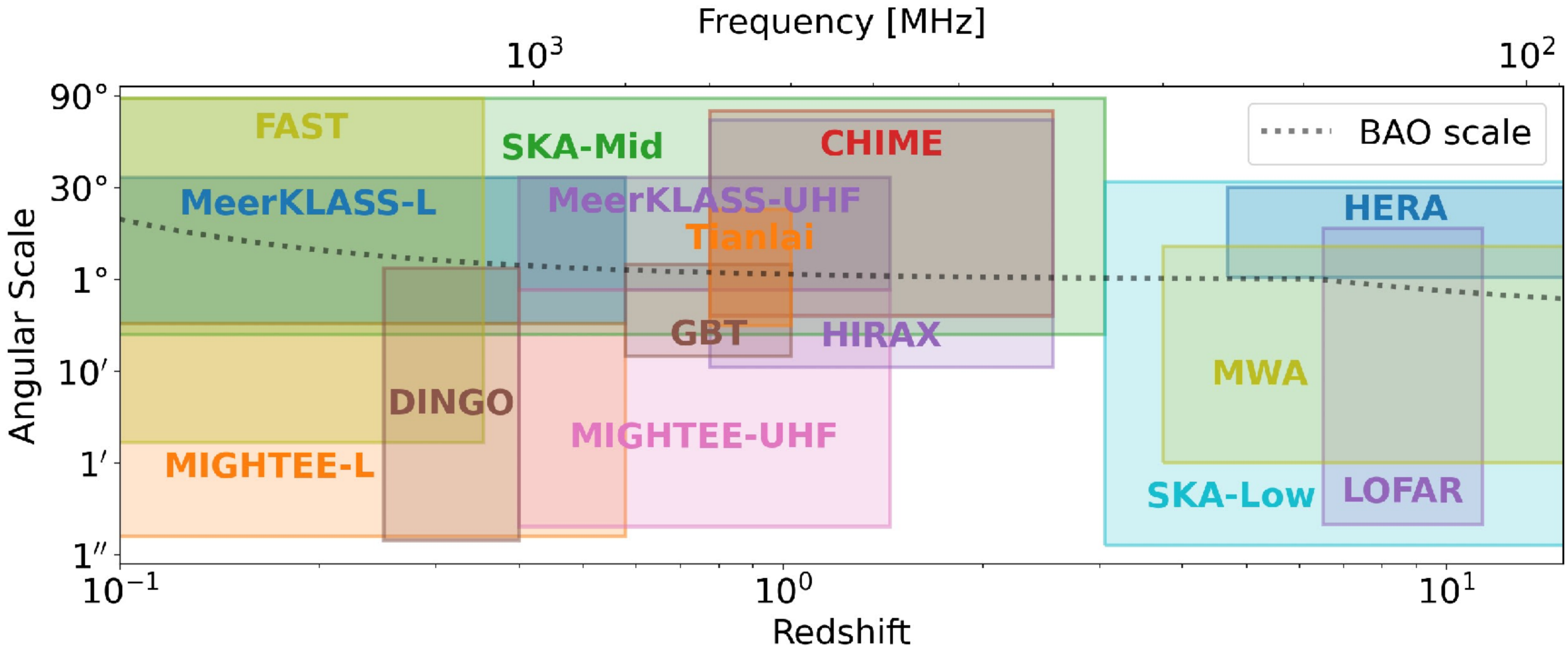
Low-redshift HI intensity mapping with single dish telescopes

TIANLAI 21CM COSMOLOGY WORKSHOP - 22/07/2024



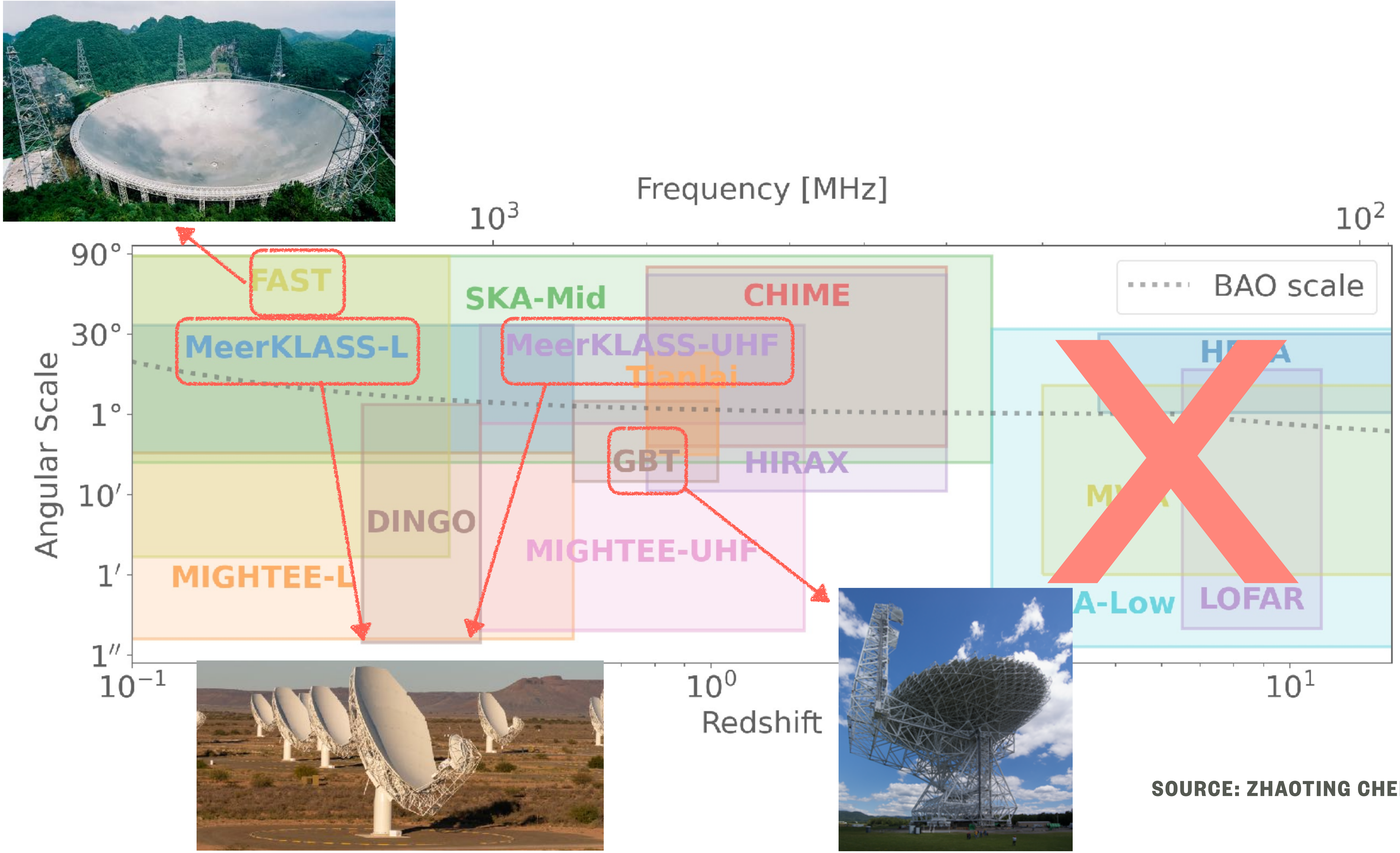
DR LAURA WOLZ - LAURA.WOLZ@MANCHESTER.AC.UK

Experiments



CAUTION: HIGHLY BIASED TOWARDS MEERKAT/SKA

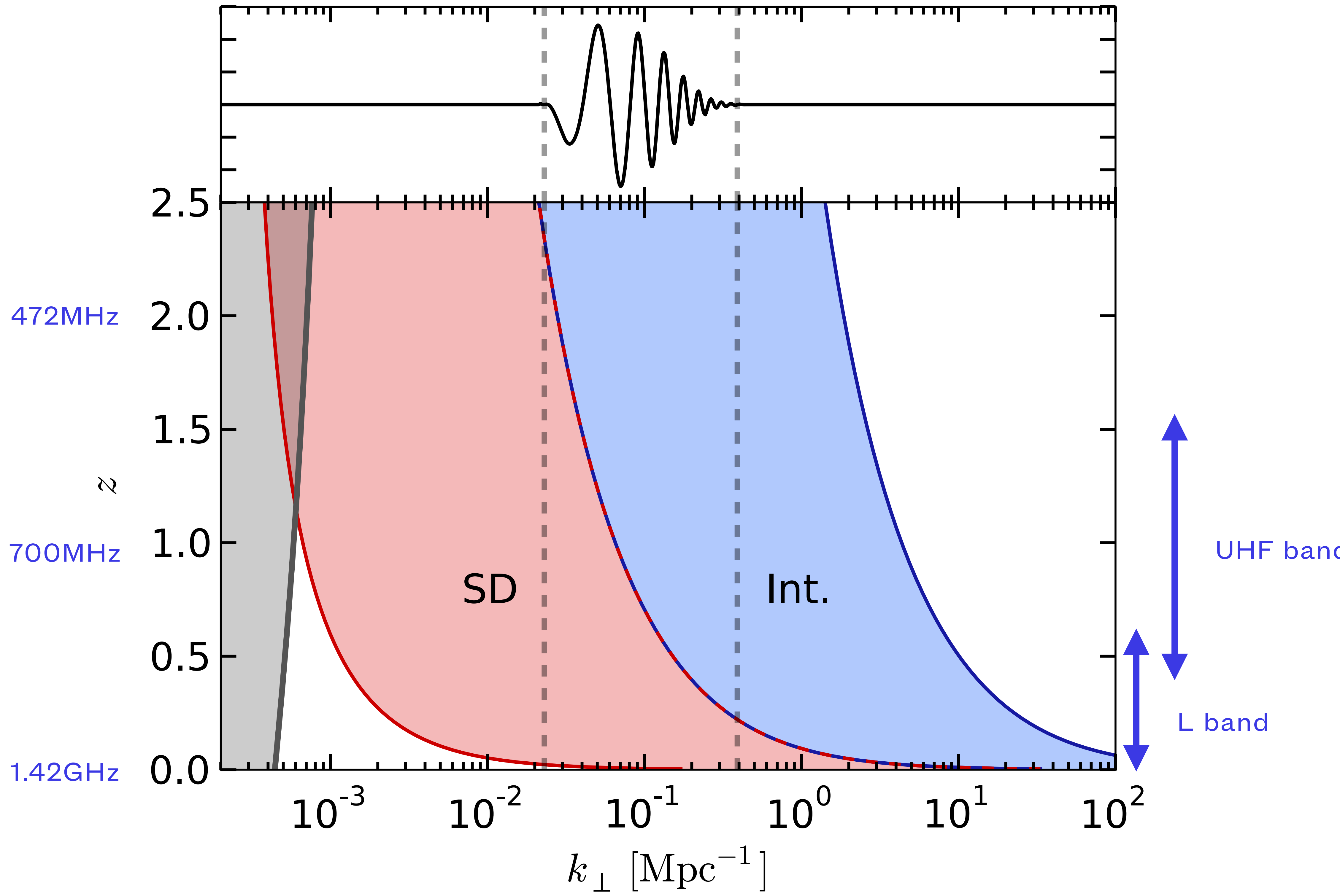
SOURCE: ZHAOTING CHEN



SOURCE: ZHAOTING CHEN

Single Dish Intensity Mapping

- **Low angular resolution** between of order of degree (SKA) or to arcmin (FAST)
- **Foregrounds contaminate** the small line-of-sight modes
- Foregrounds usually removed via blind decomposition method in image space
- **High frequency resolution** means high resolution in line-sight-modes
- Ability to resolve BAO scales is redshift dependent!



SOURCE: PHIL BULL

Science Case

Dark Energy and Dark Matter via

- Baryon Acoustic Scale detection
- Large-scale clustering via Power Spectrum
- Higher-order clustering statistics
- Redshift Space Distortions
- Non-Gaussianity via Ultra-Large Scales
- Synergies with other surveys

HI Science

Unique strengths

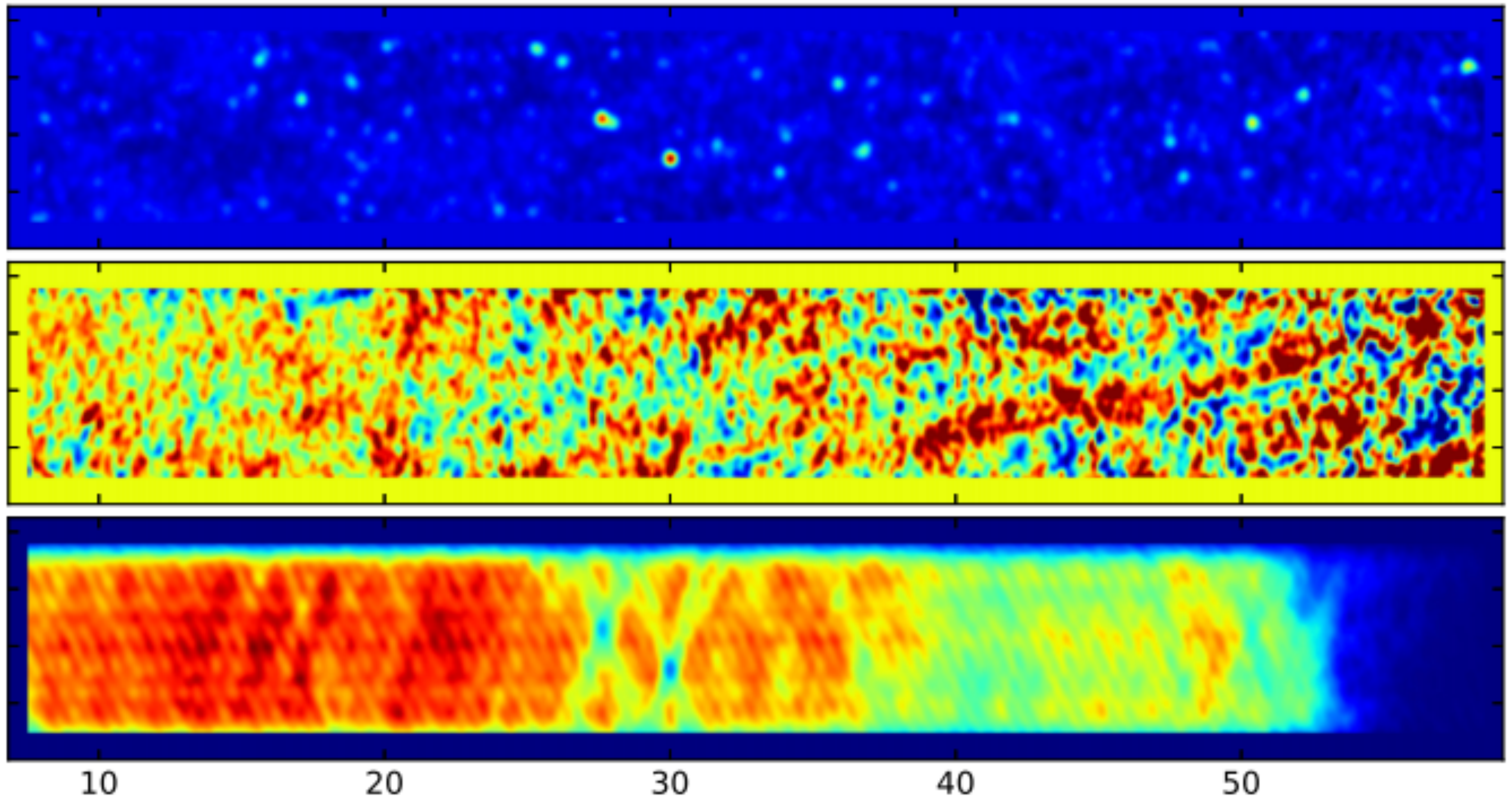
- *HI gas as new tracer*
- Continuous redshift coverage
- High redshift resolution
- Fast cover of large sky areas
- Synergies can beat errors

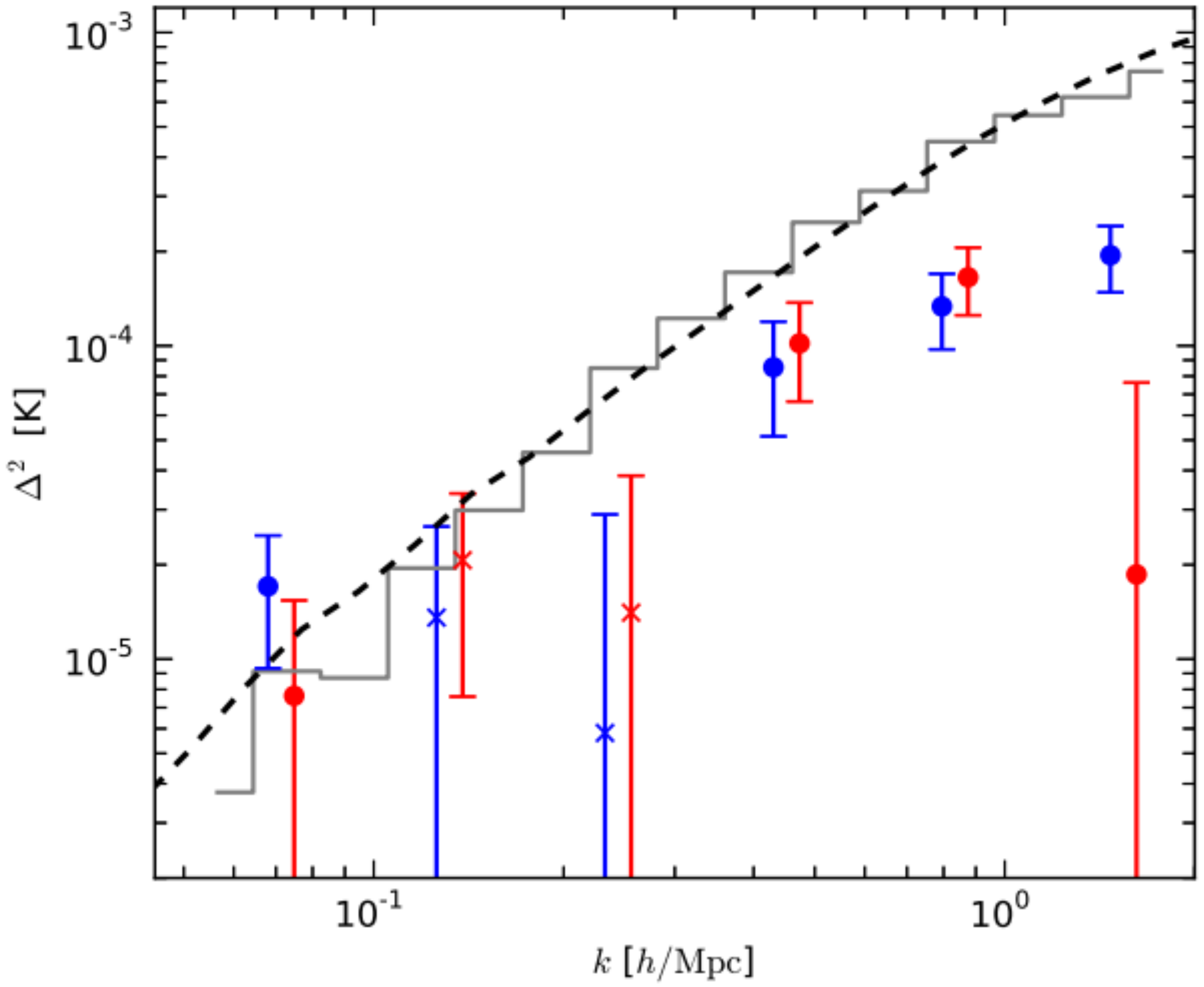
Challenges

- **Receiver Noise** amplitude comparable to signal
  Isotropic, 1/f noise can be removed, manageable in power spectrum space
  (Harper+2017, Li+2020)
- **Instrumental errors** calibration uncertainties, receiver effects, standing waves, beam sidelobes, pointing errors, polarization leakage
  Simulations of instrument response
  (Wang+2020, Cunnington+2020, Matshawule+2020, SKA Foreground challenge Spinelli+2022)
- **RFI** contaminates in spatial and frequency space
  Go to the desert, stay away from satellites *(Harper+2019, Engelbrecht+24)*
- **Foreground contaminations** Galactic emission and extra-Galactic point sources
  Avoidance and removal strategies
  (Wolz+2014, Alonso+2015, Carucci+2020, Soares+2021, Irfan&Bull21)

CAUTION: REFERENCES HIGHLY BIASED TOWARDS MEERKAT/SKA WORK

Parkes telescope detection

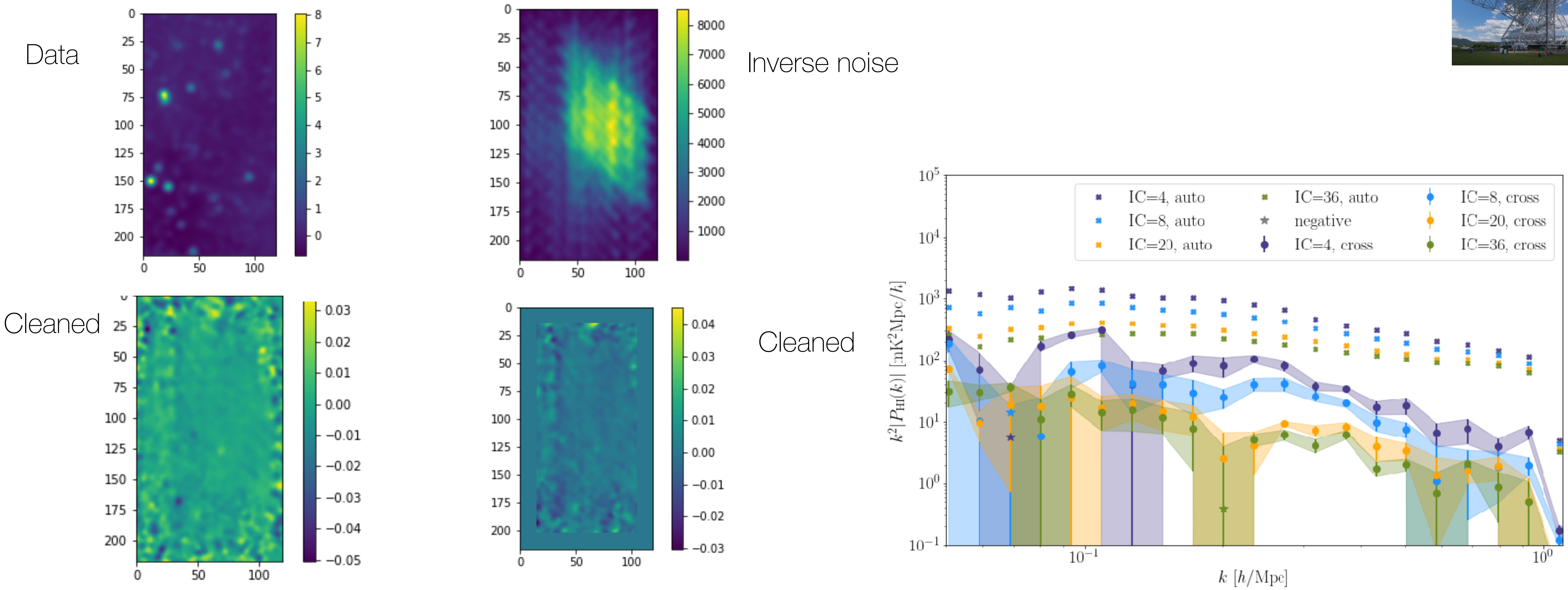




1,300sqdeg - 0.057 < z < 0.098 - 152hrs with 13beams

Anderson et al (incl LW), 2017, 1710.00424

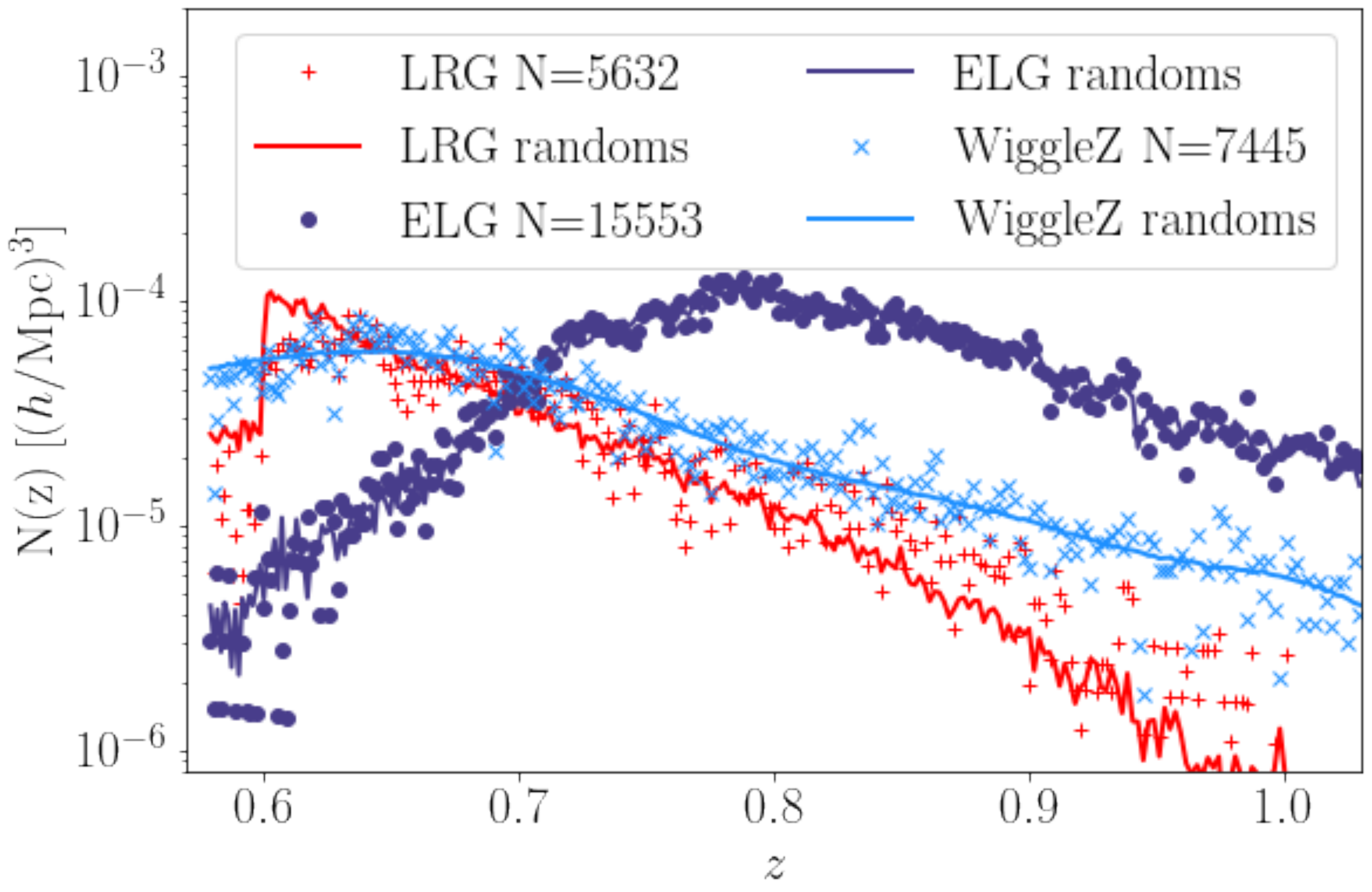
Green Bank Telescope Data

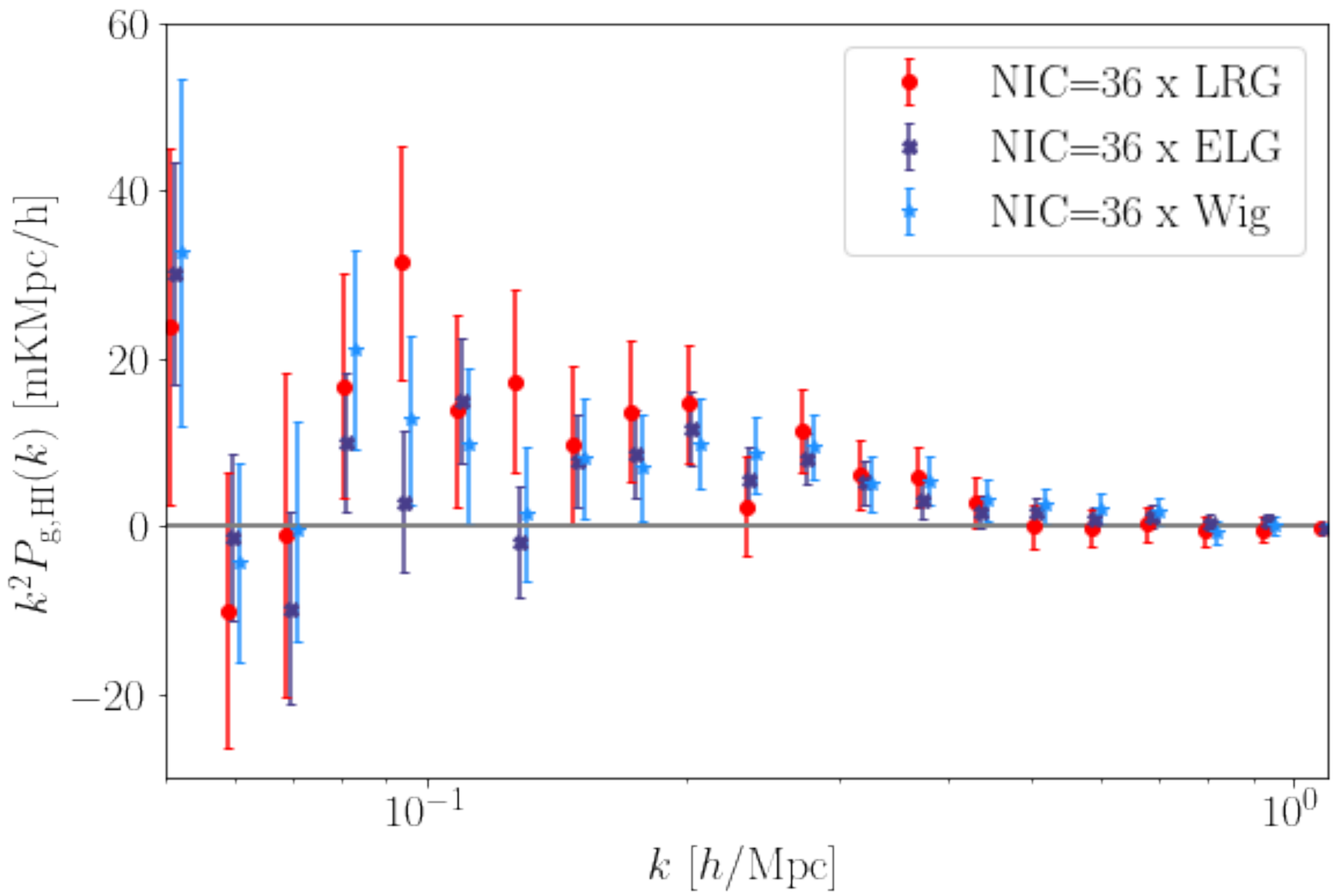


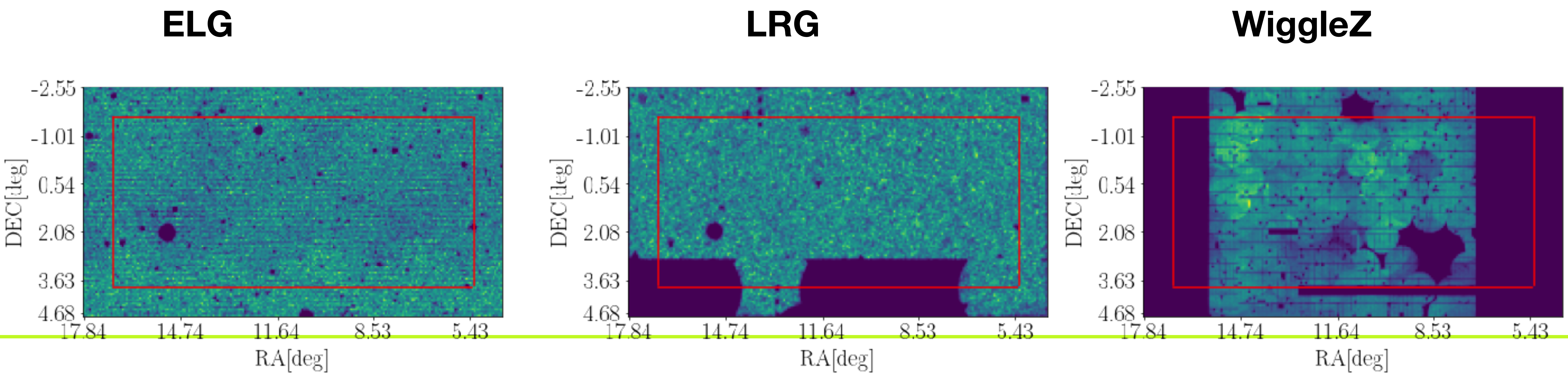
100sqdeg - 0.6<z<1.0 - 100hrs

Masui+2013, Switzer+2013, Wolz+22 2102.04946

GBT cross galaxy detections



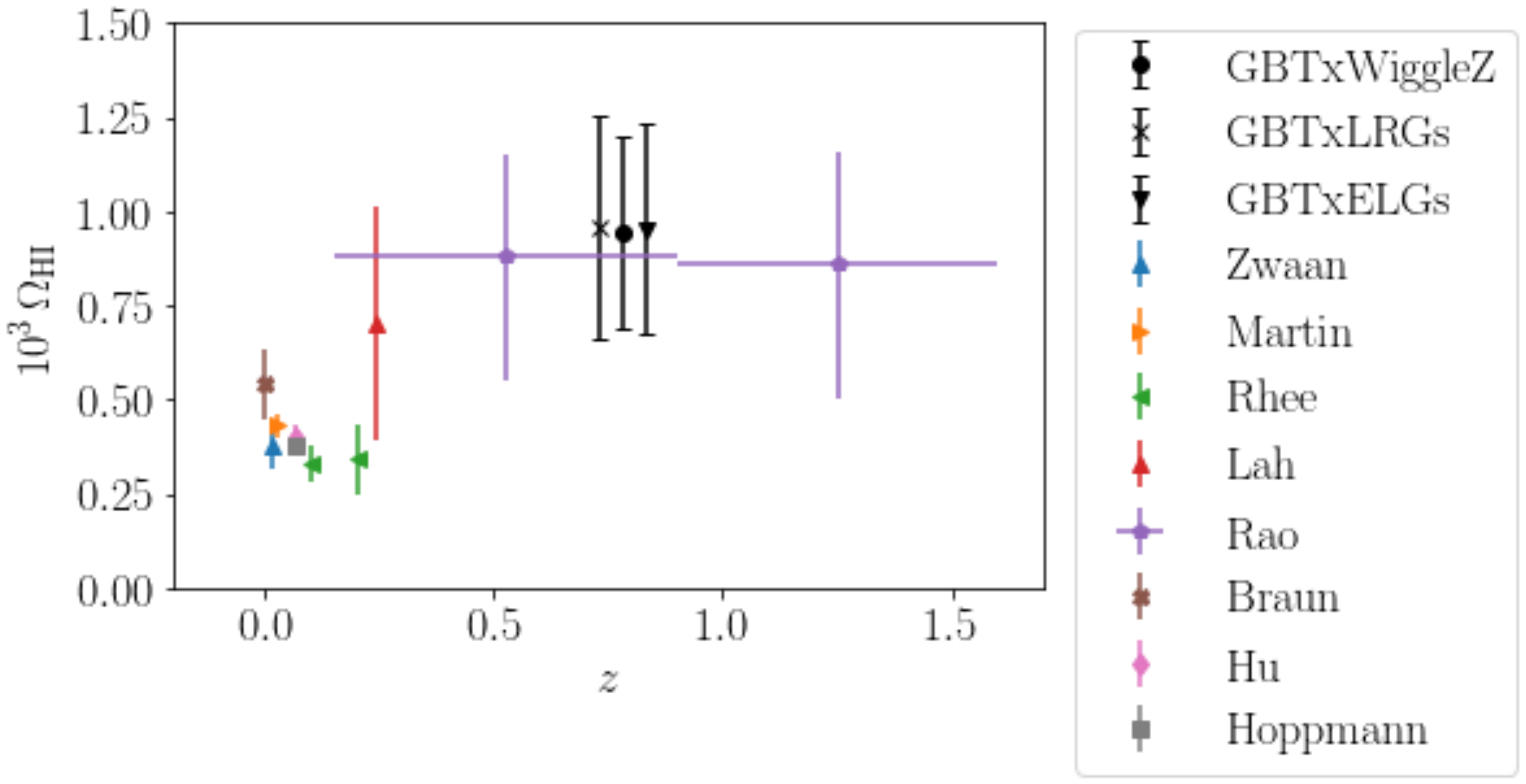




Wolz,Pourtsidou+22 2102.04946

Constrain HI density via $\Omega_{\rm HI} b_{\rm HI} r_{\rm HI-gal}$

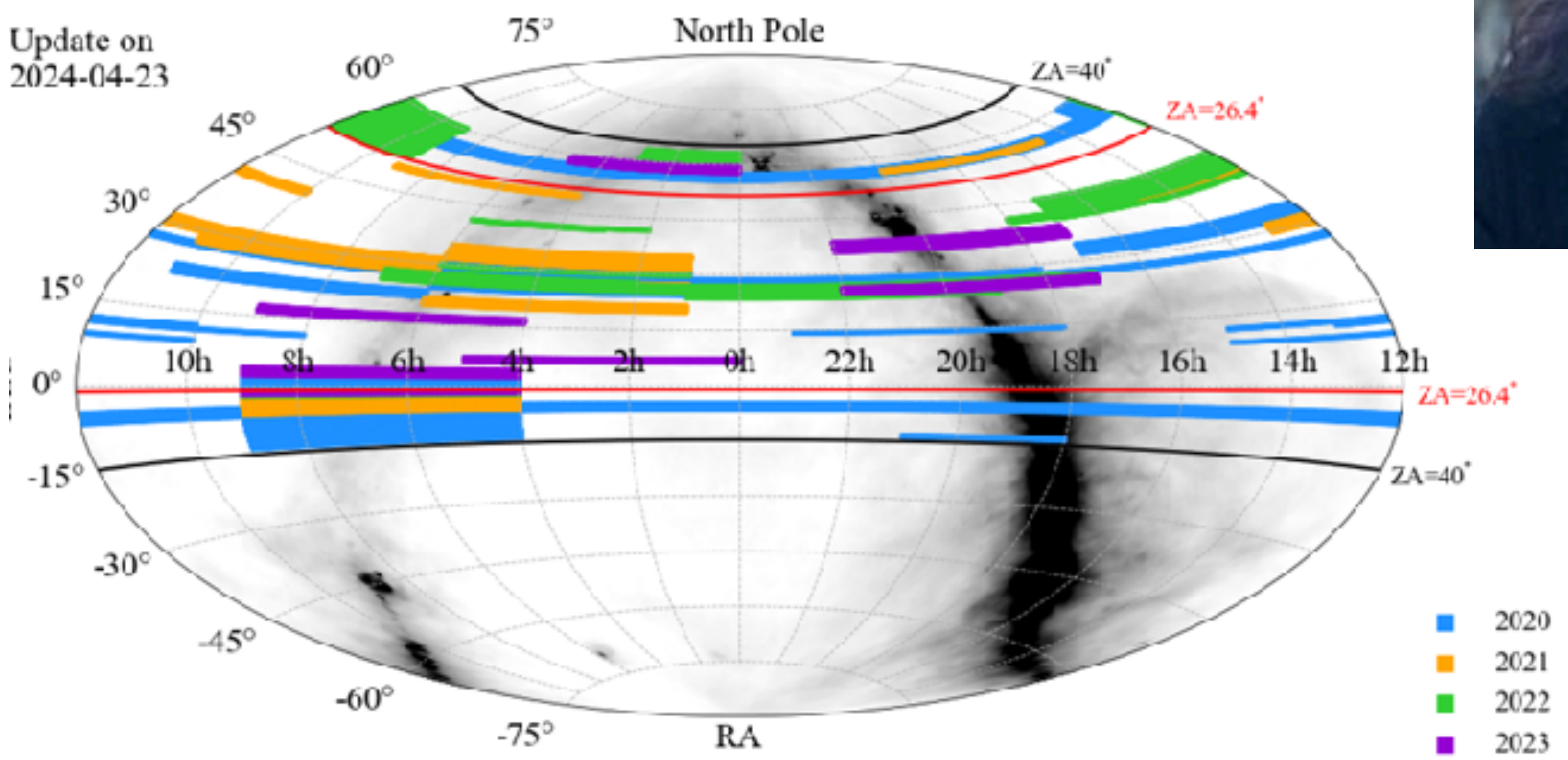
	GBTxWiggleZ	GBTxELGs	GBTxLRGs	$k_{\rm eff}$ [h/Mpc]
Case I [$k < 0.8\,h$/Mpc]				
NIC=20:	0.35 ± 0.09	0.20 ± 0.06	0.12 ± 0.06	-
NIC=36:	0.38 ± 0.08 (4.4σ)	0.26 ± 0.06 (4.5σ)	0.16 ± 0.06 (2.9σ)	0.48
Case II [$k < 0.45\,h$/Mpc]				
NIC=20:	0.53 ± 0.12	0.36 ± 0.09	0.28 ± 0.09	-
NIC=36:	0.58 ± 0.09 (4.8σ)	0.40 ± 0.09 (4.9σ)	0.35 ± 0.08 (4.4σ)	0.31
Case III [$k < 0.35\,h$/Mpc]				
NIC=20:	0.58 ± 0.17	0.48 ± 0.12	0.38 ± 0.12	-
NIC=36:	0.70 ± 0.12 (4.4σ)	0.55 ± 0.11 (5σ)	0.45 ± 0.10 (4.2σ)	0.24



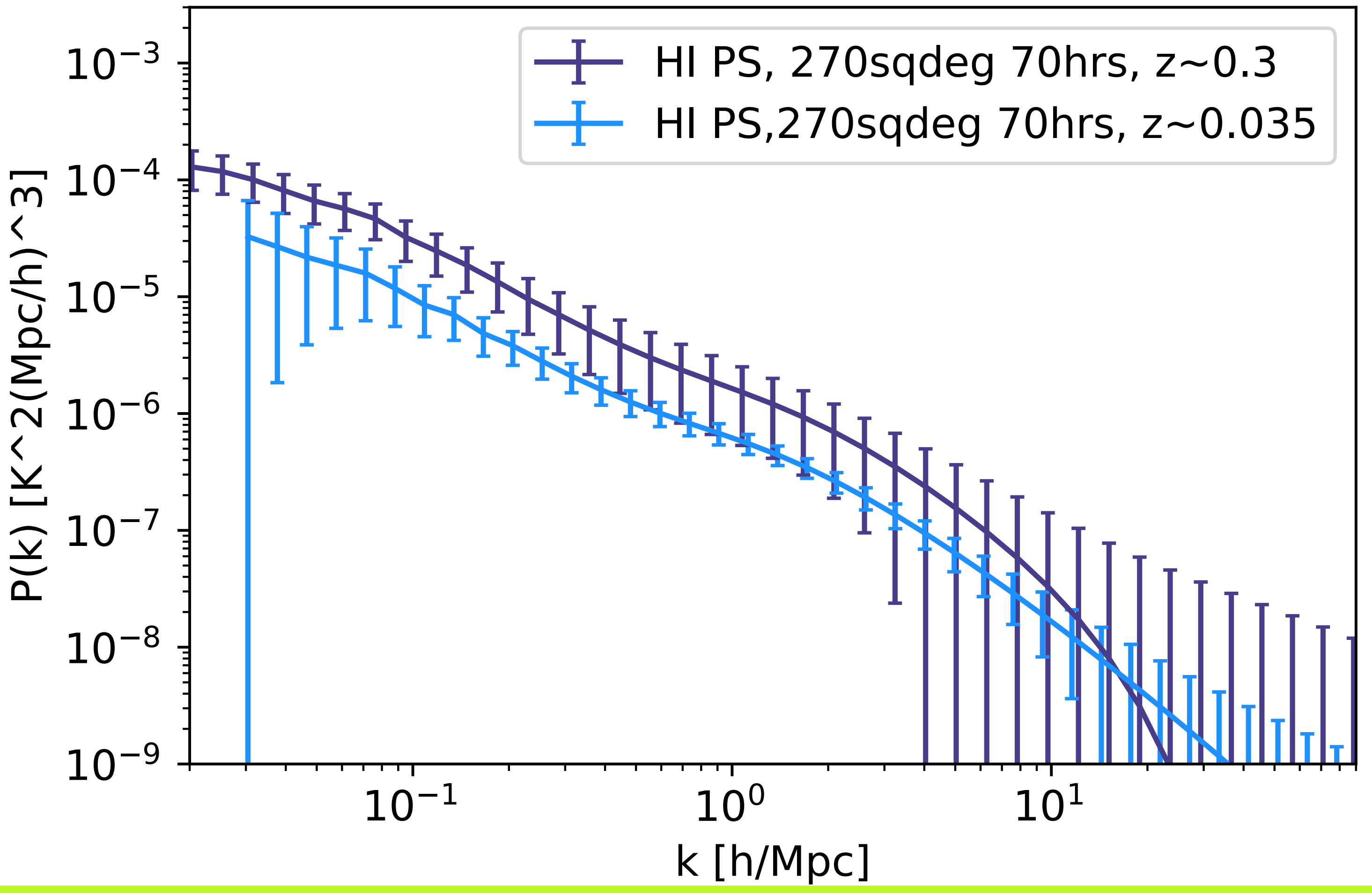
Wolz,Pourtsidou+22 2102.04946

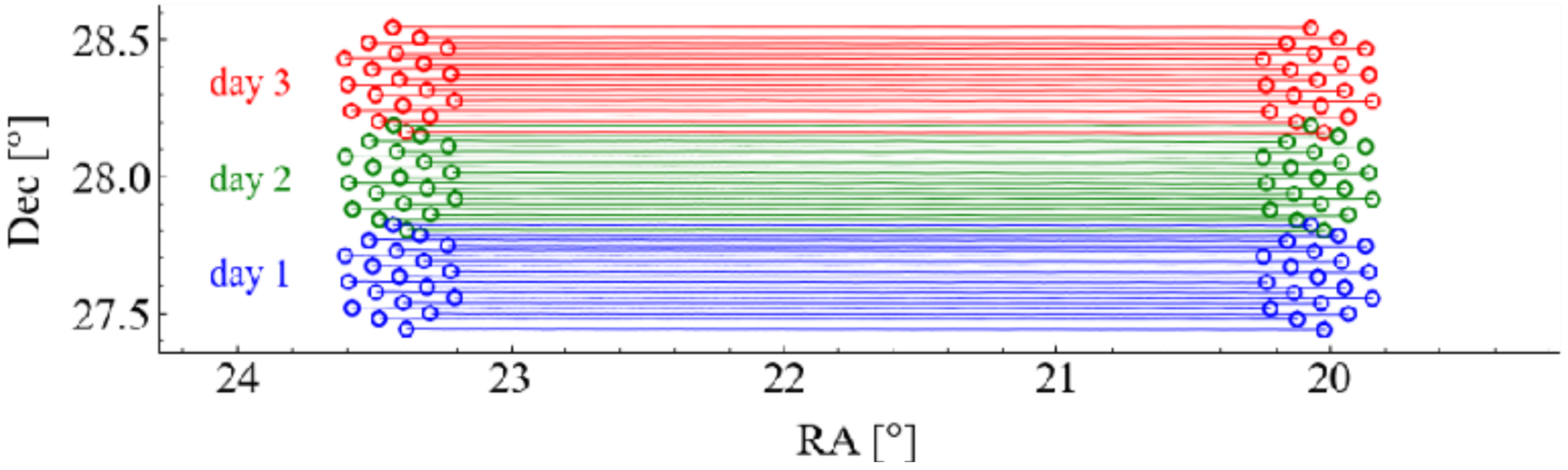
FAST HI Intensity Mapping

- FAST HI IM Pilot (Yichao Li incl LW+23) with L-band 19 beam receiver: 28hrs data over 60sq deg
- CRAFTS survey (commensal transient survey) with high-temporal resolution
- CRAFTS HI IM efforts lead by PhD student **Wenxiu Yang,** National Astronomical Observatory of China/ visiting Manchester
- Calibration pipeline development and map quality tests

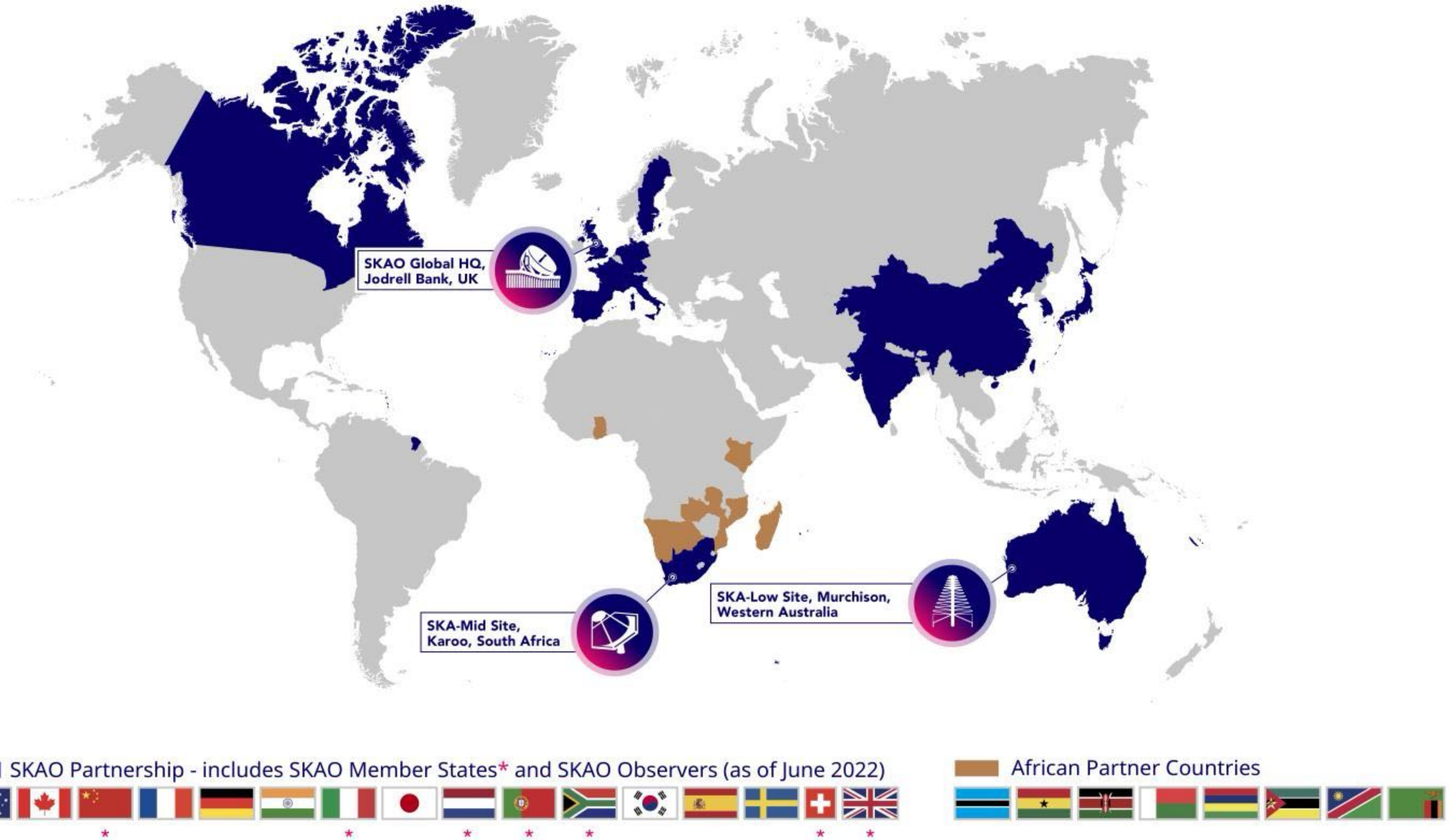


Power spectrum forecast for 270sqdeg



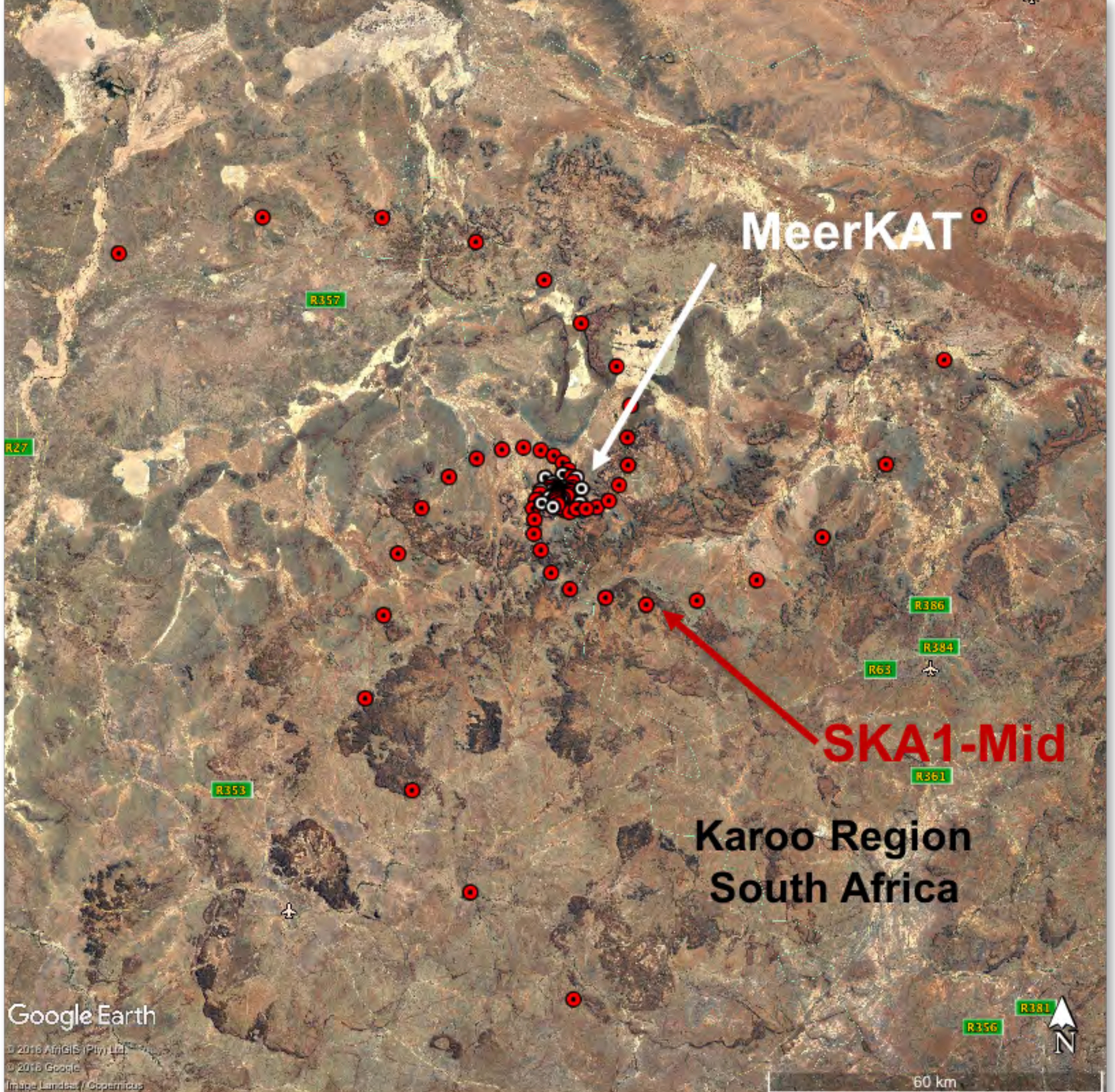


MeerKAT and the SKA




SKA1-Low
the SKA's low-frequency telescope
Location: Australia
Frequency range:
50 MHz
to
350 MHz
131,072
antennas spread between
512 stations
Maximum baseline:
~65km


SKA1-Mid
the SKA's mid-frequency telescope
Location: South Africa
Frequency range:
350 MHz
to
15.4 GHz
with a goal of 24 GHz
197 dishes
(including 64 MeerKAT dishes)
Maximum baseline:
150km


MeerKAT
SKA1-Mid
Karoo Region
South Africa
R357
R27
R386
R384
R63
R361
R353
R381
R356
N
Google Earth
60 km

Number of antennas	64 (offset Gregorian)
Dish diameter (nominal)	13.5 m
Minimum baseline	29 m
Maximum baseline	7700 m
Array phase centre	30° 42′ 39.8″ South, 21° 26′ 38.0″ East, 1086.6 m Elevation
Frequency range (UHF)	580 - 1015 MHz [544 to 1088 MHz digitised]
Frequency range (L-band)	900 - 1670 MHz [856 to 1712 MHz digitised]

From MeerKAT to SKA-MID

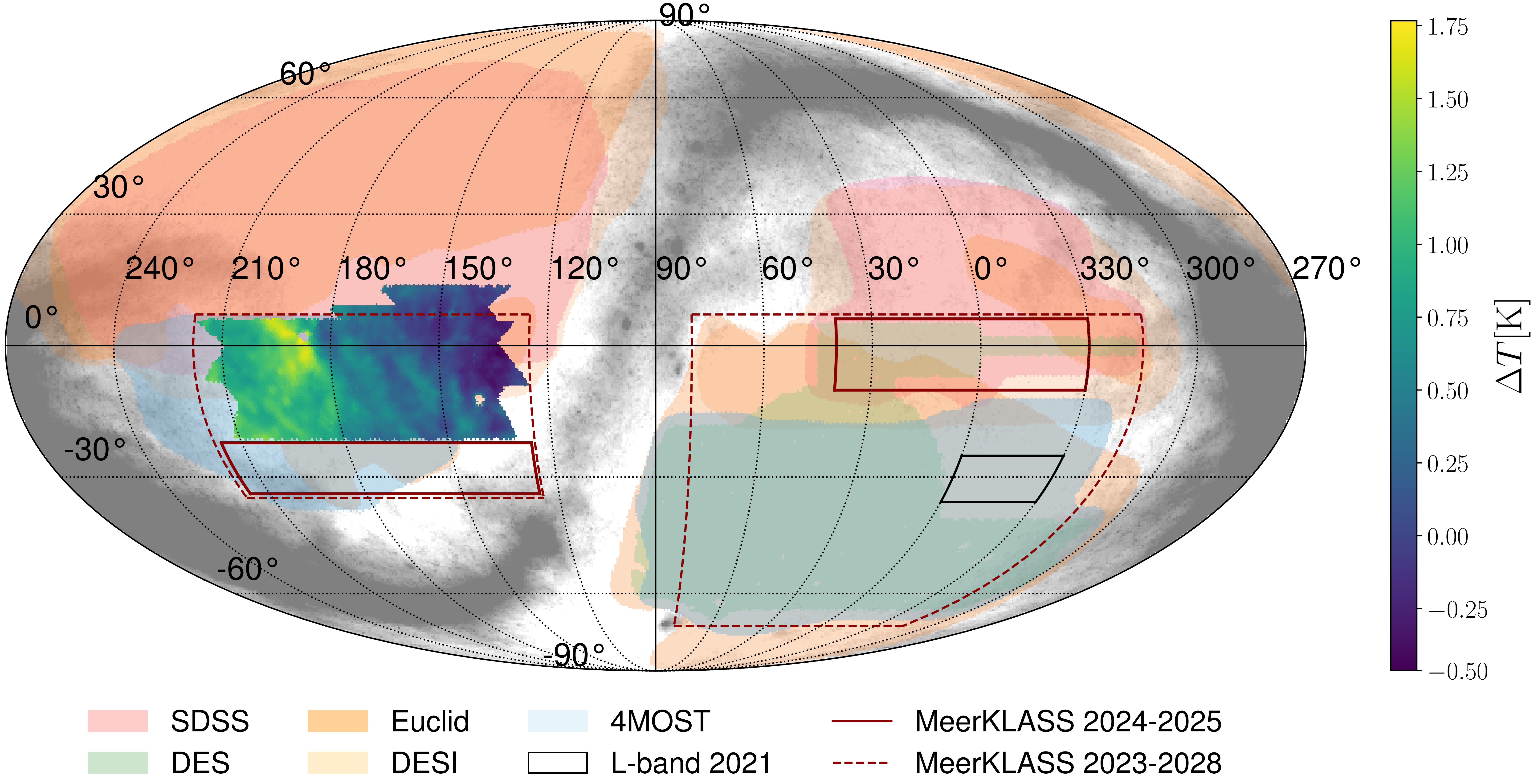
- SKAO plans a **staged delivery via array assemblies**
- MeerKAT has 64 13.5 dishes with maximum of 7.7km baseline (irrelevant for single dish…)
- There will be 20 more 15m so-called MeerKAT+dishes
- SKAO adds 64 15m dishes in the first stage, to form AA* in 2028
- SKA1 will include further ~50 dishes; timeline tba
- *MeerKAT has a third of dishes compared to SKA1-Mid*

Milestones	Mid (end-date)
AA0.5 • 4 Mid dishes • 6 Low stations	2025 May
AA1 • 8 Mid dishes • 18 Low stations	2026 Apr
AA2 • 64 Mid dishes • 64 Low stations	2027 Mar
AA* (staged delivery plan) • 144 Mid dishes • 307 Low stations	2027 Dec
Operations Readiness Review	2028 Apr

MeerKLASS - MeerKAT Large Area Synoptic Survey

PI M. SANTOS; WP LEADERS: CALIBRATION - J. WANG, W. HU, POWER SPECTRUM - S.CUNNINGTON, I.CARUCCI, SIMULATIONS - Z. FONSECA, M. SPINELLI

MeerKLASS - MeerKAT Large Area Synoptic Survey



10,000 sq deg with 1,300hr effective time in UHF band

SOURCE: MEERKLASS PROPOSAL,
CREDIT: M. SPINELLI, W. HU & OTHERS

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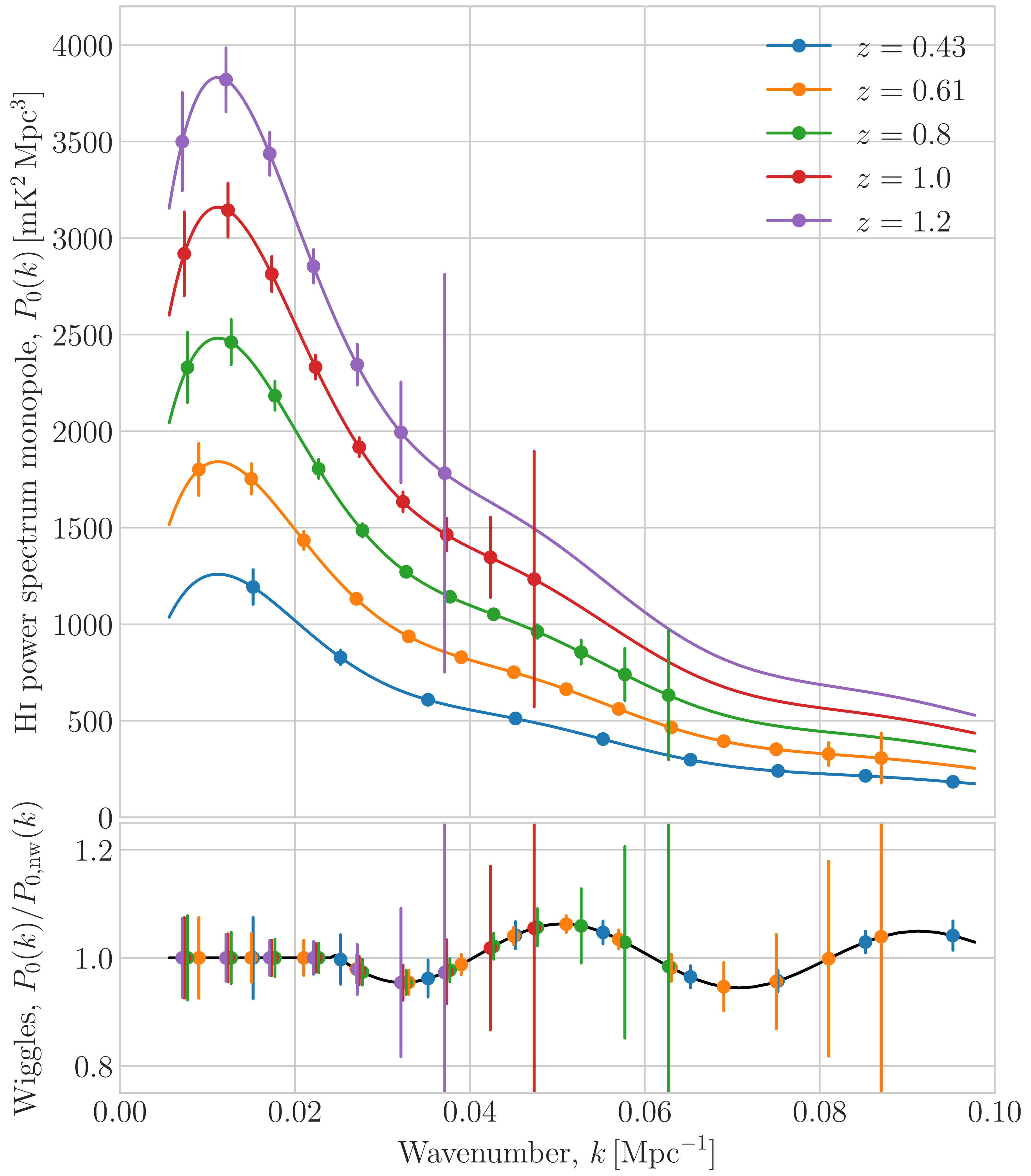
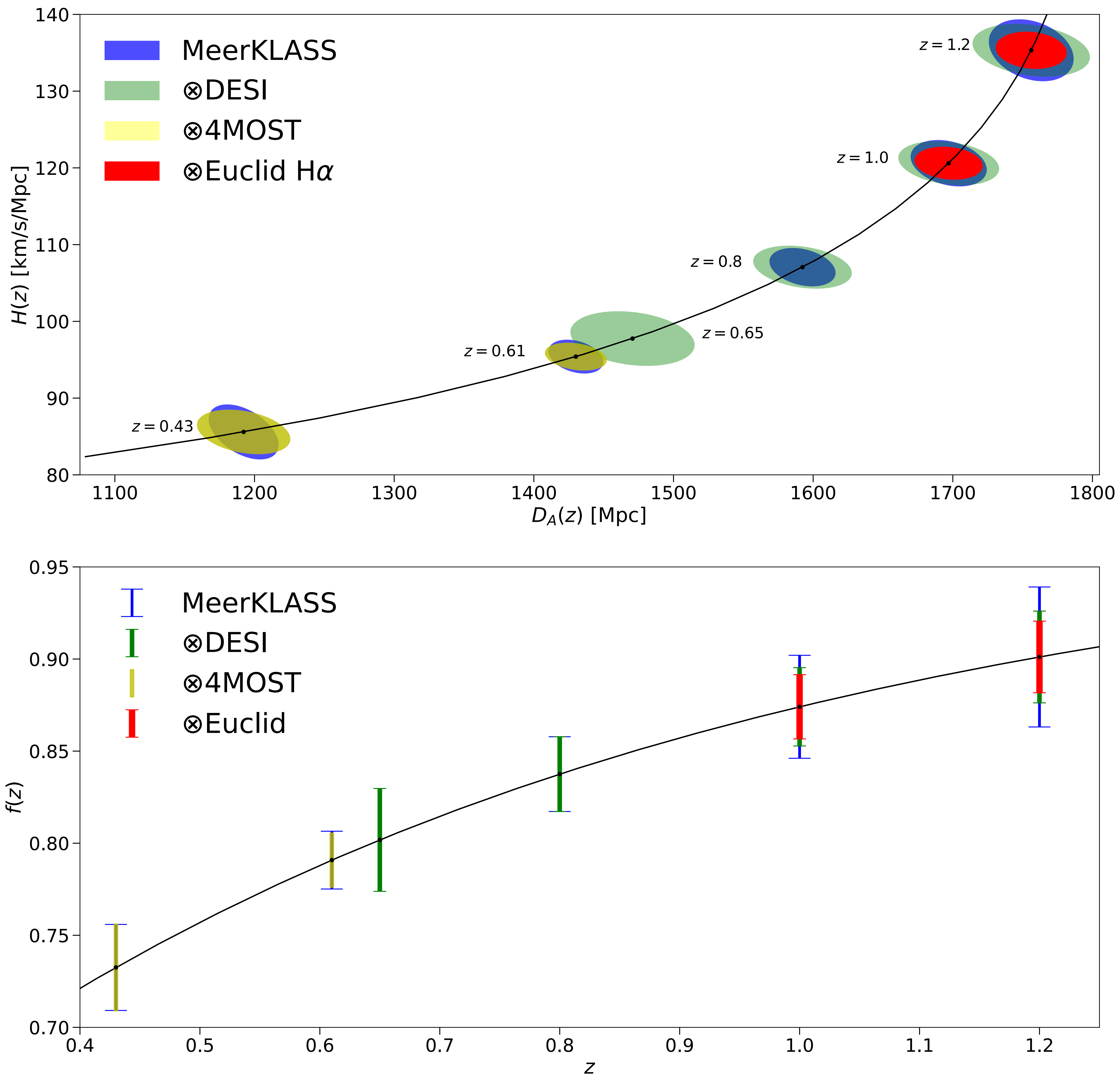
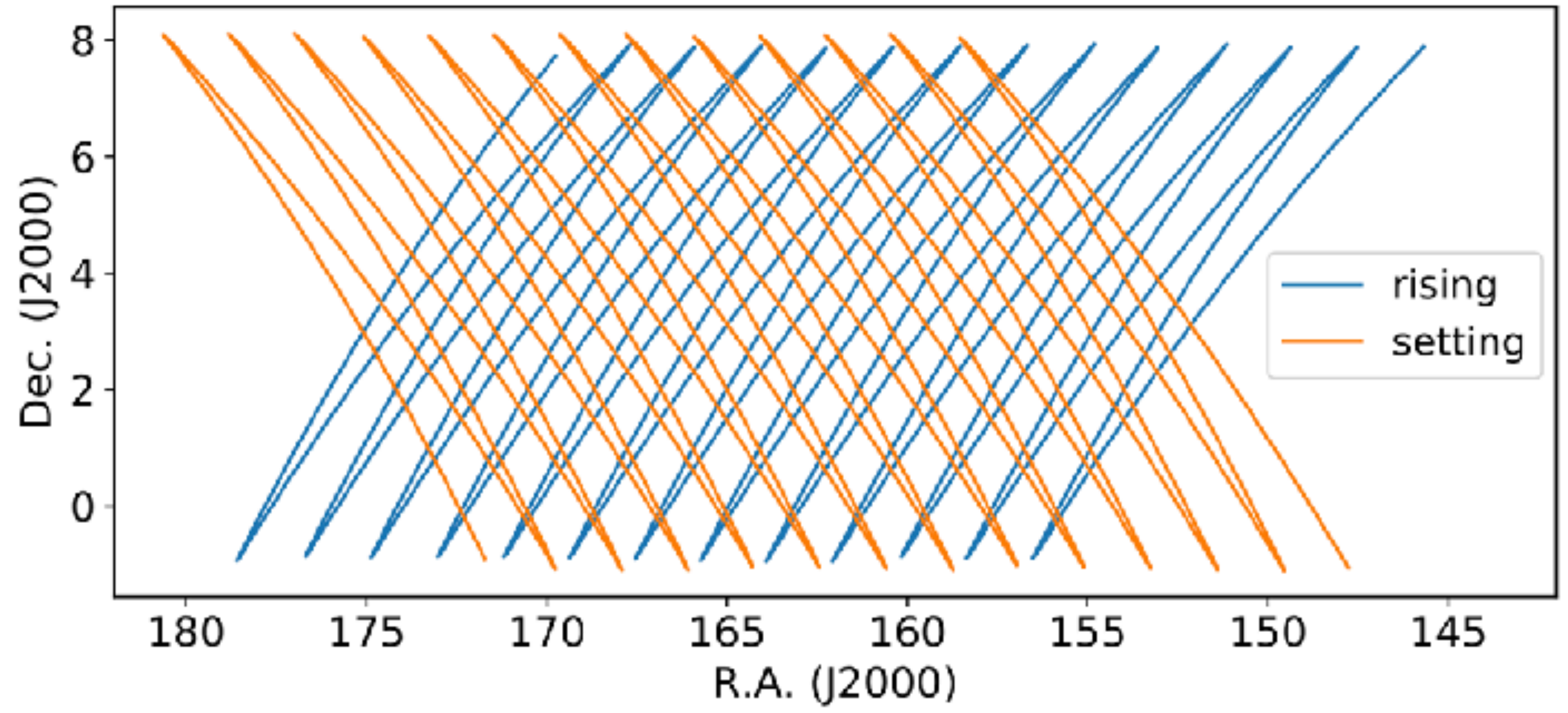


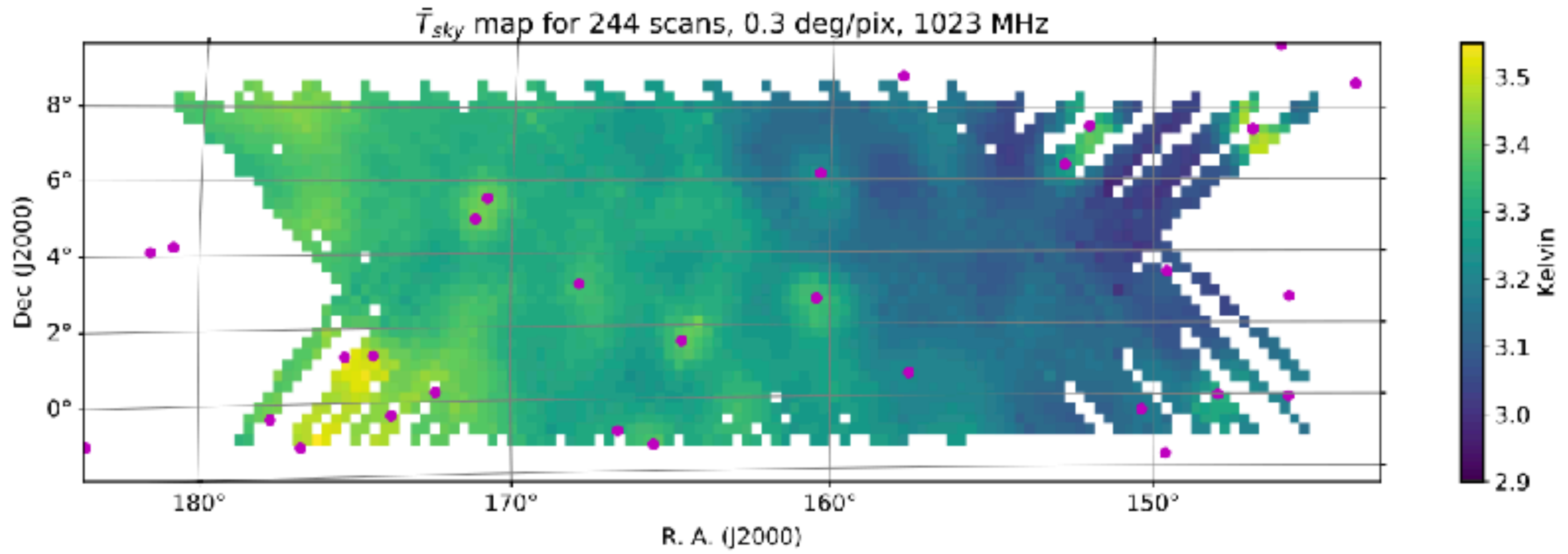


SOURCE: MEERKLASS PROPOSAL,
CREDIT: Z. FONSECA, S. CAMERA

MeerKLASS - Single Dish

- Each patch is about **300sqdeg with 1.5hrs** on-target
- Azimuth scans at constant elevation (5arcmin/s for L-band) with 2s integration
- Repeated scans per block for both rising and setting
- Successful calibration pipeline, see **Jingying Wang**'s talk
- Many optimisation efforts for data analysis, see **Isabella Carucci**'s talk
- 2 cross-correlation detections in L-band with galaxy samples so far, see **Steve Cunnington**'s talk





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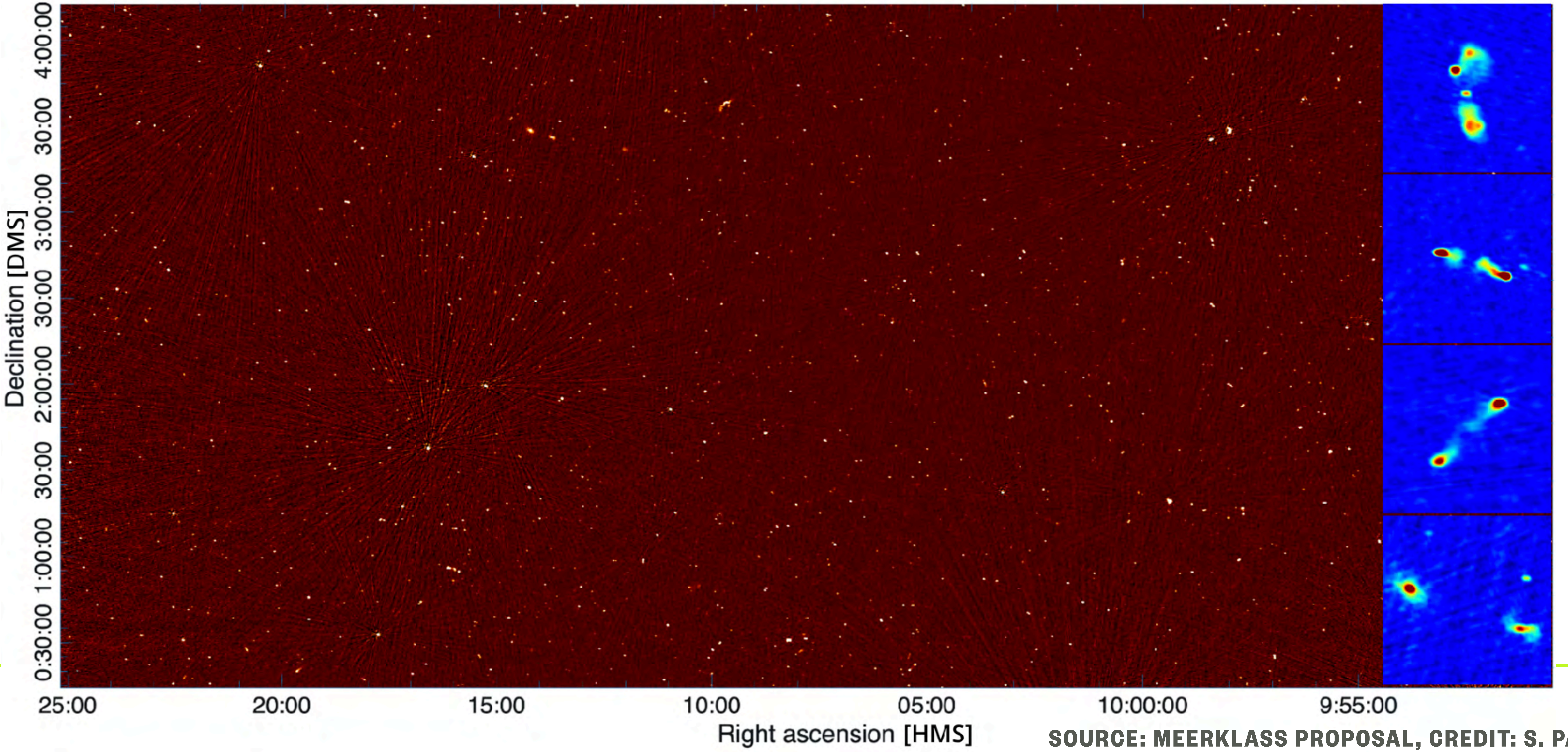
Wang et al 21; arXiv:2011.13789

MeerKLASS - OTF Continuum



SOURCE: MEERKLASS PROPOSAL, CREDIT: S. PAUL

SKA Cosmology surveys

a) Medium–Deep Survey of 5,000 deg^2 at 0.95-1.4 GHz for
- HI galaxy redshift survey with 3.5 million objects
- Weak Lensing shape measurements with ~50 million objects
- Continuum galaxy survey with ~60 million objects

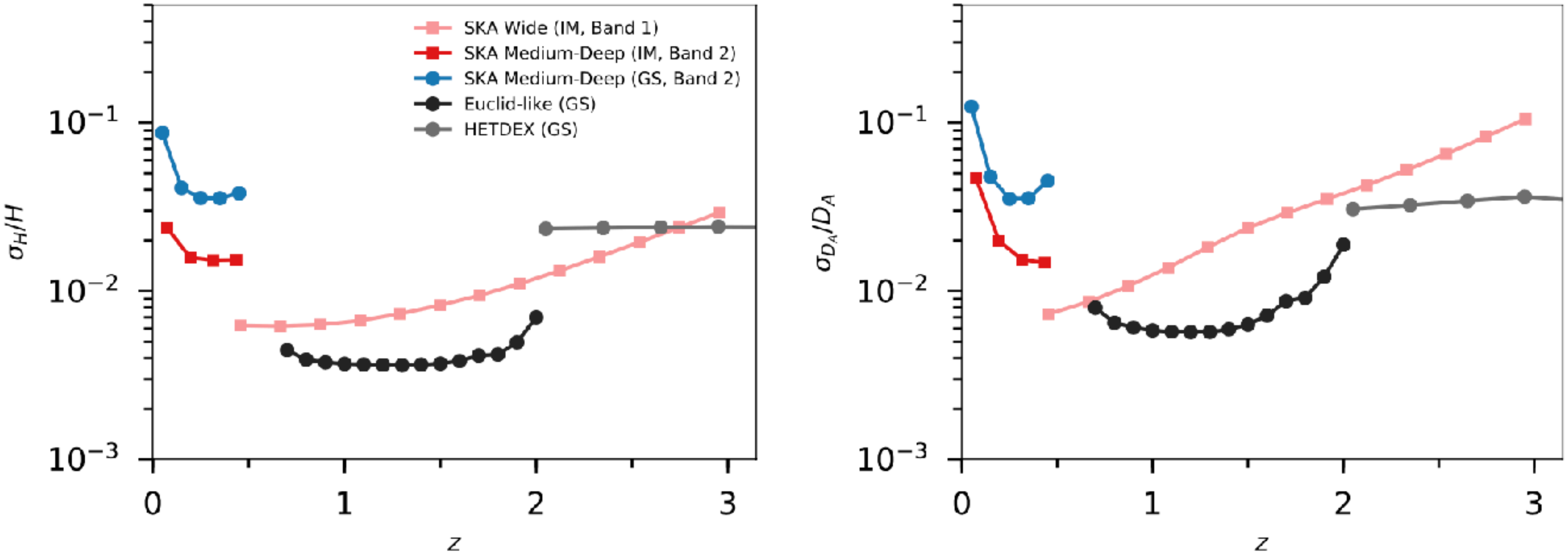
b) Wide Survey of 20,000 deg^2 at 0.35-1.05 GHz for
- Continuum galaxy survey with ~100 million objects
- HI intensity maps for $0.35<z<3$

c) Deep Survey 100 deg^2 at 200-350 MHz for
- HI intensity maps for $3<z<6$

SKA Cosmology SWG Red Book, arxiv:1811.02743

Update for SKA Science Book in 2025!

SKA HI Intensity Mapping



Note: SKA-MID has lower frequency coverage than MeerKAT f>300

SKA-Low can observe for f<300MHz: important for continuous mapping!

SKA Cosmology SWG Red Book, arxiv:1811.02743

Questions moving forward

- Transition from pilot to survey era: are our pipelines scalable? Are our estimators appropriate?
- Beam models: are they good enough for precision cosmology?
- Low-level RFI: how can we deal with (increasing amount of) contaminations?
- Can we overlap between independent surveys to detect auto-power with high significance?
- For MeerKAT & SKA-MID: how do we measure the scales between single dish and interferometry?
- For SKA-Mid and -LOW: how do we consistently map transition at z=3?
- **MeerKAT produces lots of data every day, get involved!**