Cosmological detections from HI intensity mapping using the SKAO pathfinder MeerKAT

Steve Cunnington - University of Manchester

(work in collaboration with) Yichao Li, Mario G. Santos, Jingying Wang, Isabella P. Carucci, Melis O. Irfan, Alkistis Pourtsidou, Marta Spinelli, Laura Wolz, Paula S. Soares, Chris Blake, Philip Bull, Brandon Engelbrecht, José Fonseca, Keith Grainge, Yin-Zhe Ma

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Karoo Desert, South Africa

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The University of Manchester

UK Research and Innovation

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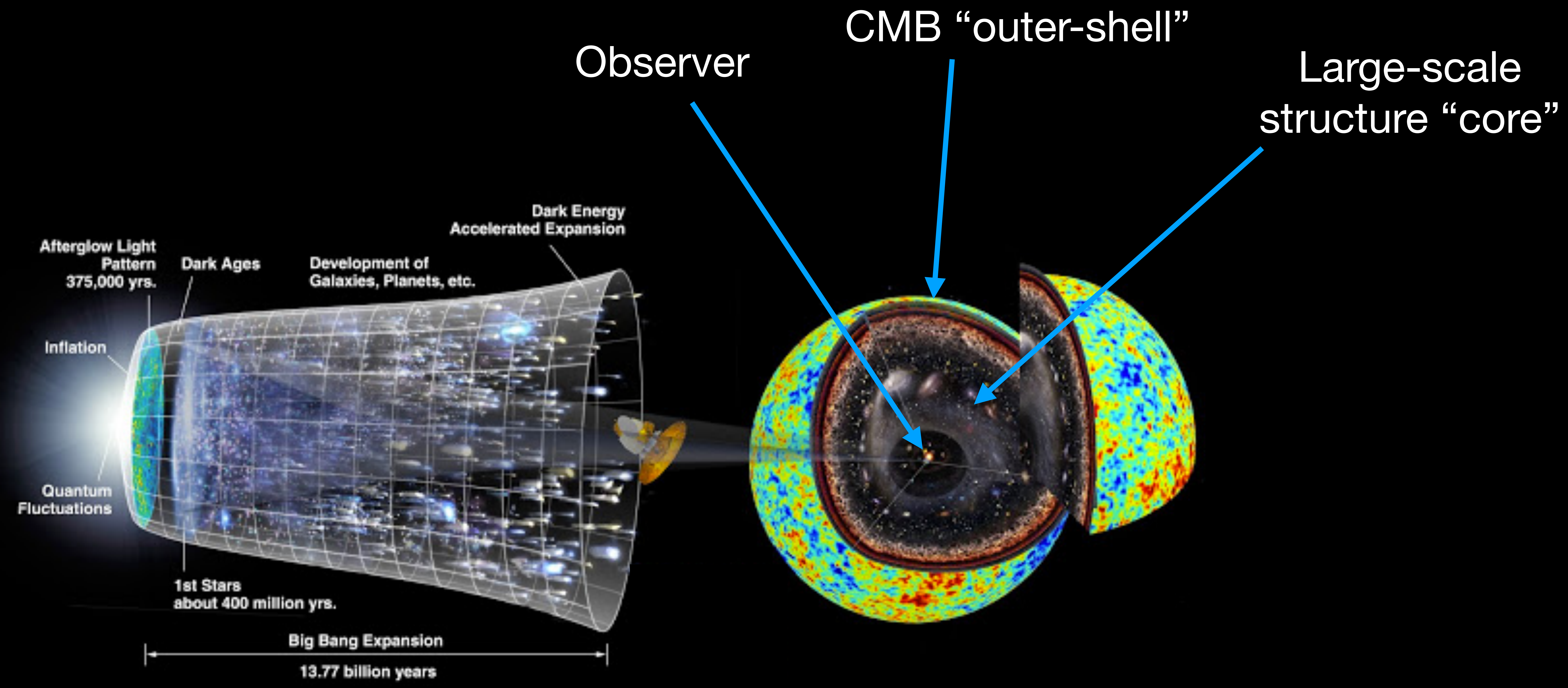
Why study large-scale cosmic structure?



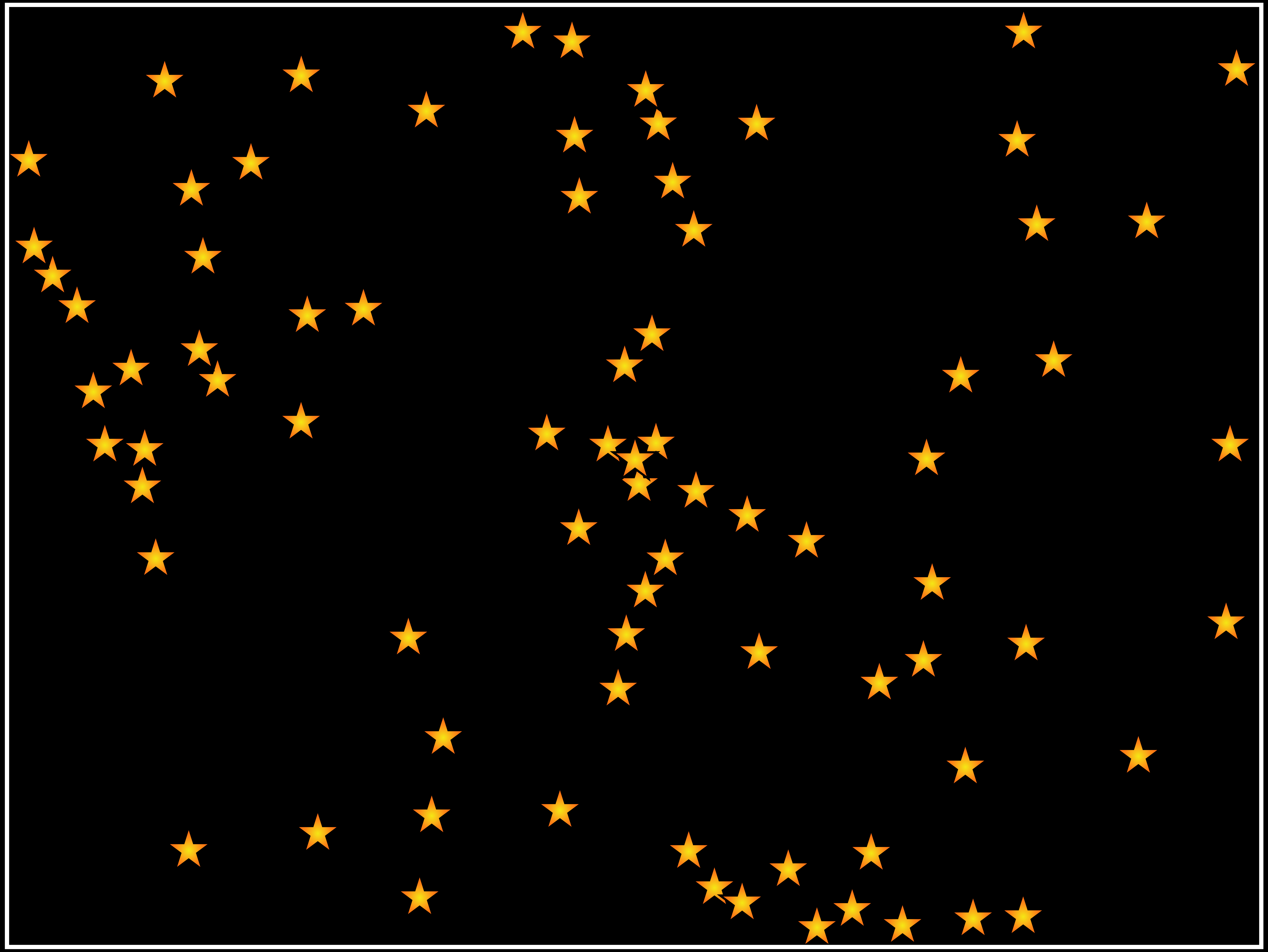
Observer

CMB “outer-shell”

Large-scale structure “core”

Steve Cunnington [steven.cunnington@manchester.ac.uk]

Probing large-scale cosmic structure



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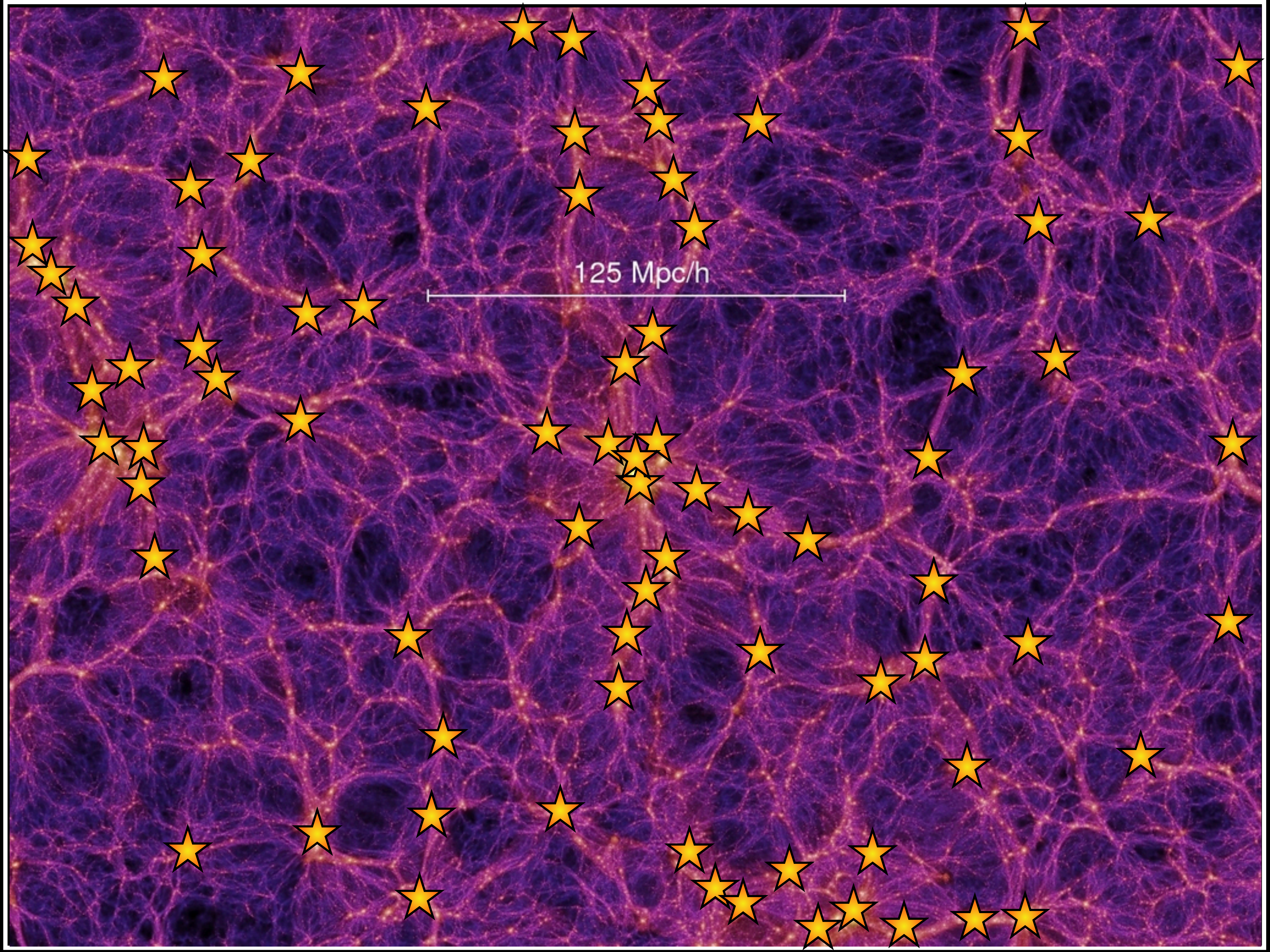
Probing large-scale cosmic structure



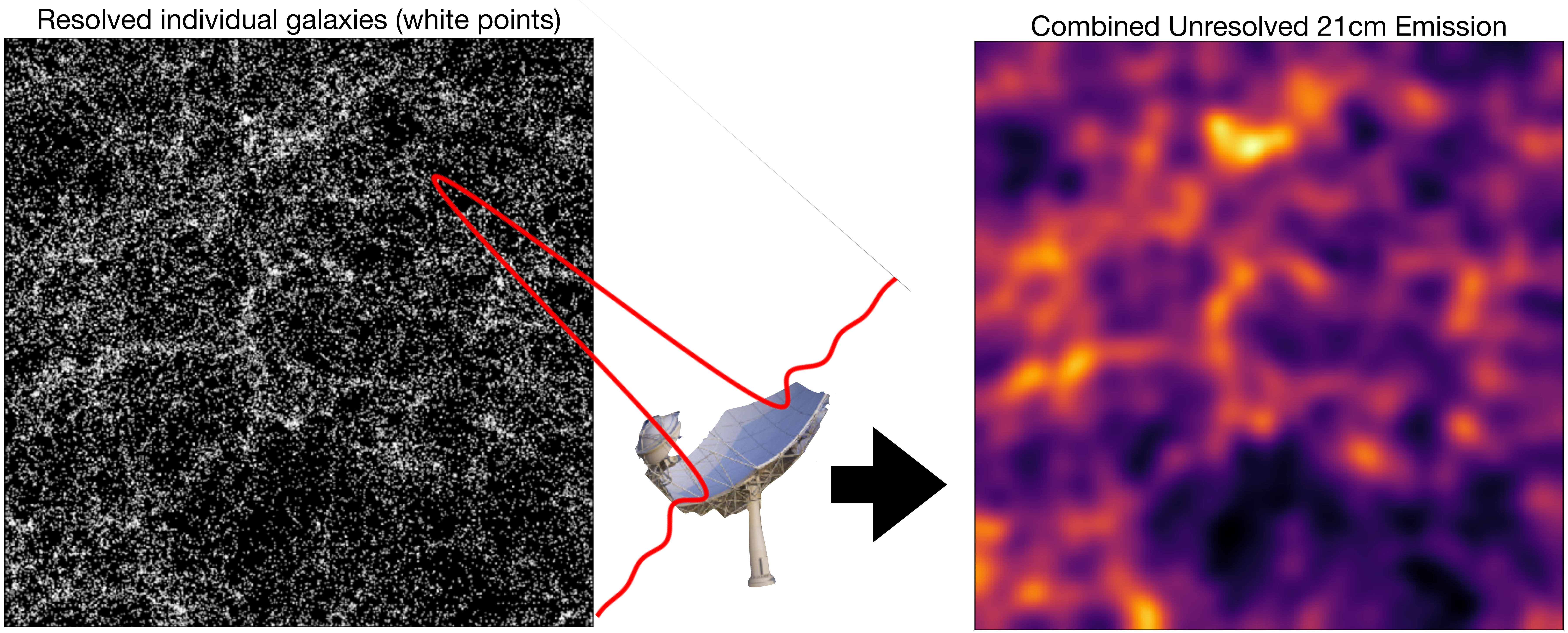
The Millennium
Simulation Project

Steve Cunnington [steven.cunnington@manchester.ac.uk]

Other ways to map large-scale structure?

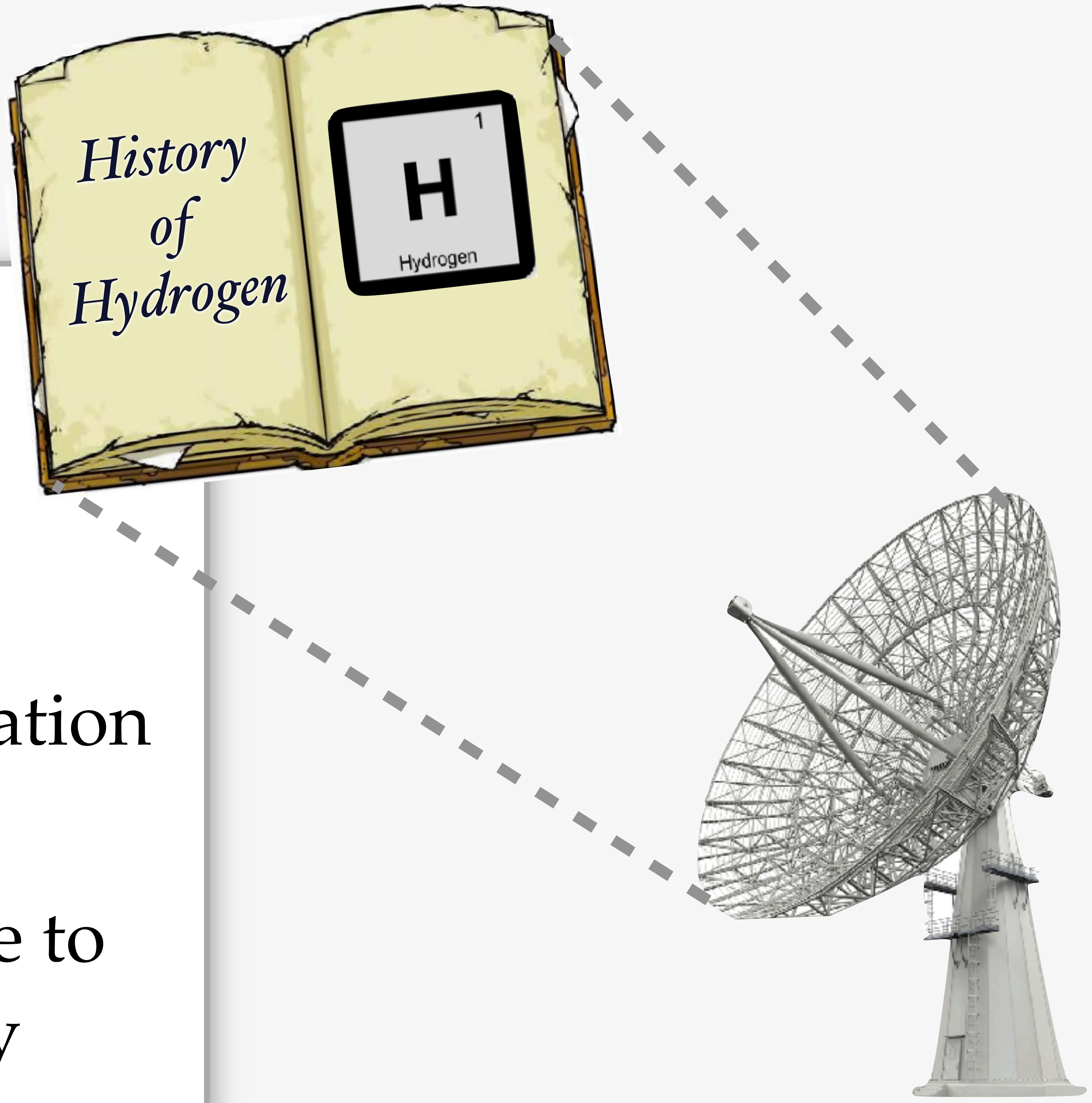
- Record the combined and unresolved emission from all sources?

This is known as … **intensity mapping**



Why 21cm HI (neutral hydrogen)?

- Most abundant element in the Universe
- In the late Universe it remains un-ionised (neutral) inside galaxies so can emit 21cm radiation
- 21cm spectral feature is a very “clean” feature to detect with radio receivers which are relatively cheap to mass produce



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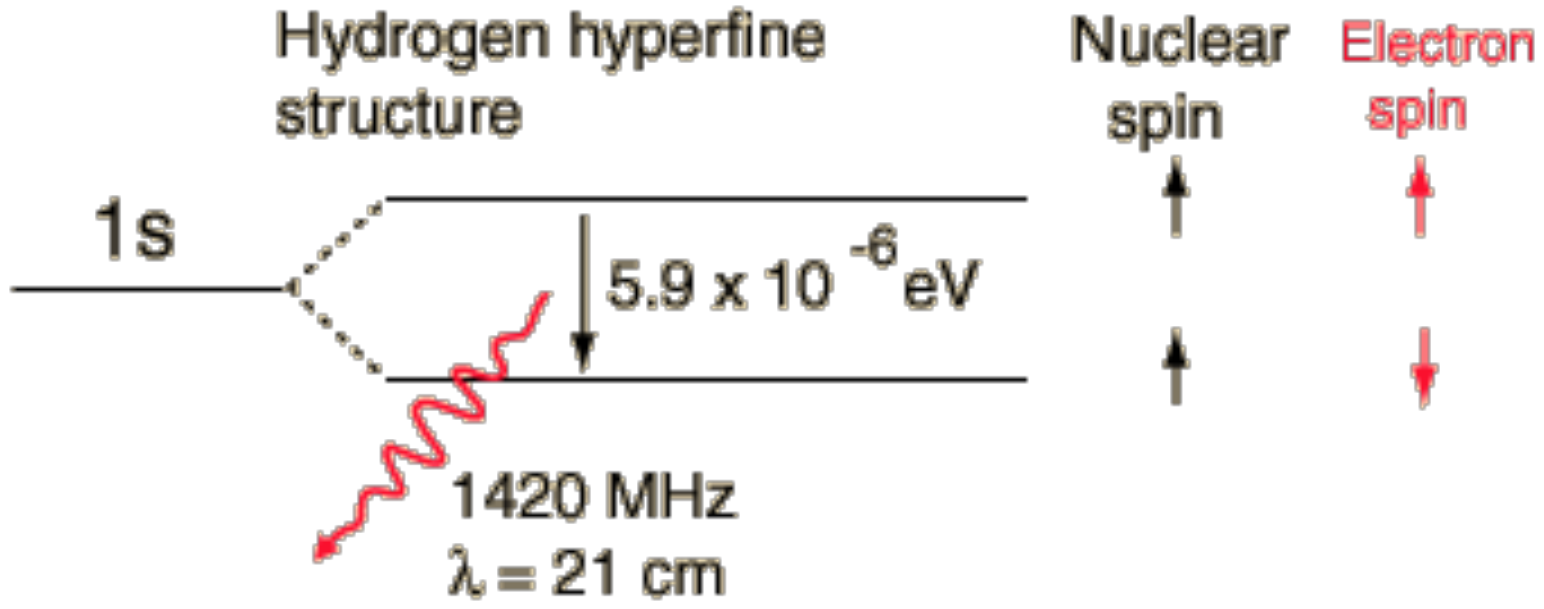
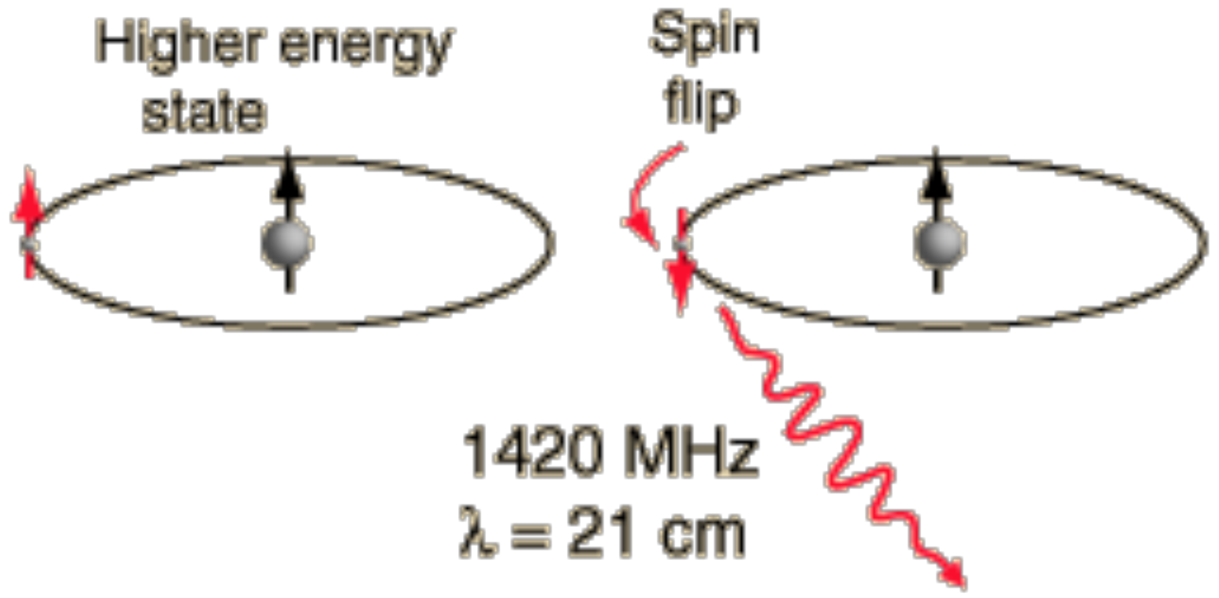
Why 21cm HI (neutral hydrogen)?

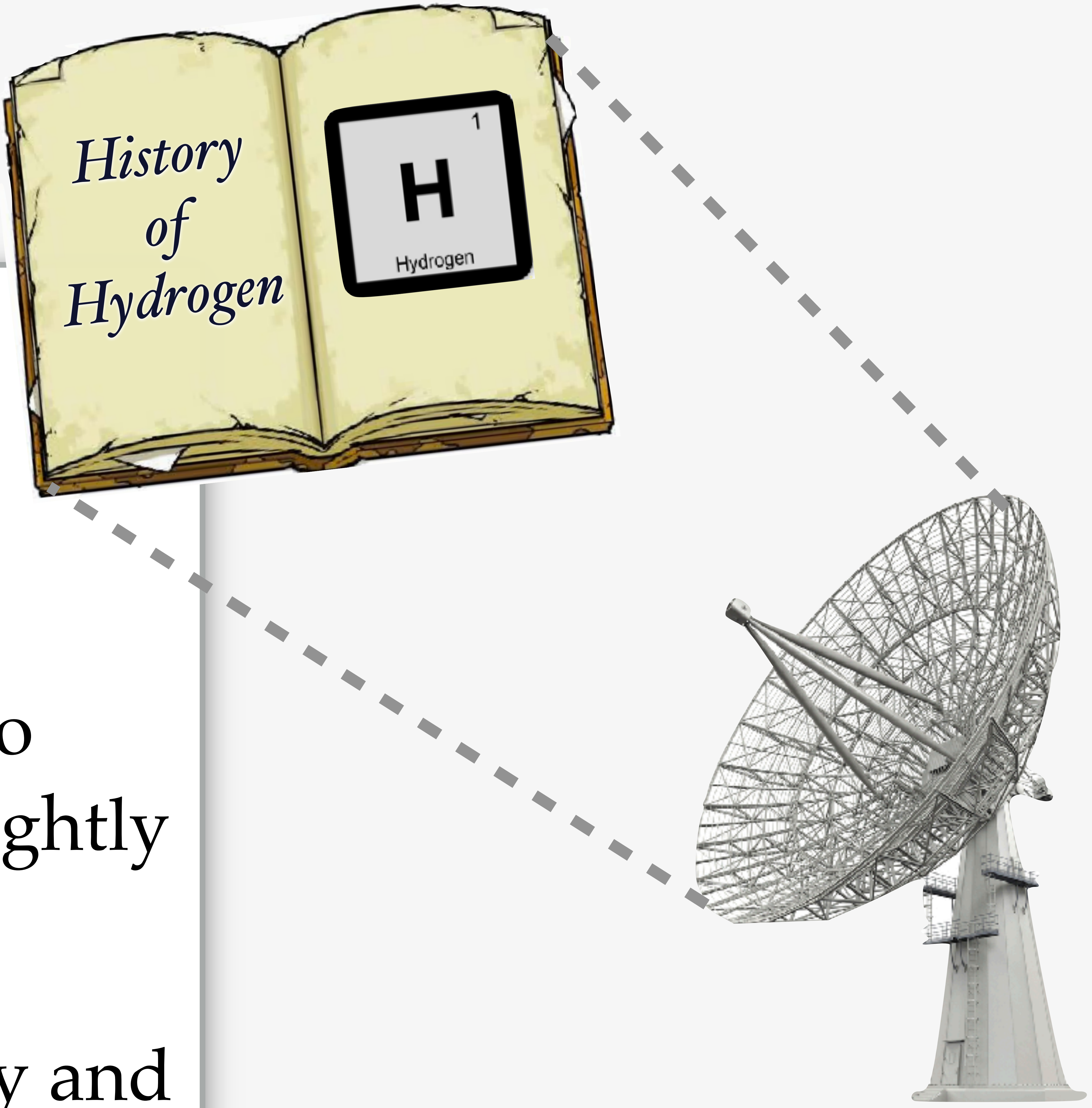
HI ground state has hyperfine structure





This allows its electron to undergo a spin flip to slightly lower energy state

This emits a photon with small amount of energy and consequently a large (radio) wavelength of **21cm**



CAASTRO
ALL-SKY ASTROPHYSICS

Challenges to overcome with intensity mapping

Cosmological HI

Extra-galactic point sources

Galactic free-free

Foregrounds

Galactic synchrotron

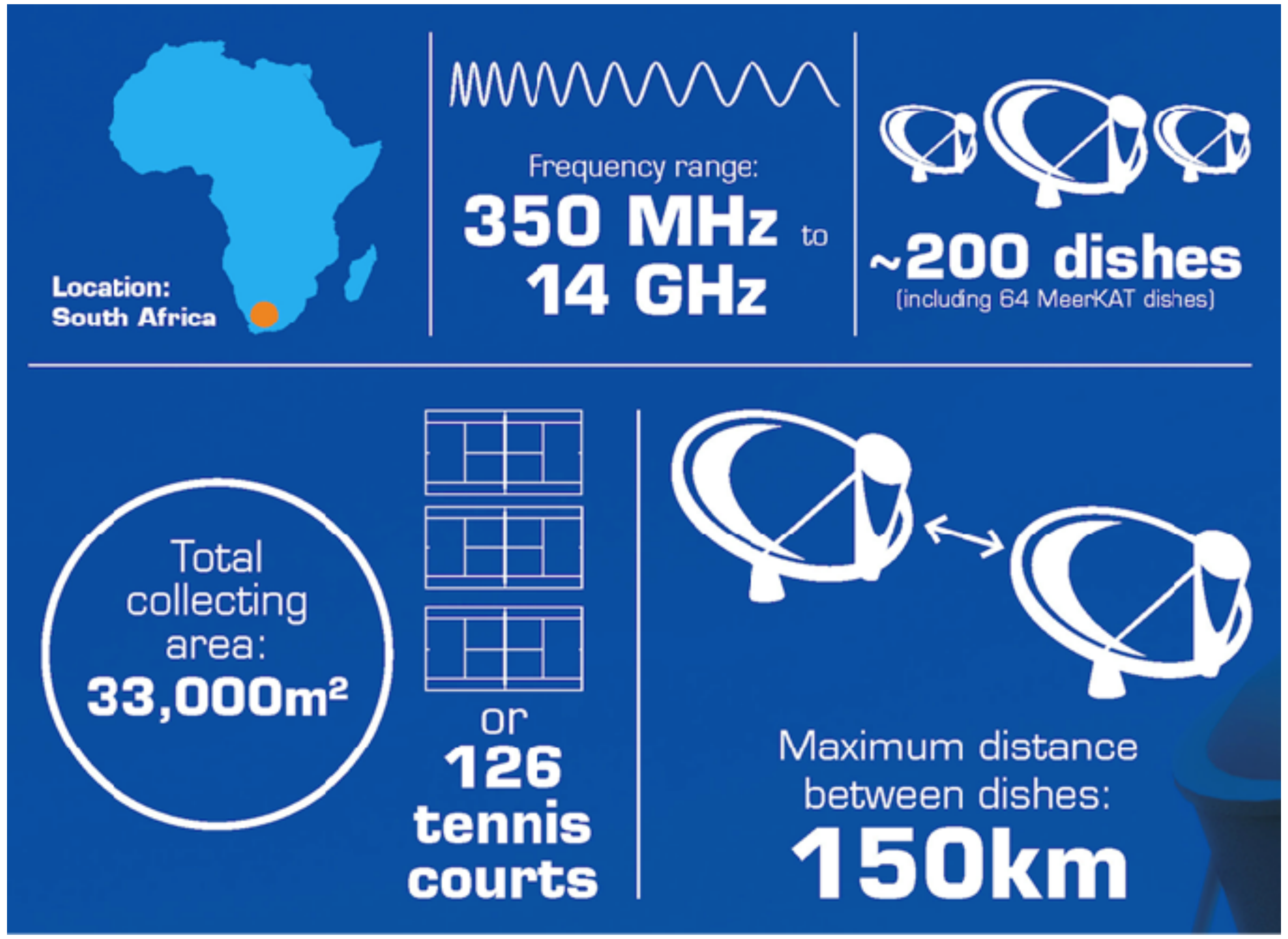
RFI (Radio Frequency Interference)

Instrumental noise

21cm intensity mapping experiments

Square Kilometre Array Observatory (SKAO)
- first light: LATE 2020’s

SKA1 - MID (South Africa)

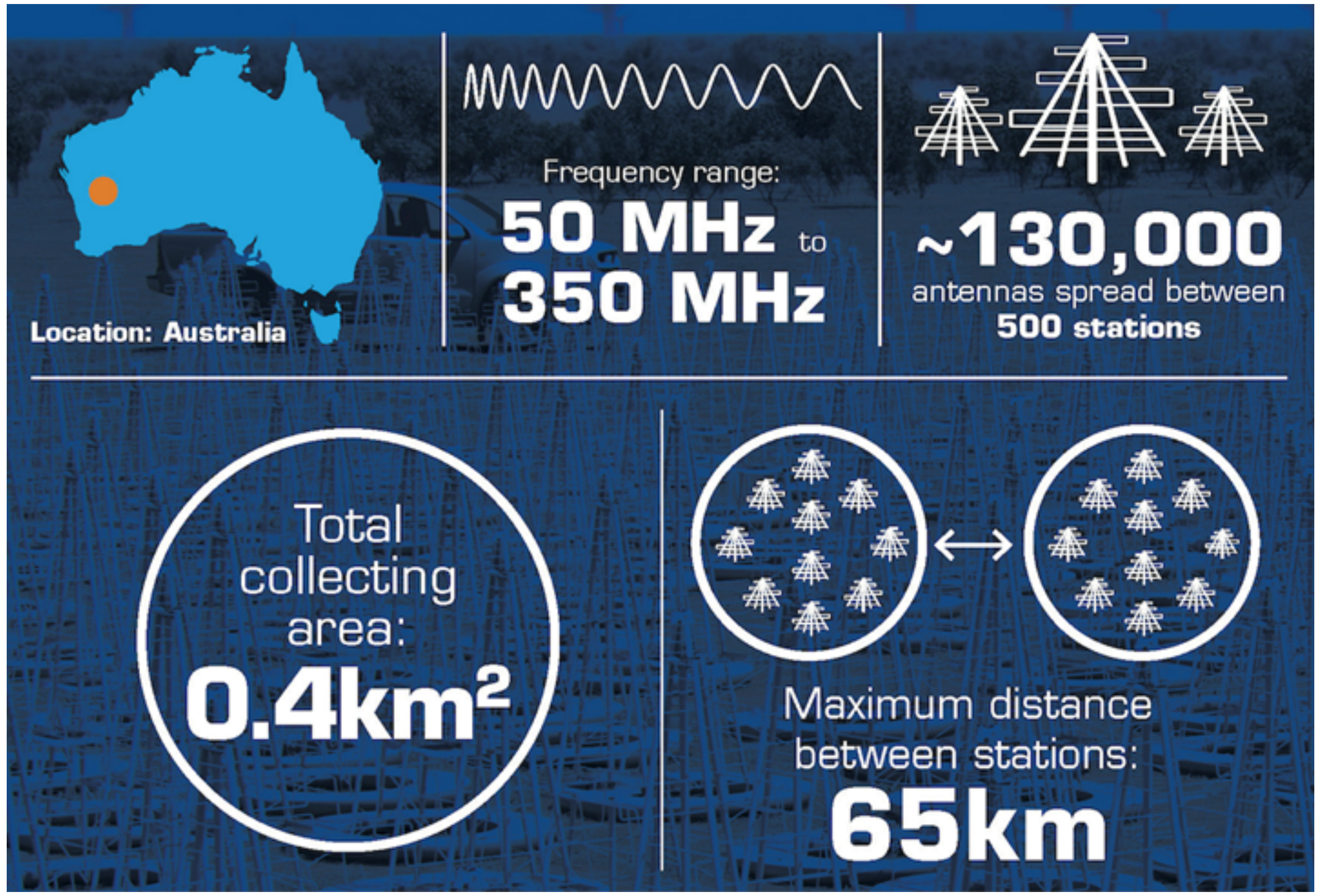


- Redshift range: $0 < z < 3$

21cm intensity mapping experiments

Square Kilometre Array Observatory (SKAO)
- first light: LATE 2020's

SKA1 - LOW (Australia)



- Redshift range: $z > 3$

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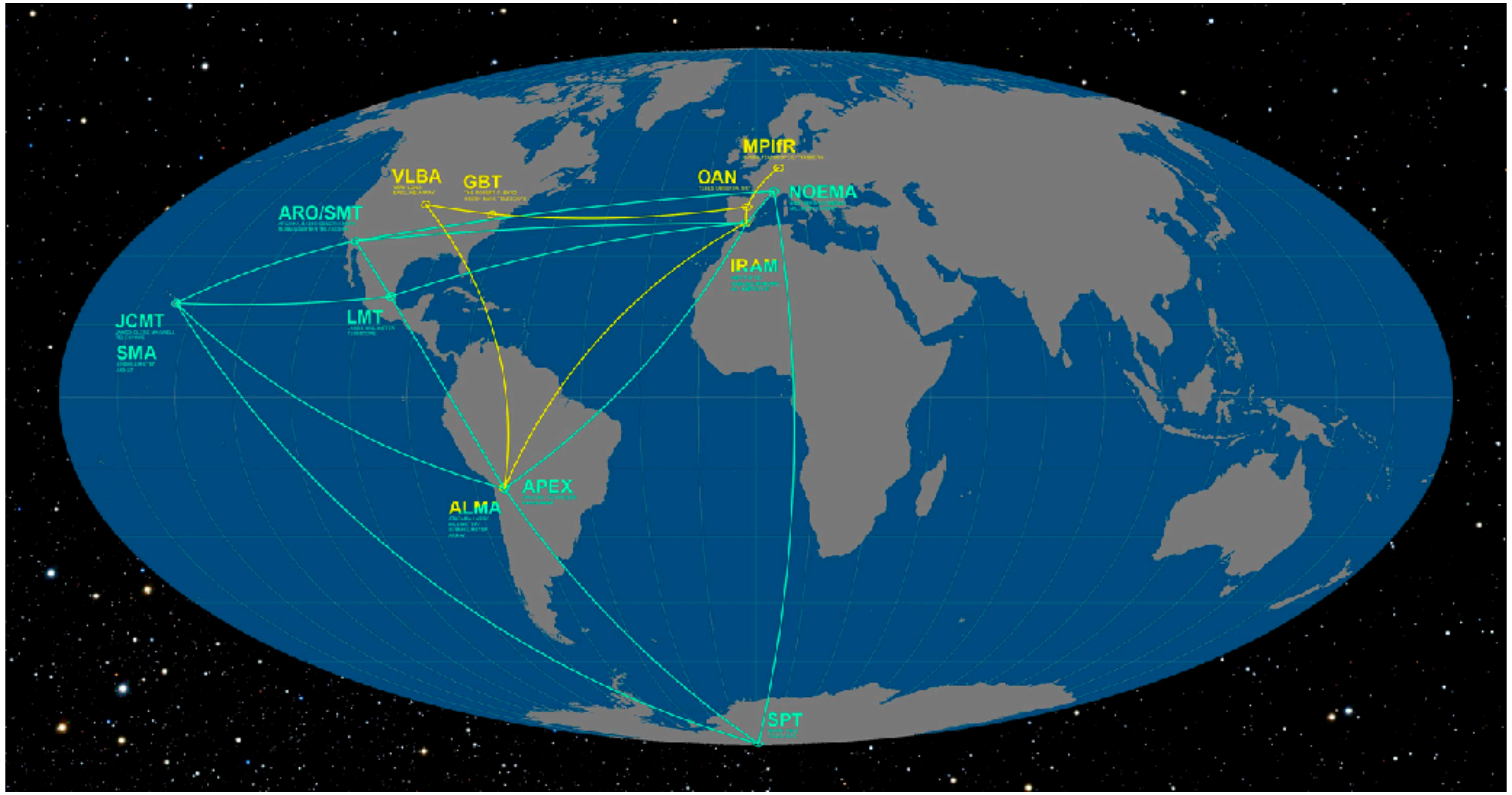
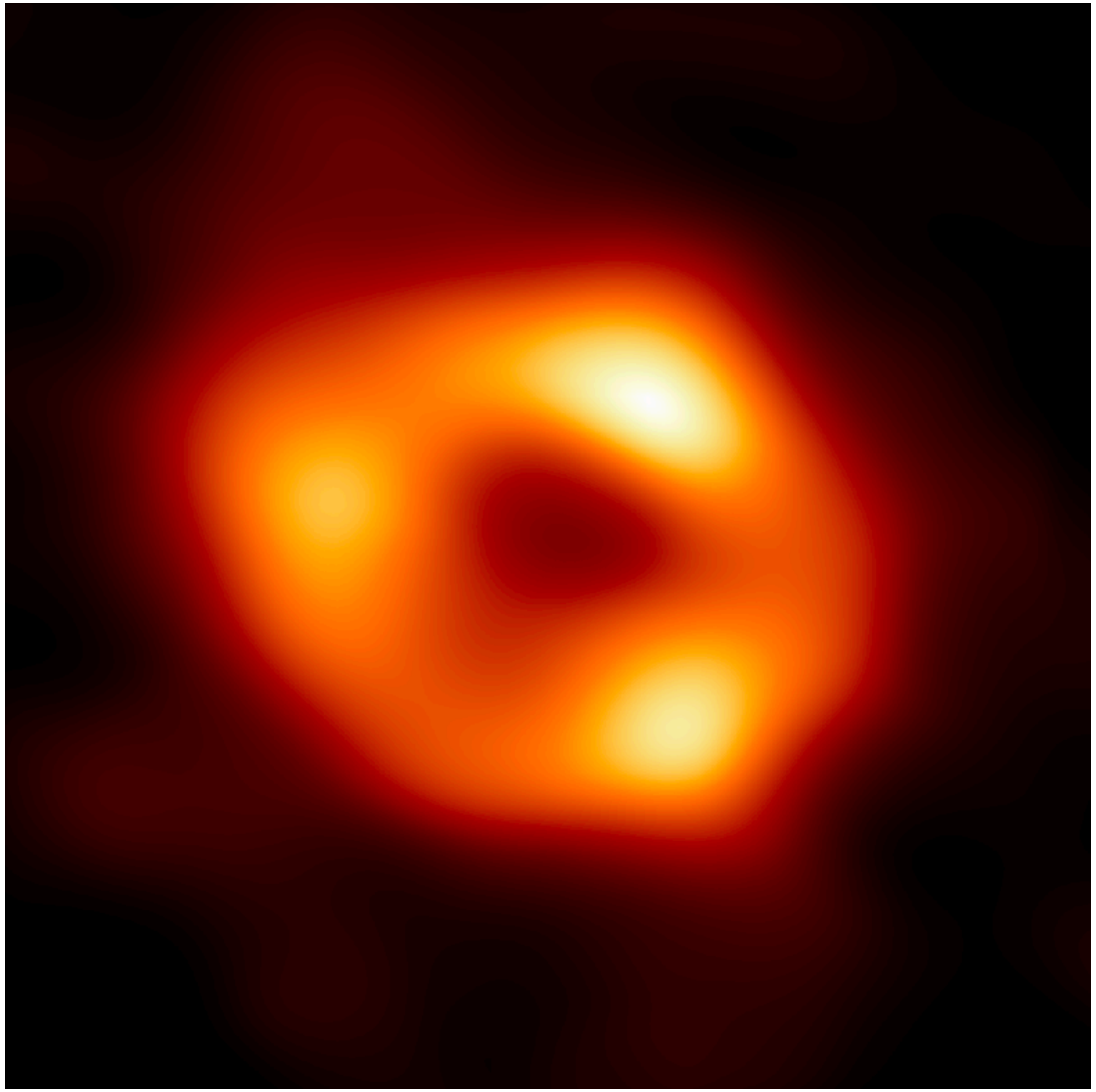
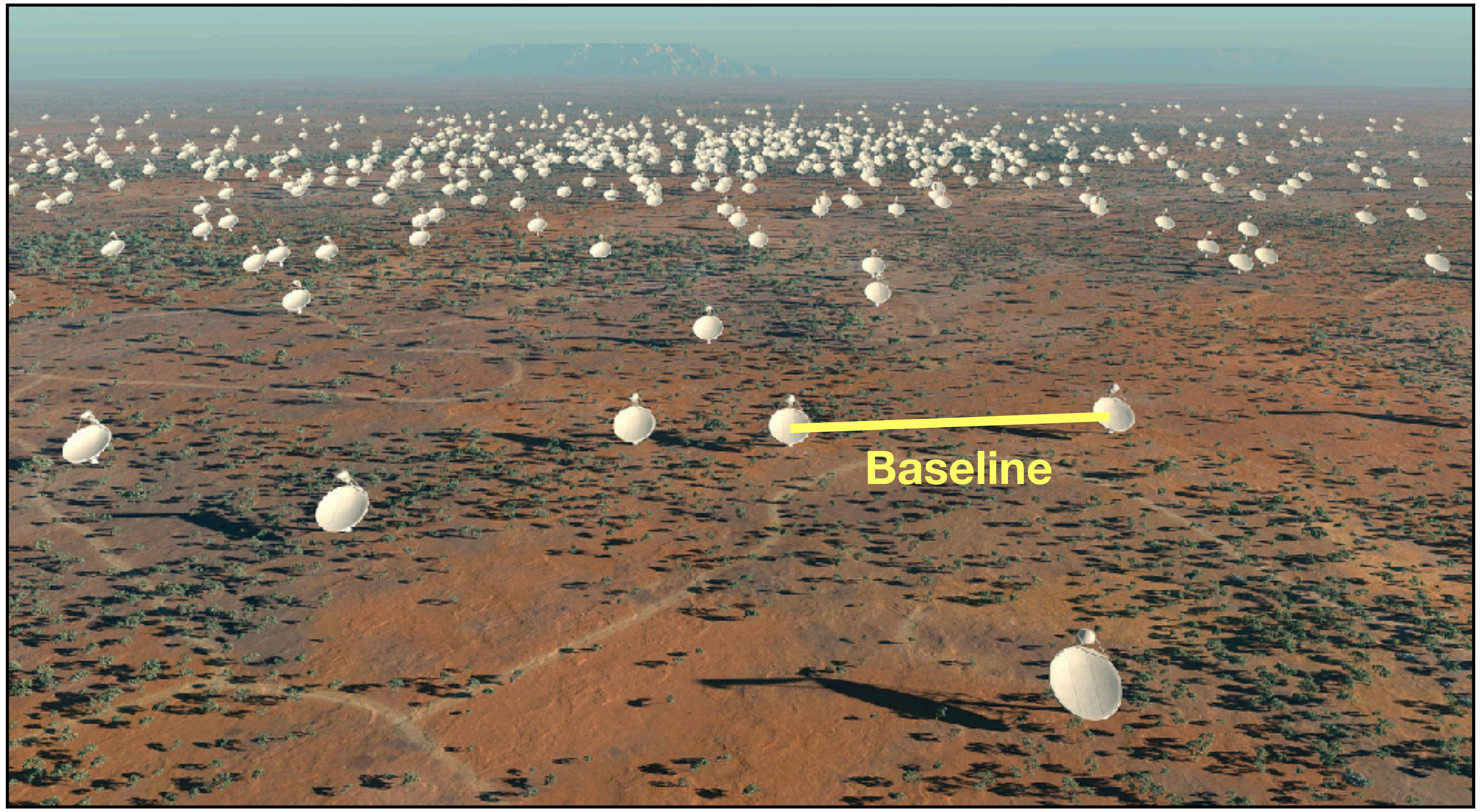
Interferometers:
multiple-dish arrays acting as one telescope





Black hole imaged by the Event Horizon Telescope

Interferometer has limitations for large-scale cosmology



Using SKAO as an **interferometer** means the largest scales we can probe are limited by how small the baselines are i.e. how *tightly-packed* the dishes are

Advantages achieved by using “single-dish mode”:

☑ Largest cosmological scales become accessible

☑ Increases observation time by a factor of $N_{\rm dish}$

SKAO Pathfinder: MeerKAT

- 64 dishes
- Will become part of SKA-MID
- $0.2 < z < 0.58$ (L-band)
- $0.4 < z < 1.45$ (UHF-band)
- ~4000 sq.deg surveys

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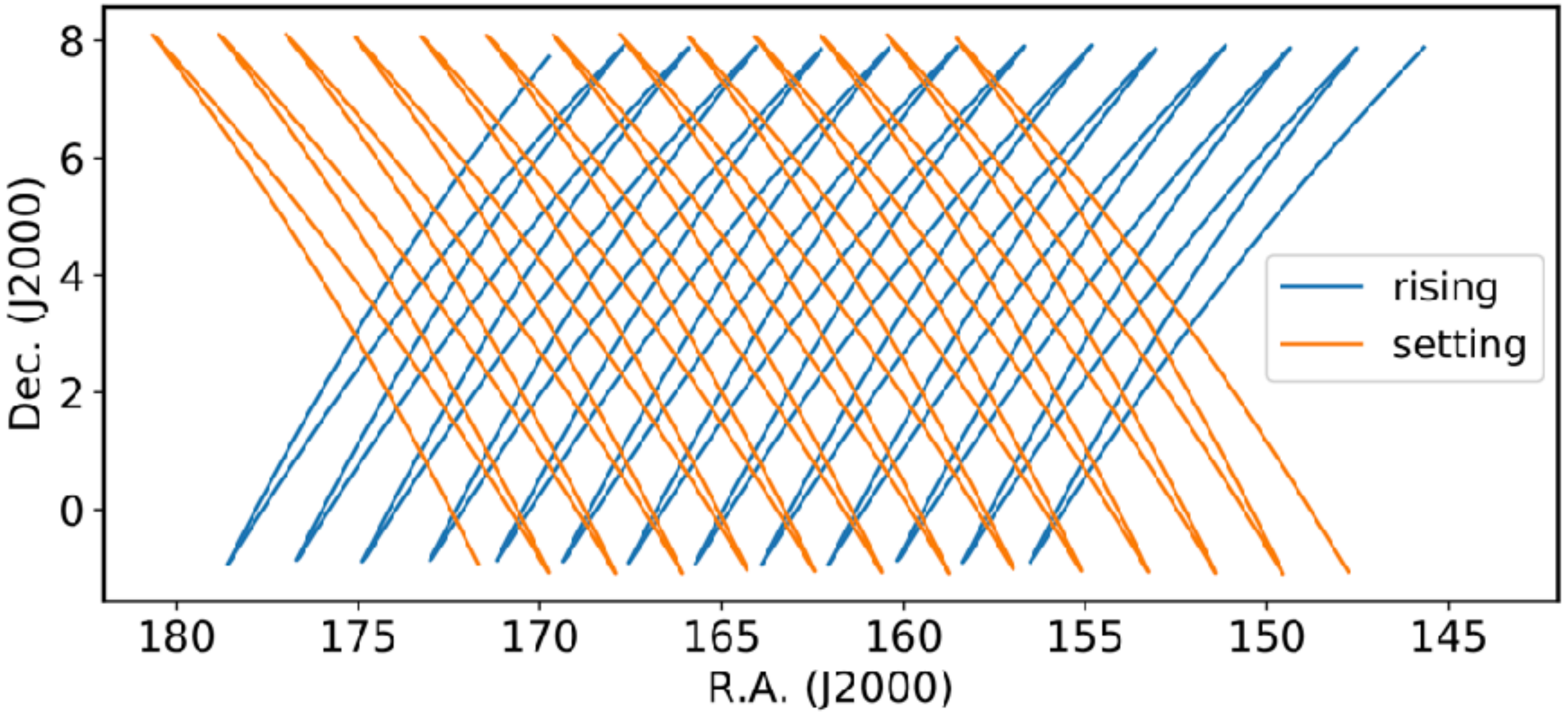
GROVE

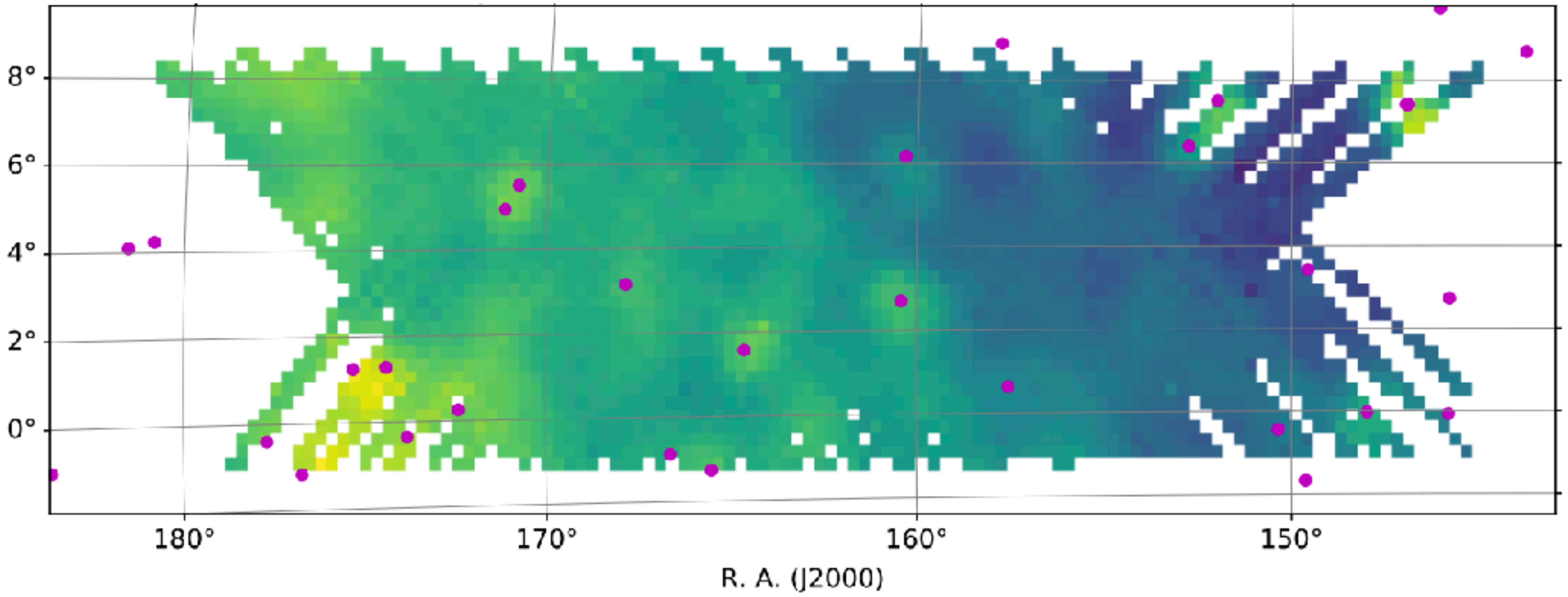
Conducting single-dish intensity mapping observations with MeerKAT

Pilot survey data:

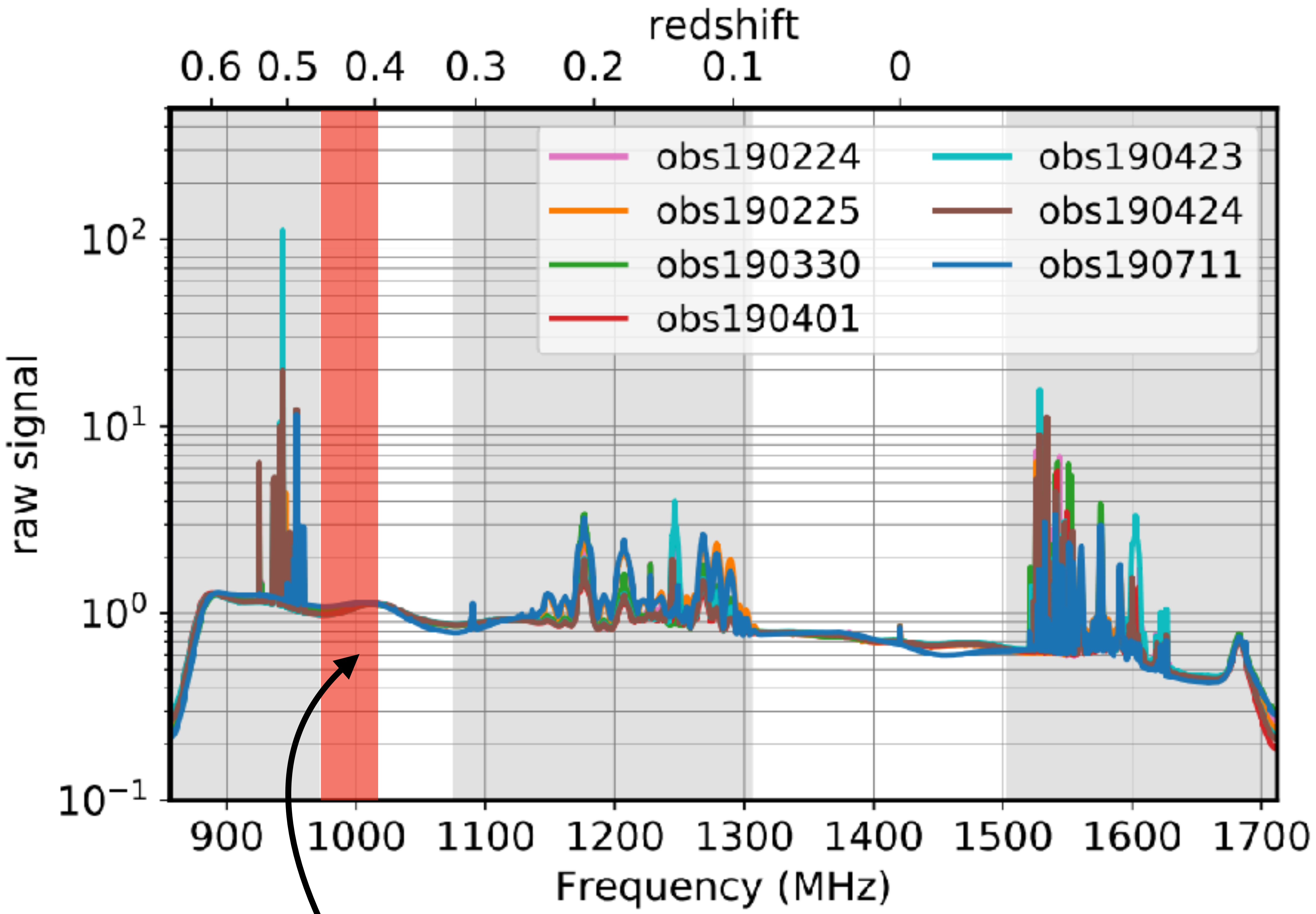
- 10.5 hours of data from six nights of observations
- Overlapping with the WiggleZ11hr field (~200 deg^2)
- We use data in range 973-1015 MHz ($0.40 < z < 0.46$)

J.Wang, …, SC+21 [arXiv:2011.13789]





Radio Frequency Interference (RFI) flagging



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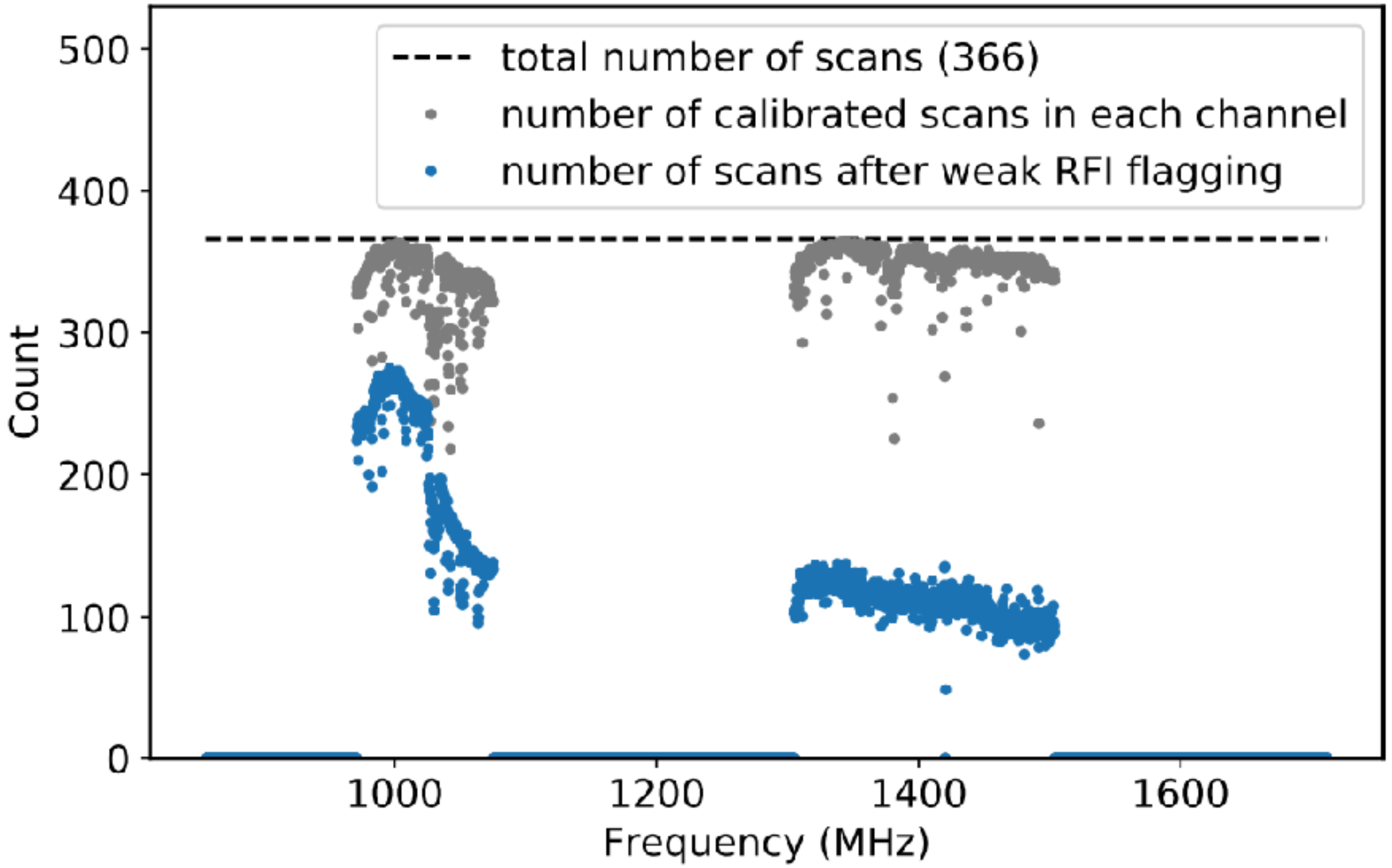


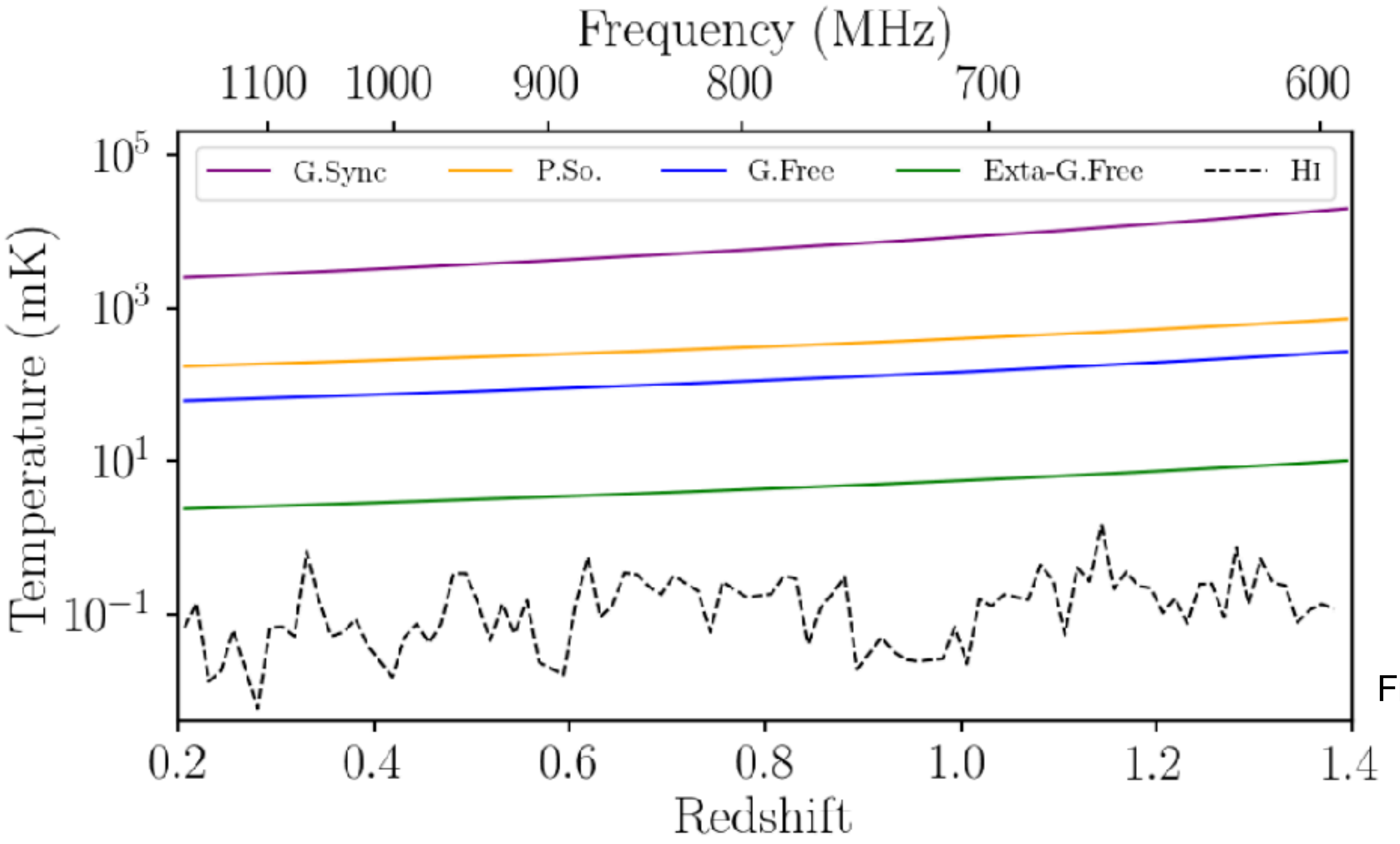
Channels used for analysis

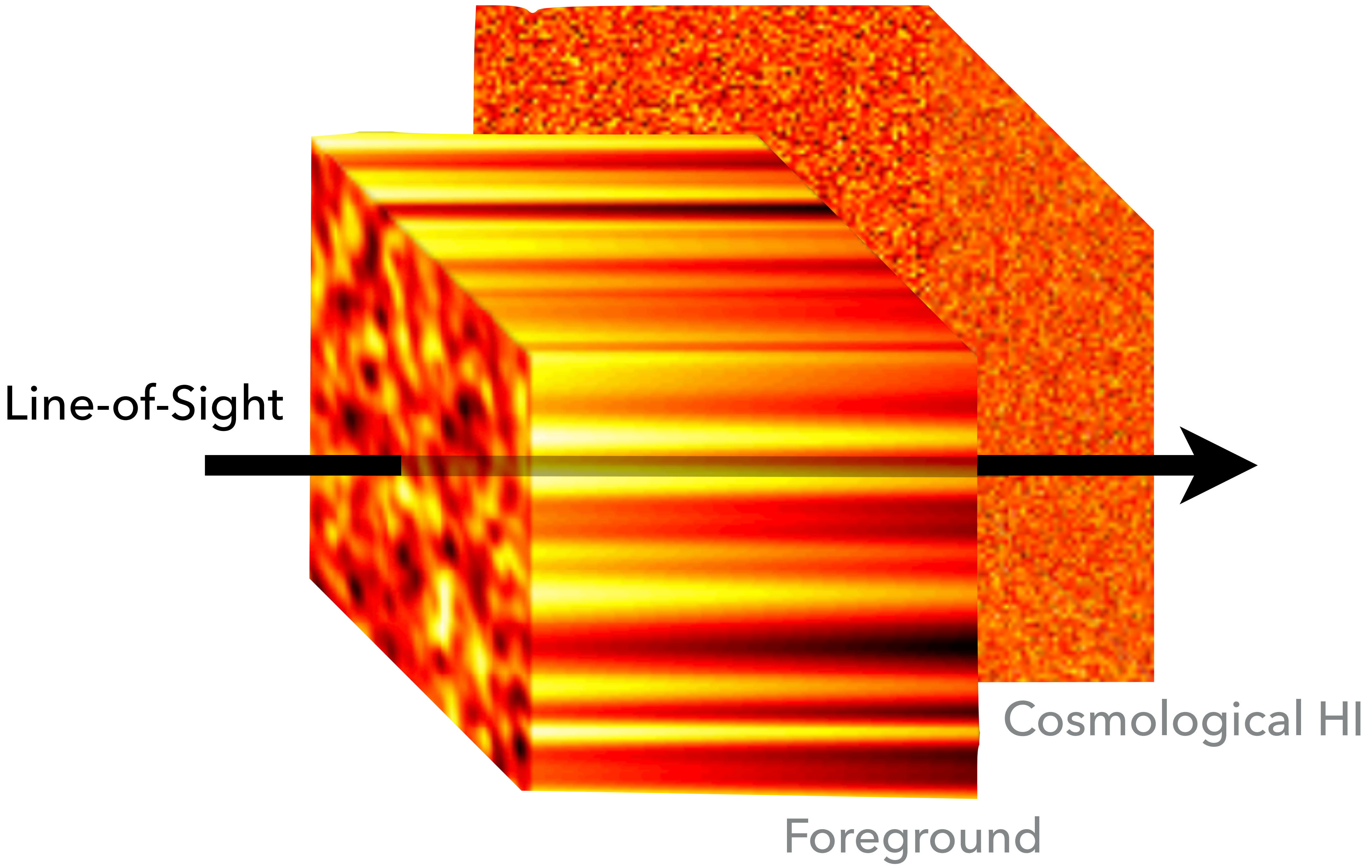
199 frequency channels at 973.2 – 1014.6 MHz.

- A further 32 within this range are also removed due to their dominant contributions

Foreground cleaning MeerKAT HI intensity maps

Idealised simulation demo:



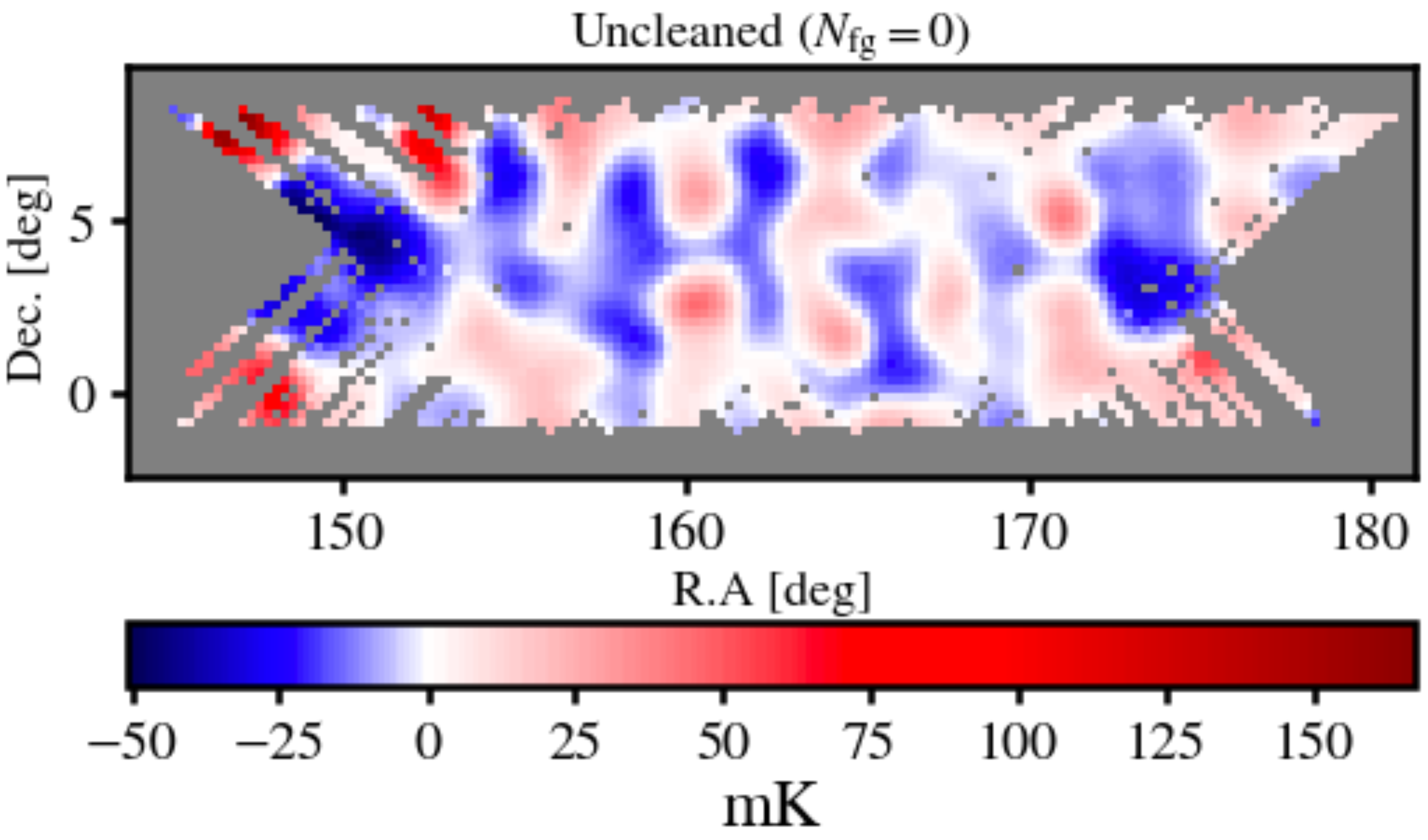


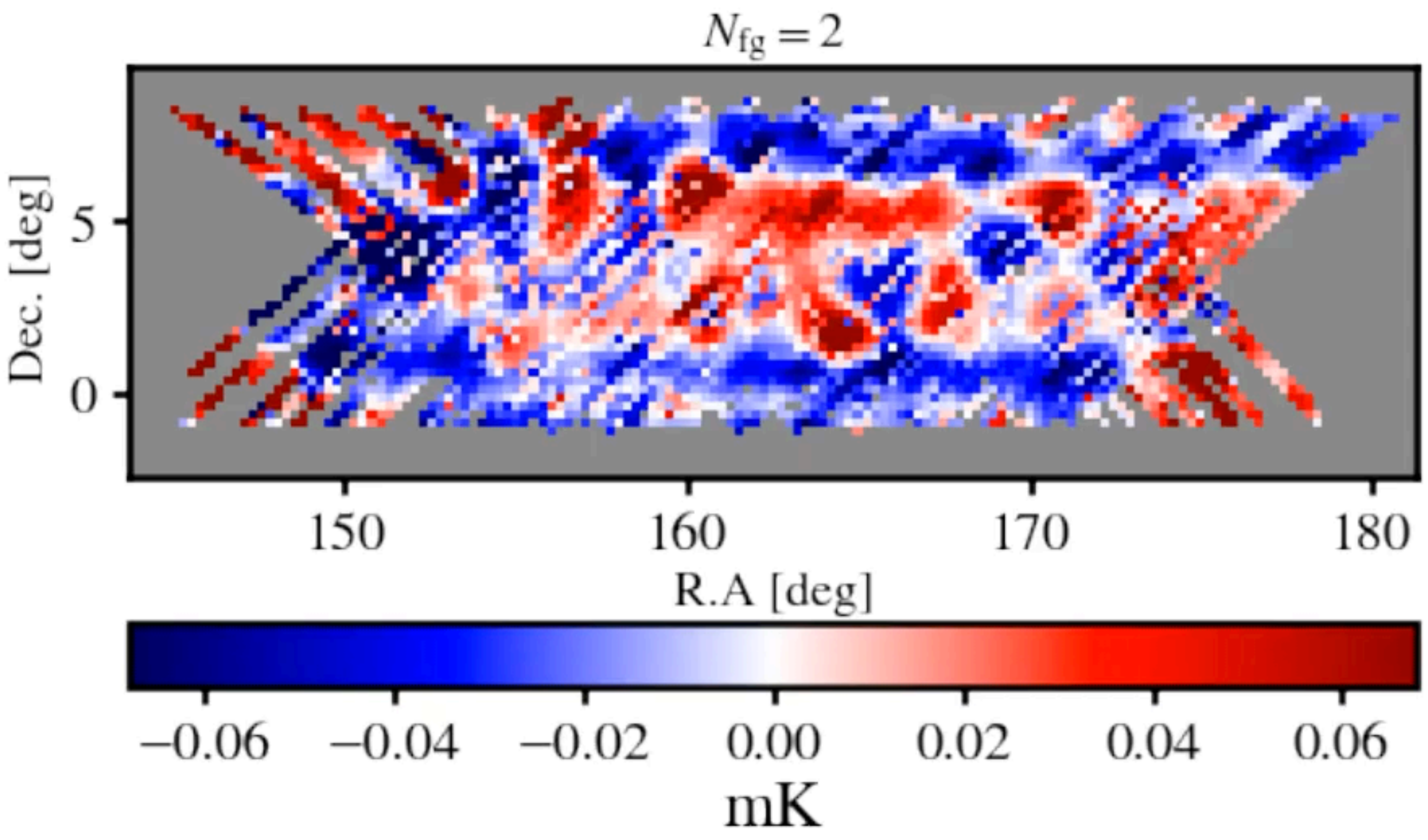
From S.Cunnington+19 [arXiv:1904.01479]

- We utilise smooth foreground spectra to distinguish them from cosmological signal

Foreground cleaning MeerKAT HI intensity maps

Principal Component Analysis foreground cleaning





HI auto-correlation for MeerKAT pilot survey intensity maps

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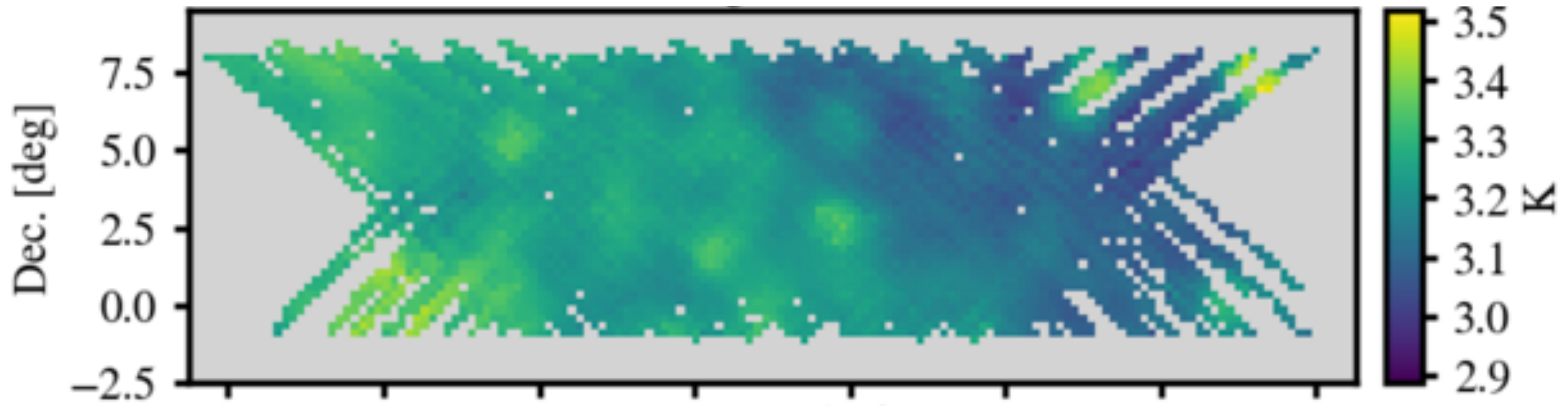
Correcting for signal loss in foreground clean

Foreground transfer function:



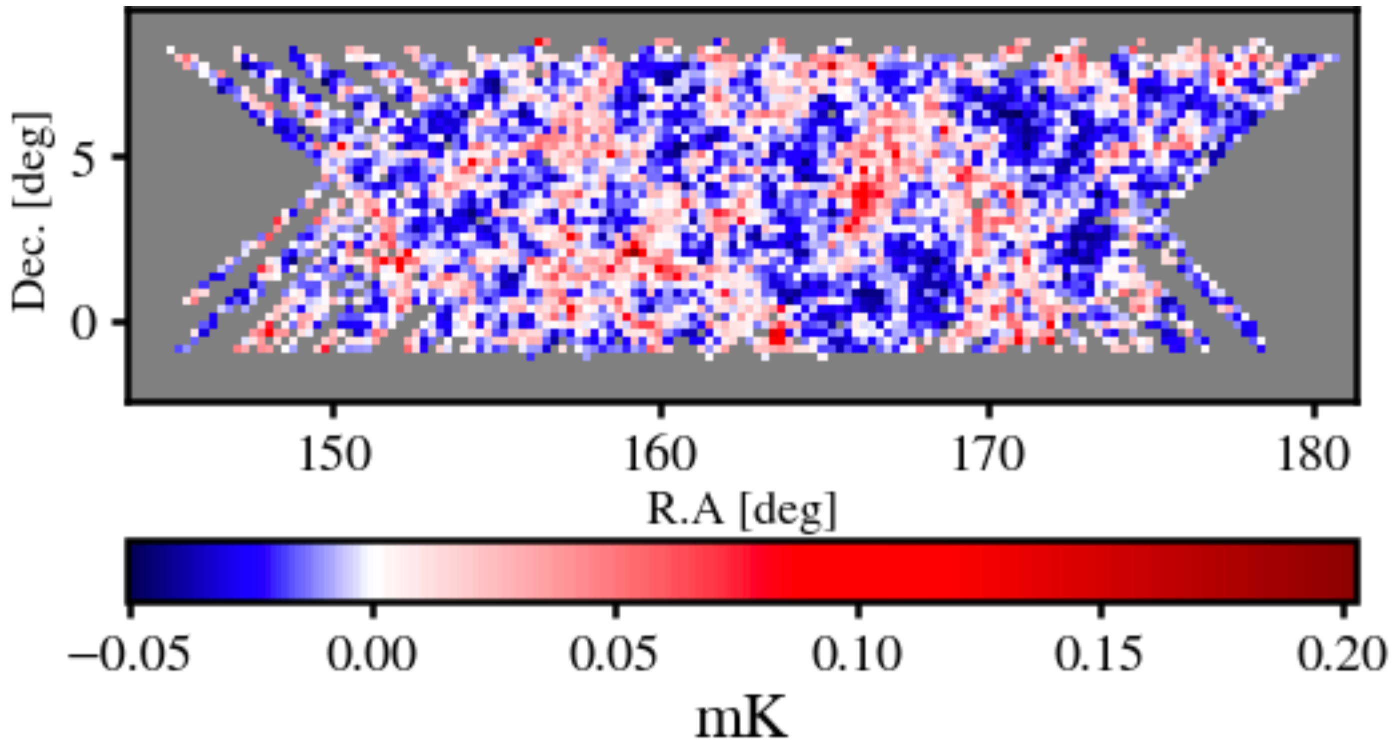
Survey data

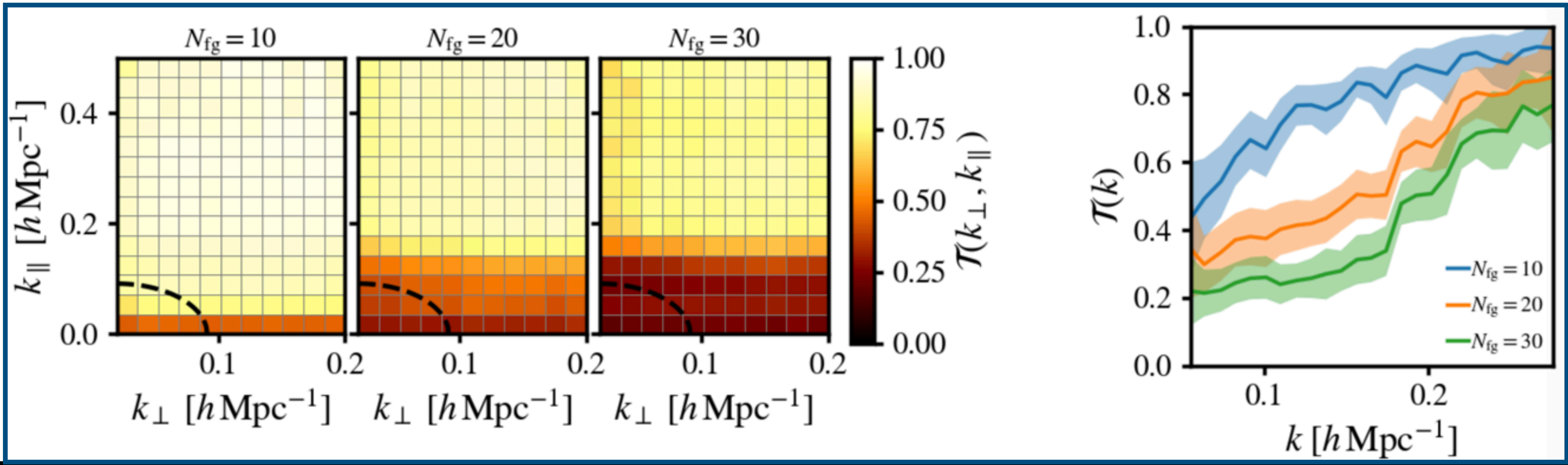
Mock galaxy map

$$\mathcal{T}(k) = \left\langle \frac{\mathcal{P}\left(\mathbf{M}^{\mathrm{HI}}_{\mathrm{cleaned}}, \mathbf{M}_{\mathrm{g}}\right)}{\mathcal{P}(\mathbf{M}_{\mathrm{HI}}, \mathbf{M}_{\mathrm{g}})} \right\rangle$$

$$\mathbf{M}^{\mathrm{HI}}_{\mathrm{cleaned}} = \left[\mathbf{M}_{\mathrm{HI}} + \mathbf{X}^{\mathrm{HI}}_{\mathrm{obs}}\right]_{\mathrm{PCA}} - \left[\mathbf{X}^{\mathrm{HI}}_{\mathrm{obs}}\right]_{\mathrm{PCA}}$$

Mock HI intensity map





Cross-correlations mitigate systematics

Optical

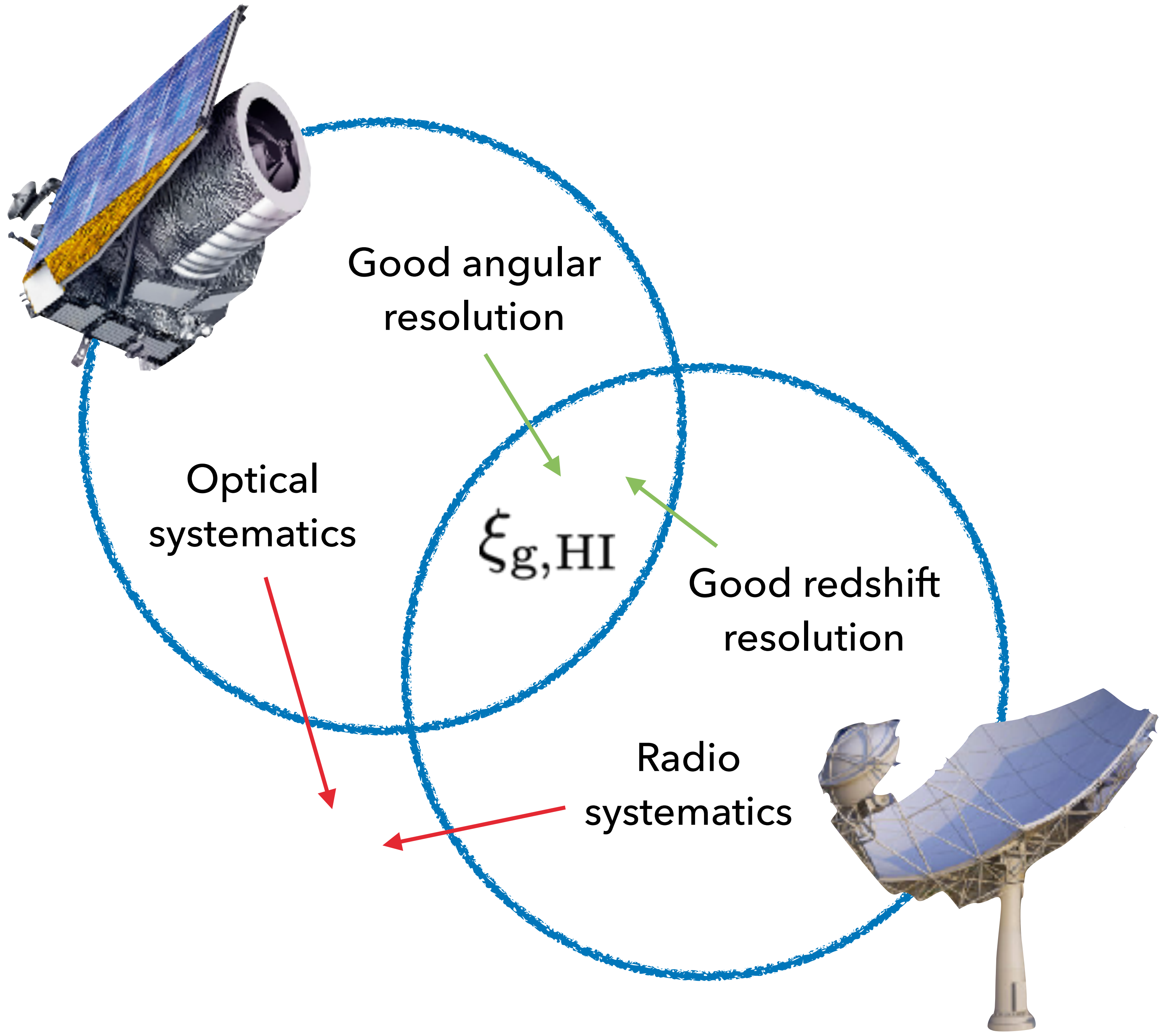
Anglo-Austrailian
Observatory

$$\mathbf{X}_{\rm opt} = \mathbf{S}_{\rm opt} + \mathbf{N}_{\rm opt}$$

Radio

MeerKAT radio
telescope

$$\mathbf{X}_{\rm rad} = \mathbf{S}_{\rm rad} + \mathbf{N}_{\rm rad}$$



Auto Correlation:

uncorrelated

$$\langle \mathbf{X}_{\rm rad}\mathbf{X}_{\rm rad}\rangle = \langle \mathbf{S}_{\rm rad}\mathbf{S}_{\rm rad}\rangle + 2\,\cancel{\langle \mathbf{S}_{\rm rad}\mathbf{N}_{\rm rad}\rangle} + \langle \mathbf{N}_{\rm rad}\mathbf{N}_{\rm rad}\rangle$$

$$\langle \mathbf{X}_{\rm rad}\mathbf{X}_{\rm rad}\rangle = \boxed{\langle \mathbf{S}_{\rm rad}\mathbf{S}_{\rm rad}\rangle} + \boxed{\langle \mathbf{N}_{\rm rad}\mathbf{N}_{\rm rad}\rangle}$$

signal you want *noise/residuals/systematics you don't want*

Cross Correlation:

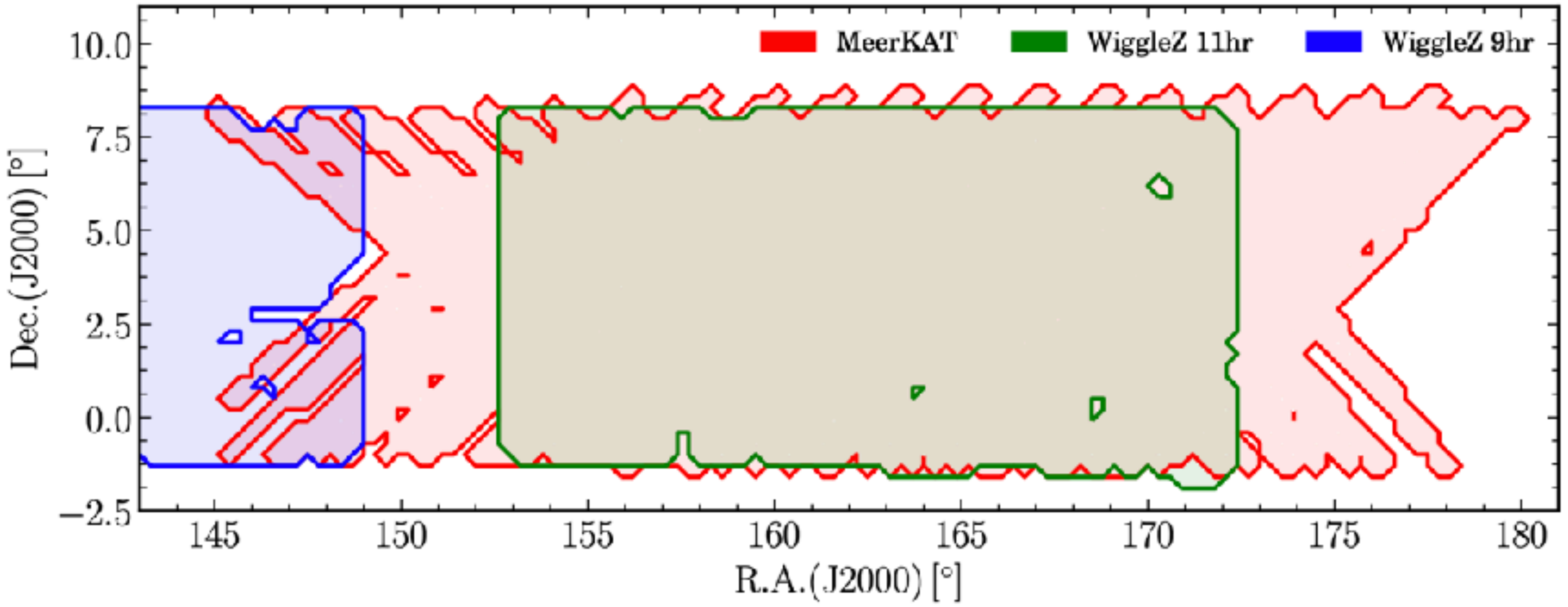
$$\langle \mathbf{X}_{\rm opt}\mathbf{X}_{\rm rad}\rangle = \boxed{\langle \mathbf{S}_{\rm opt}\mathbf{S}_{\rm rad}\rangle} + \cancel{\langle \mathbf{S}_{\rm opt}\mathbf{N}_{\rm rad}\rangle} + \cancel{\langle \mathbf{S}_{\rm rad}\mathbf{N}_{\rm opt}\rangle} + \cancel{\langle \mathbf{N}_{\rm opt}\mathbf{N}_{\rm rad}\rangle}$$

21cm intensity mapping will provide benefits in future cross-correlations

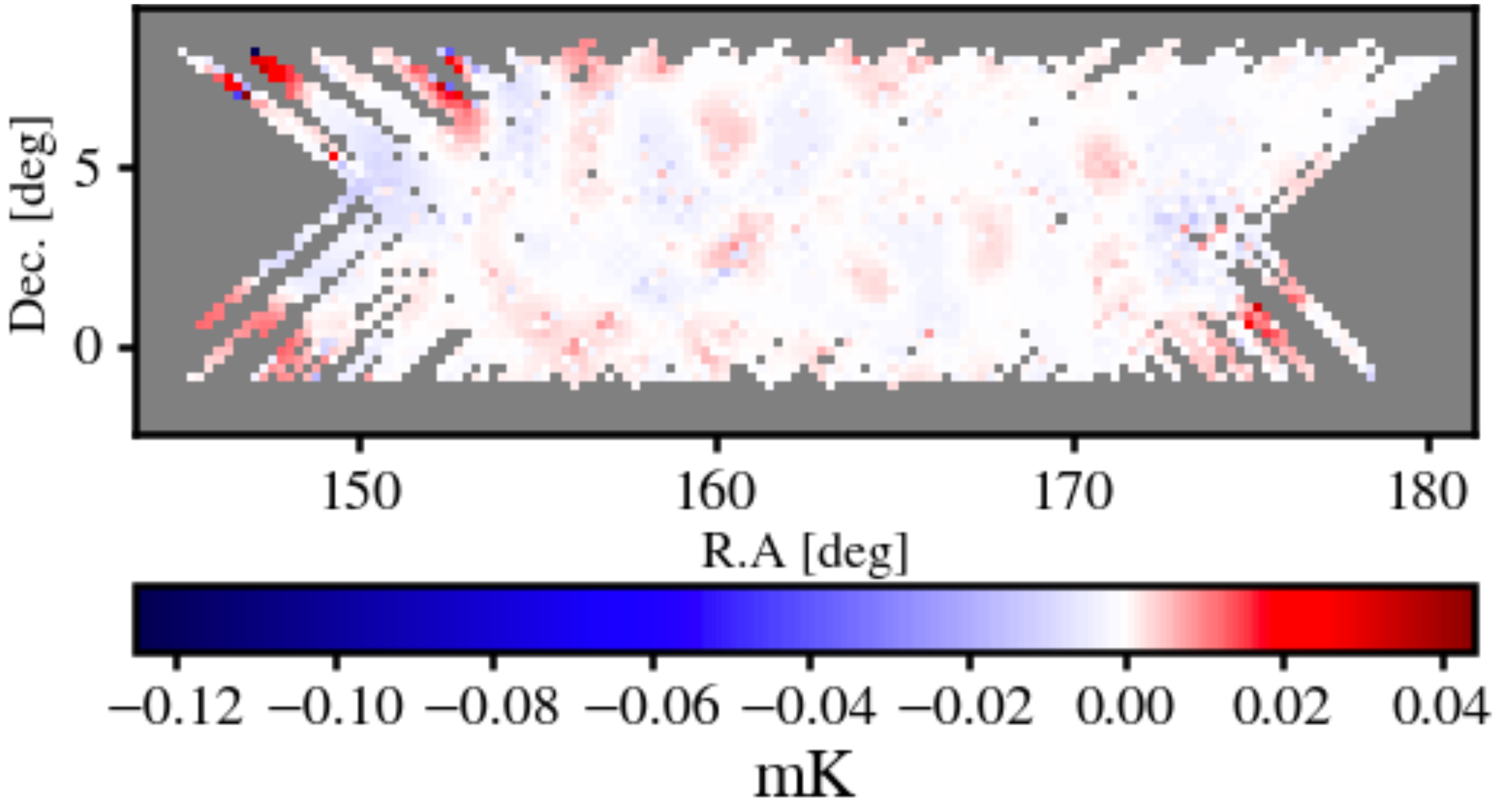
Steve Cunnington [steven.cunnington@manchester.ac.uk]

MeerKAT X Galaxies

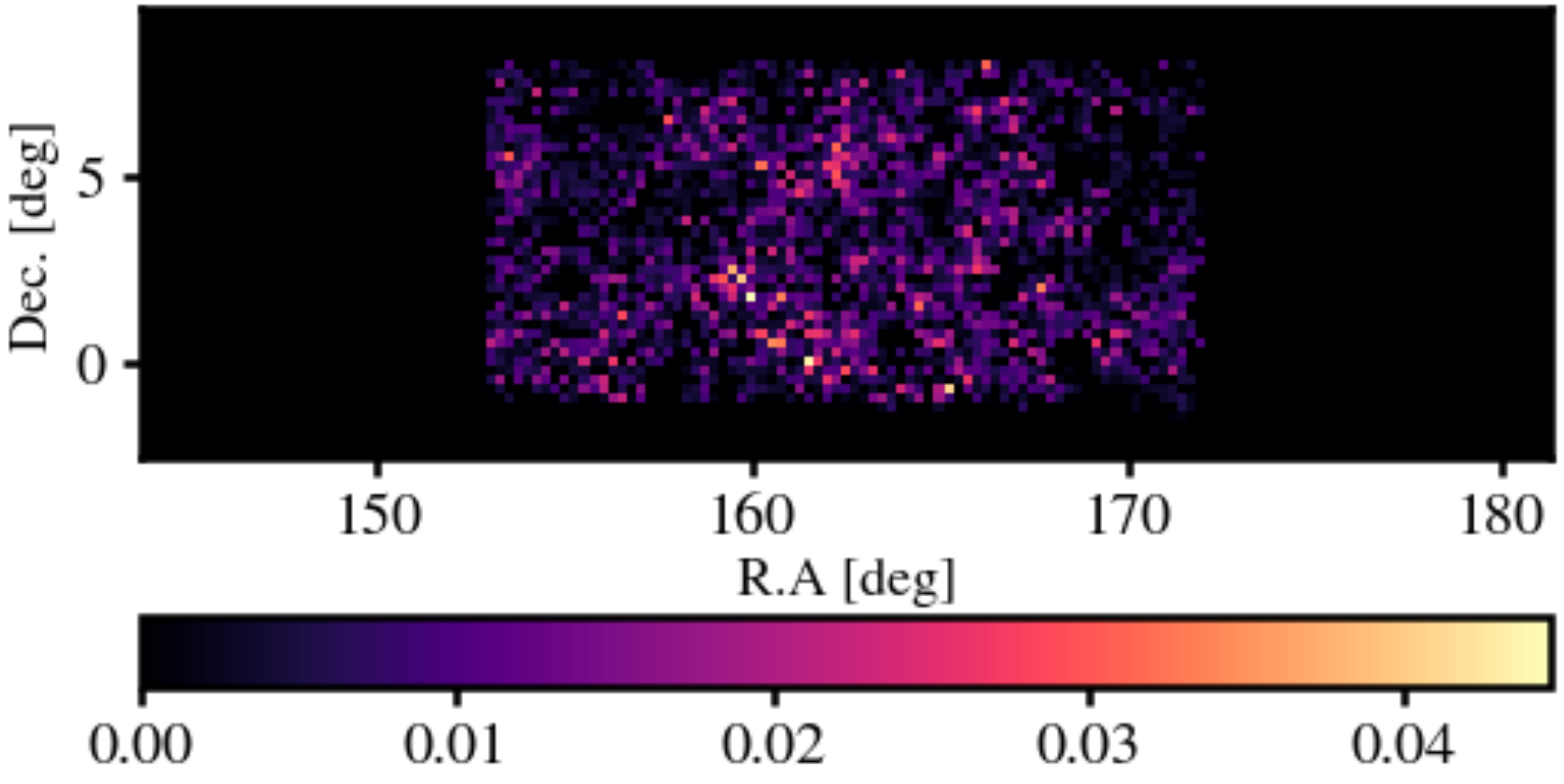
MeerKAT pilot observations conducted in WiggleZ 11hr field for the purpose of potential cross-correlations with a galaxy survey



Final foreground cleaned MeerKAT HI intensity map



WiggleZ Dark Energy Survey galaxies



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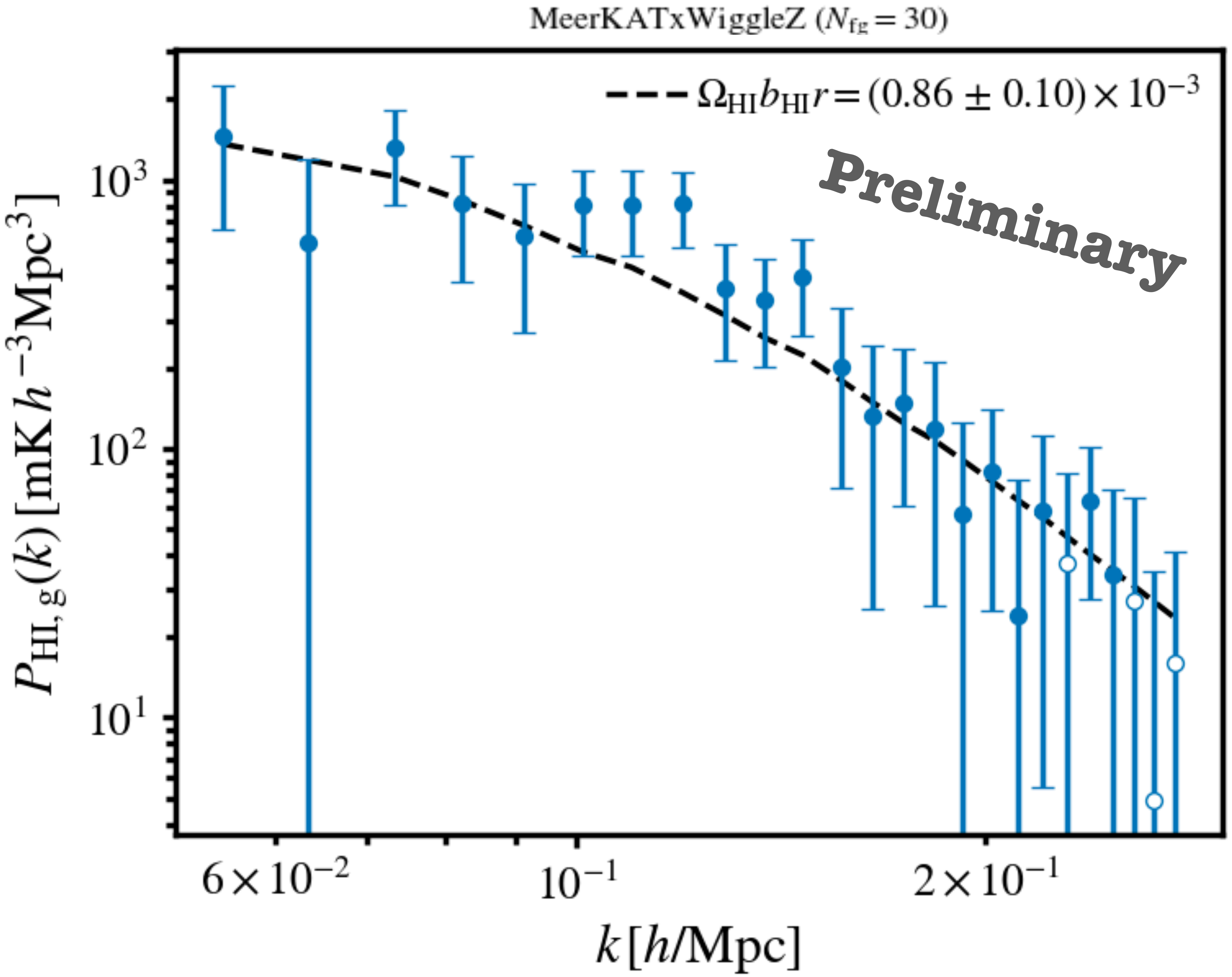
Detecting cosmological clustering with MeerKAT pilot intensity mapping survey

- Positive correlation (7.7σ) between galaxy survey and array of dishes in single-dish mode
- The first detection of its kind
- Important milestone for doing LSS cosmology with SKA intensity mapping



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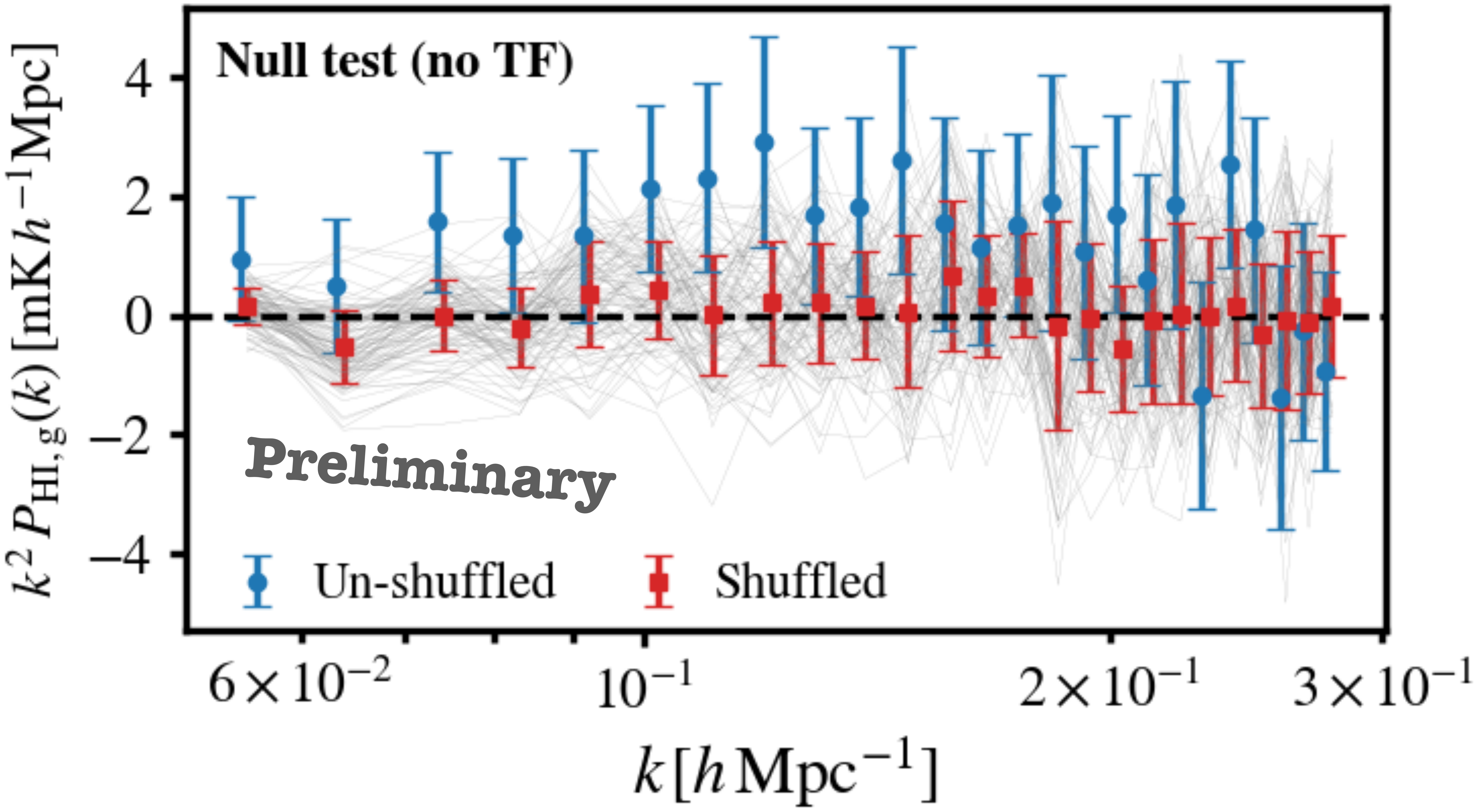
Null testing the cross-correlation detection



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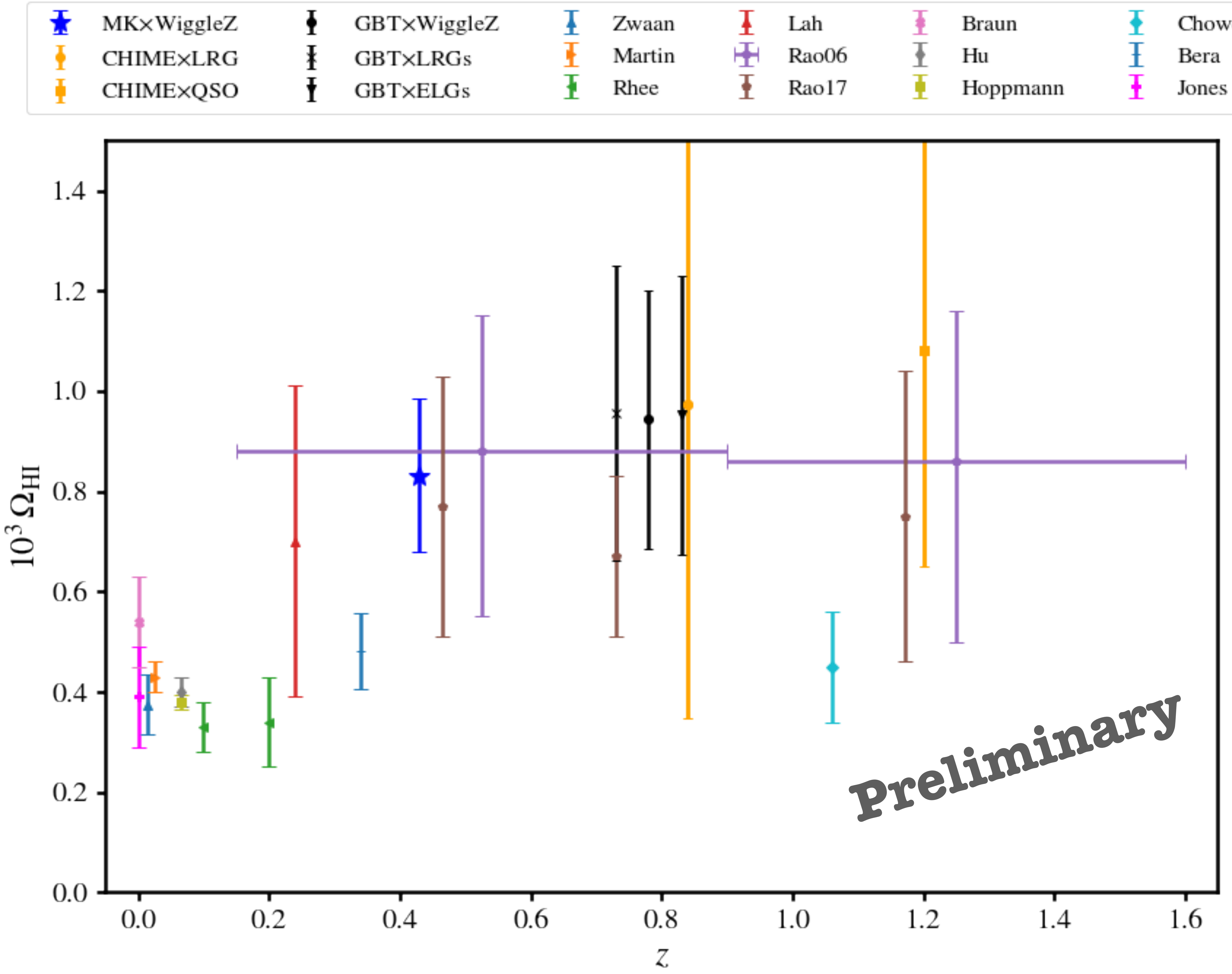
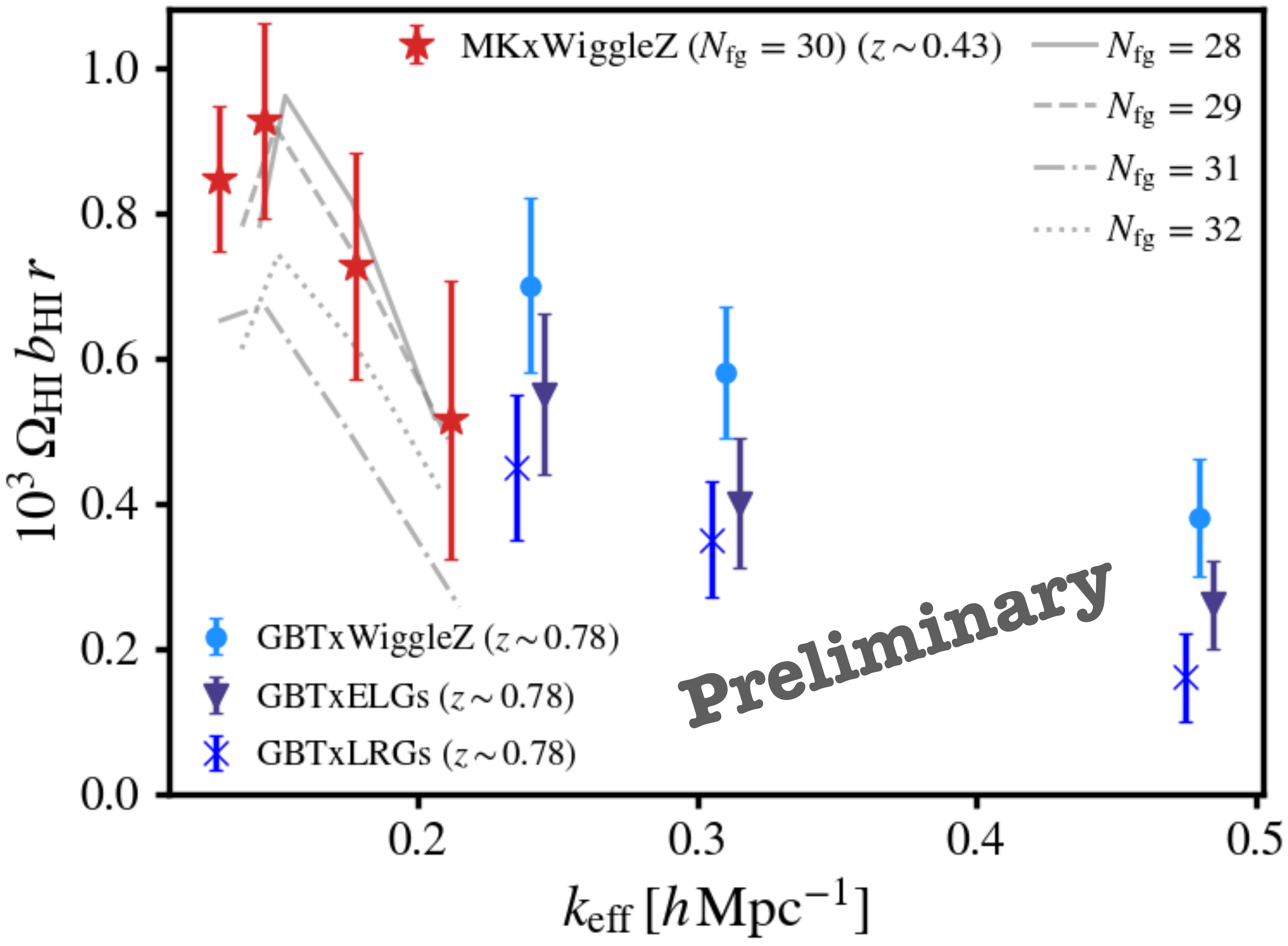
Constraining the HI abundance



$$\Omega_{\rm HI} b_{\rm HI} r = [0.86 \pm 0.10\,({\rm stat}) \pm 0.12\,({\rm sys})] \times 10^{-3}$$



Future prospects with MeerKAT & SKAO intensity mapping

Future observations

☑ Overlapping data with KiDS survey to explore HI IM x photo-z galaxies

☐ ~500 sq.deg field in MeerKAT's UHF band (0.40 < z < 1.45) to explore higher redshift probes (proposal submitted)

☐ ~4000 sq.deg survey is ultimate aim for MeerKLASS (MeerKAT Large Area Sky Survey)

➡ L-band or UHF ?

Science goals

☑ Achieve detection with array in single-dish mode

☐ HI auto correlation

☐ Redshift-space distortions in HI - detecting a quadrupole

☐ Bispectrum? Could reveal systematics

☐ BAO in HI

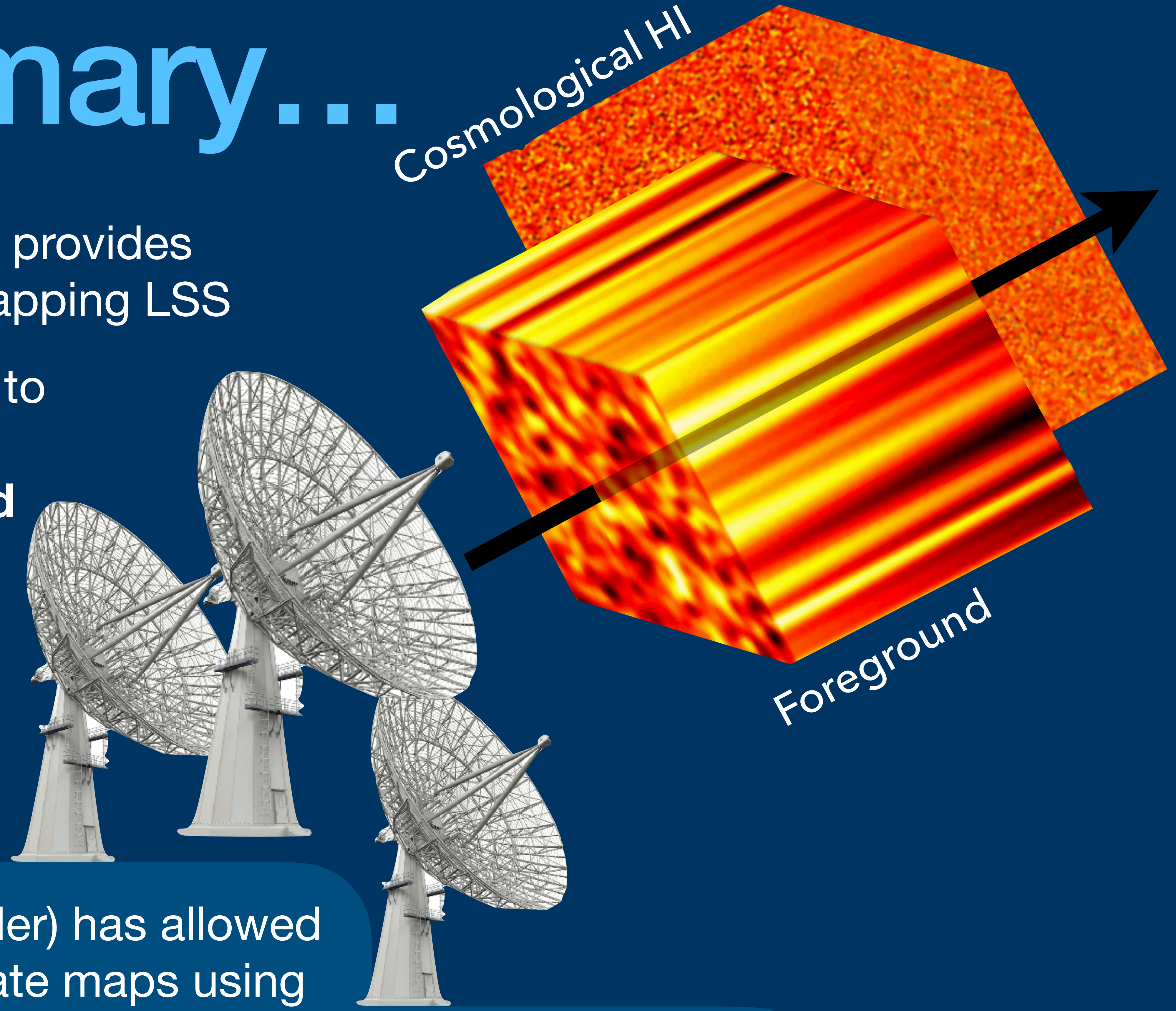
☐ Detecting the power spectrum turnover

☐ Constraints on f_{NL}

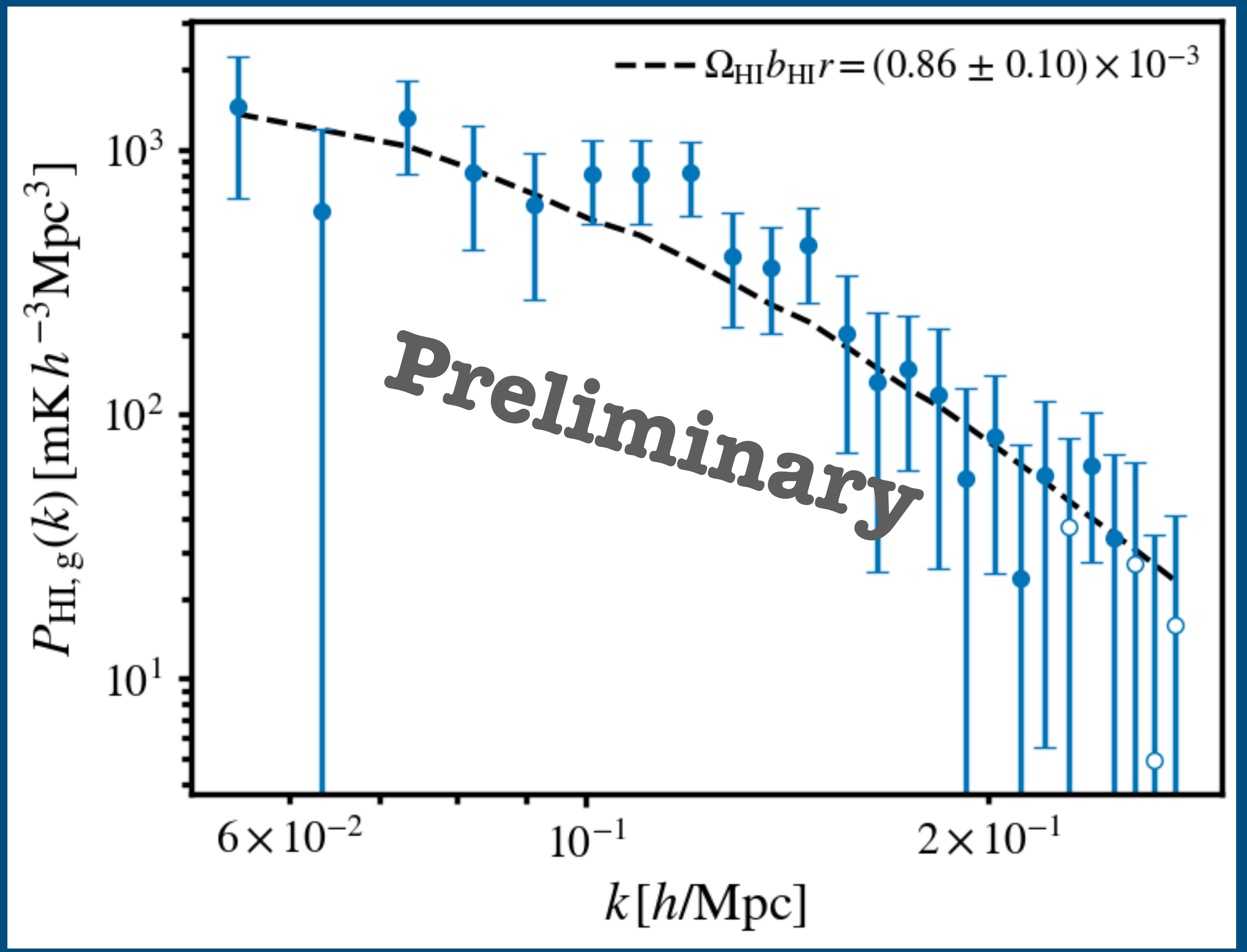
In Summary…

21cm **intensity mapping** provides potential for efficiently mapping LSS

Numerous complications to overcome, perhaps most challenging is **foreground** contamination

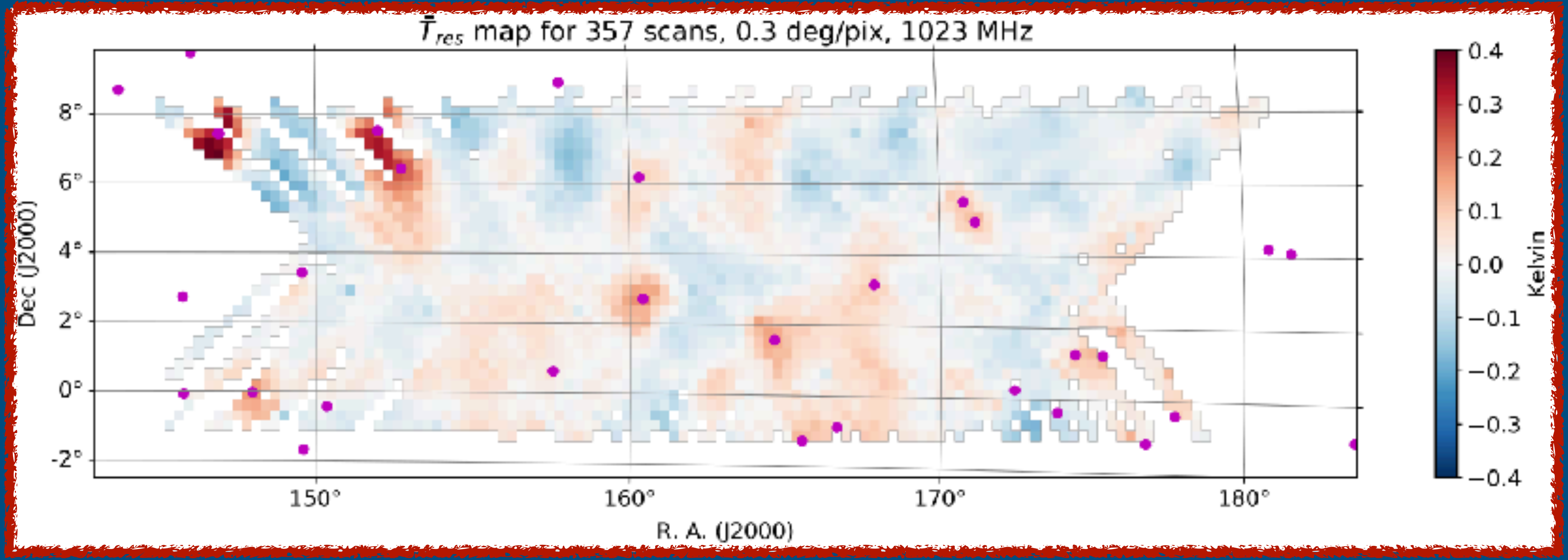


MeerKAT's pilot survey data is providing a positive correlation with overlapping galaxy surveys

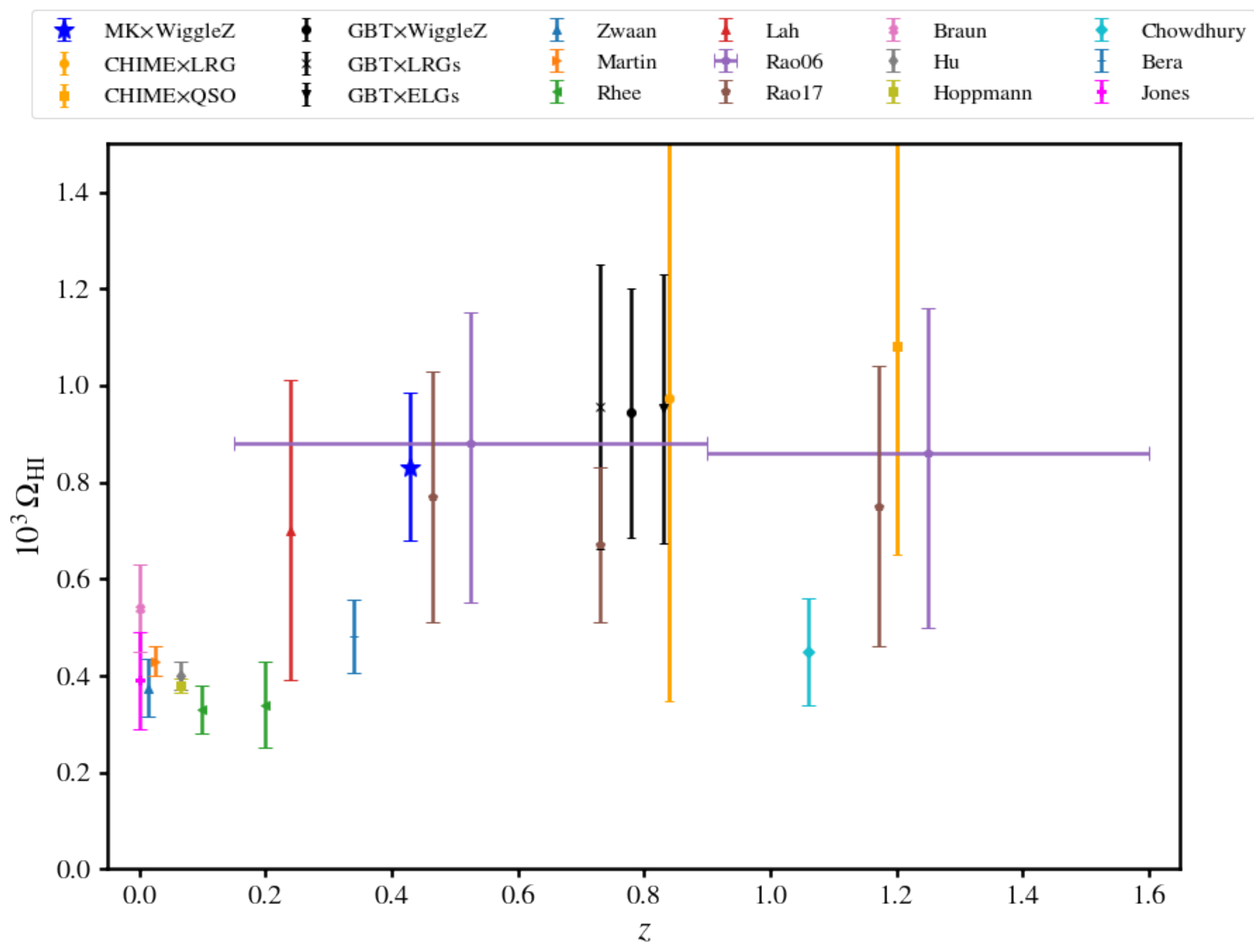


This provides encouraging evidence that SKA intensity mapping will be a novel large-scale structure probe

MeerKAT (SKA's pathfinder) has allowed us to successfully calibrate maps using an array of dishes in "single-dish mode"



Cosmological constraints will soon be possible, but for now, we can already deliver competitive astrophysical constraints



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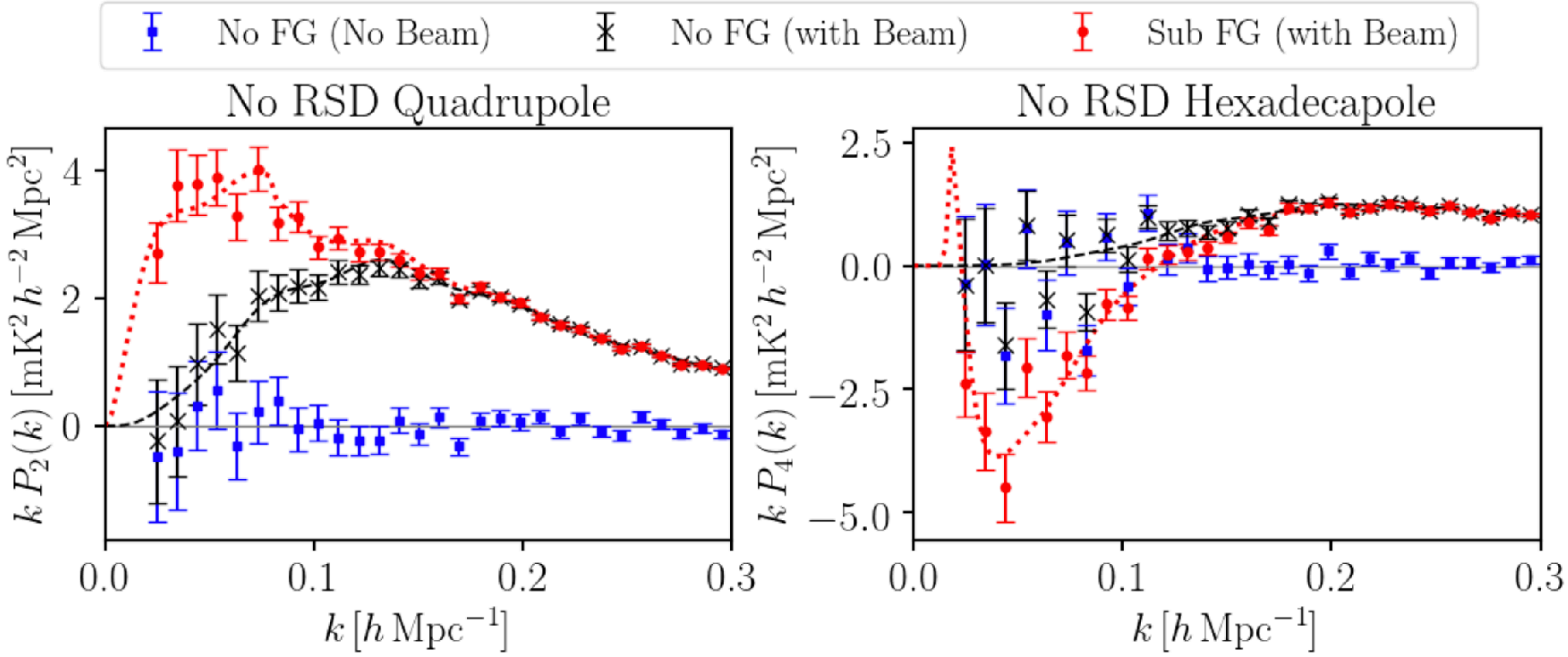
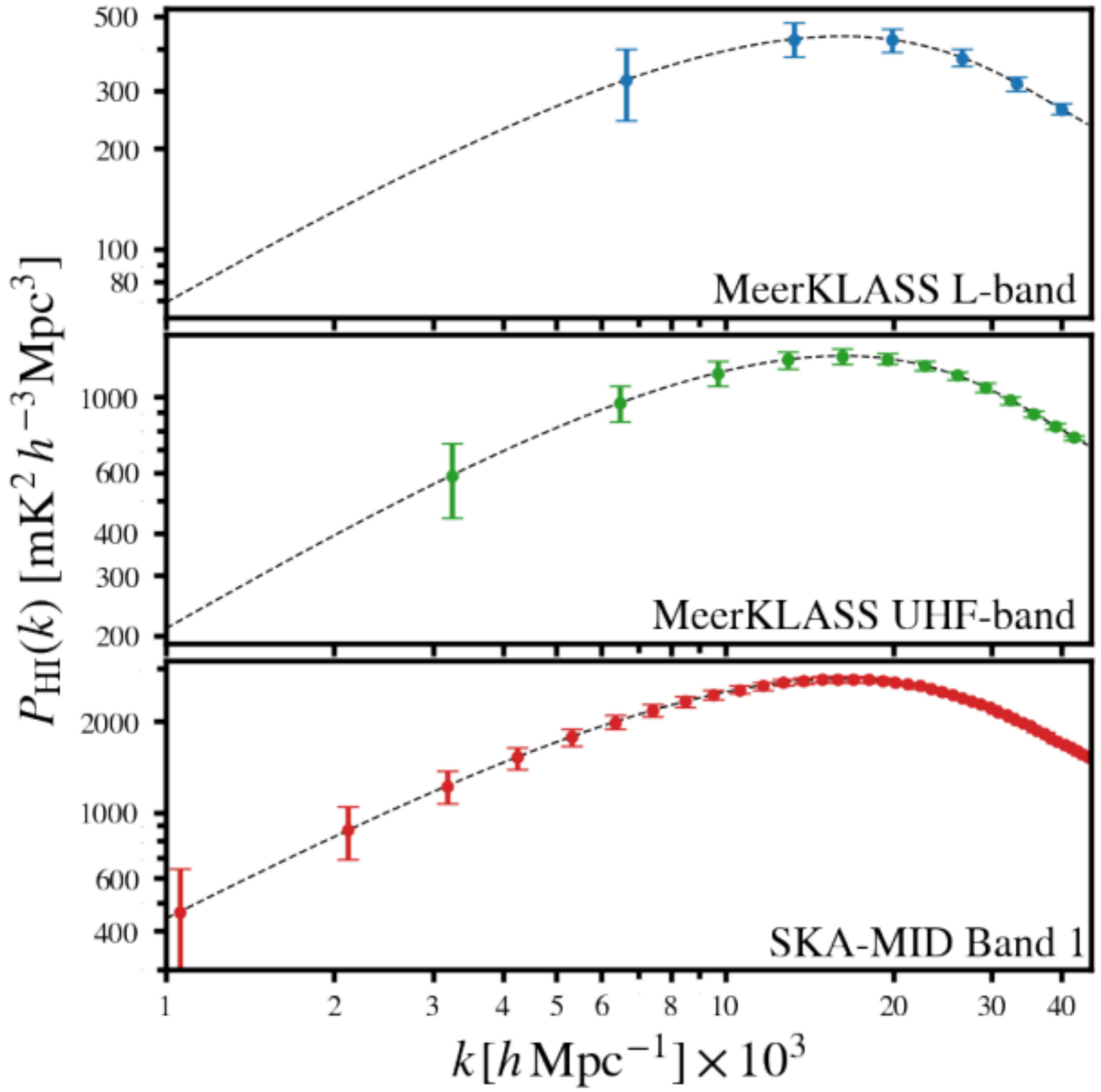
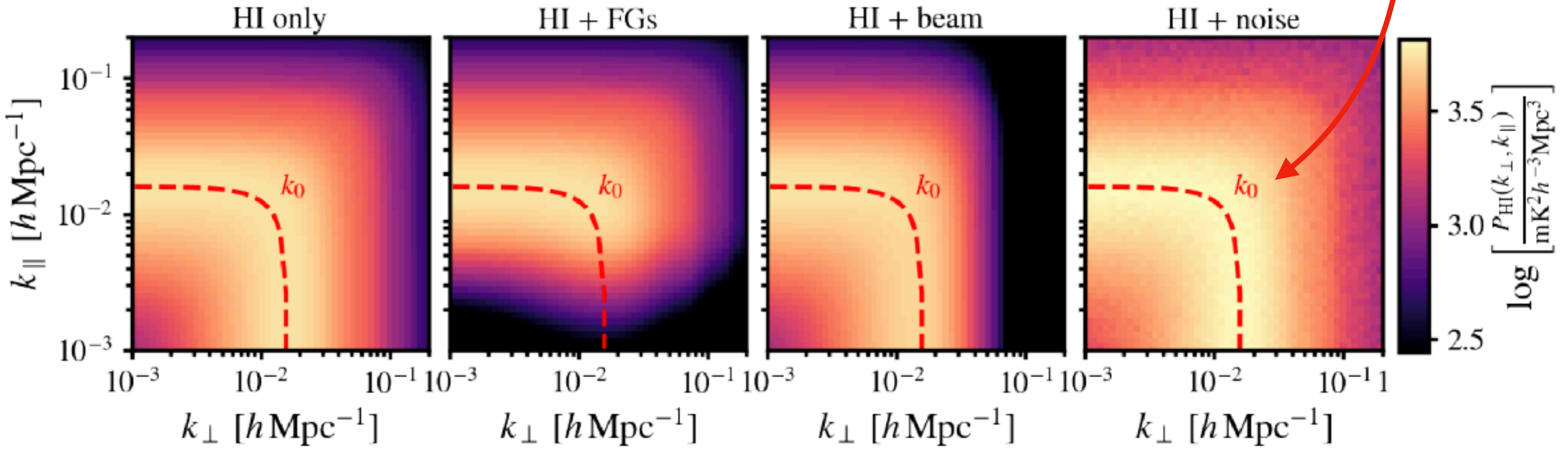
Backup Slides

Redshift-space distortions with intensity mapping

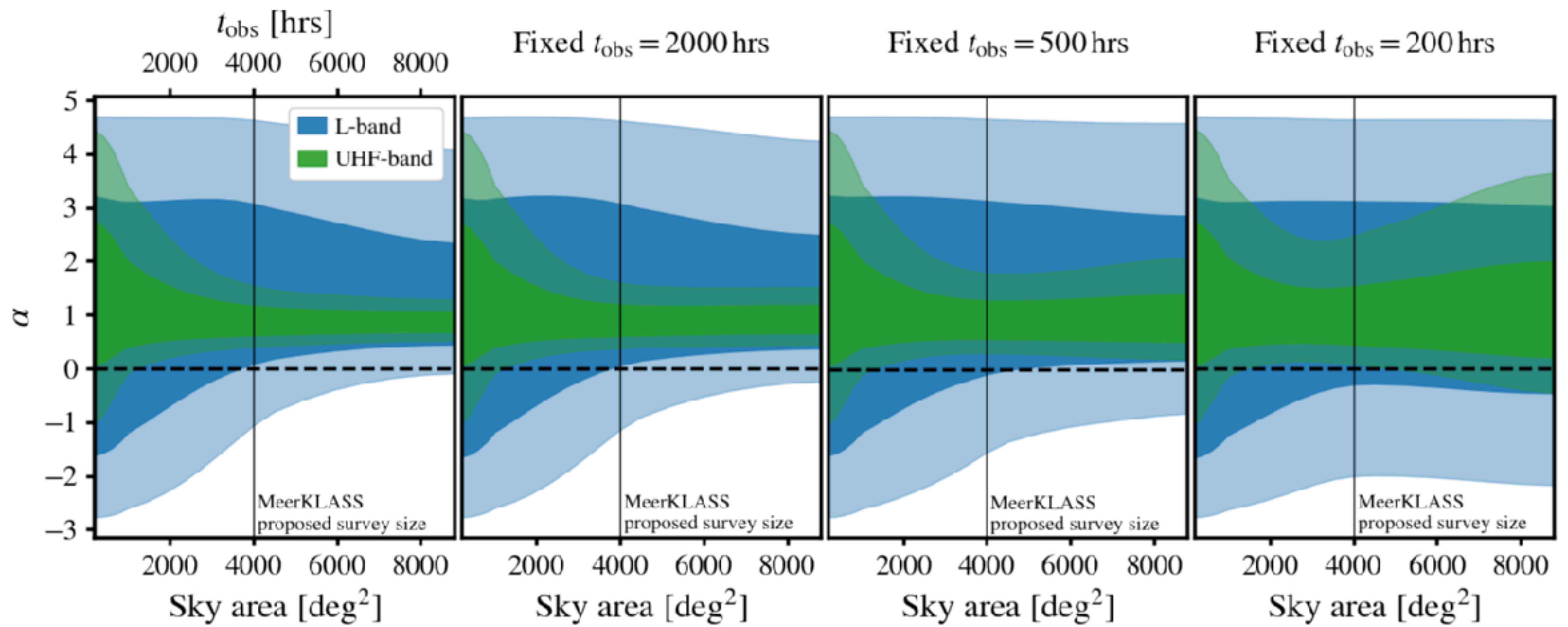


BAO detection initially challenging - can we aim for the turnover instead?





Turnover scale



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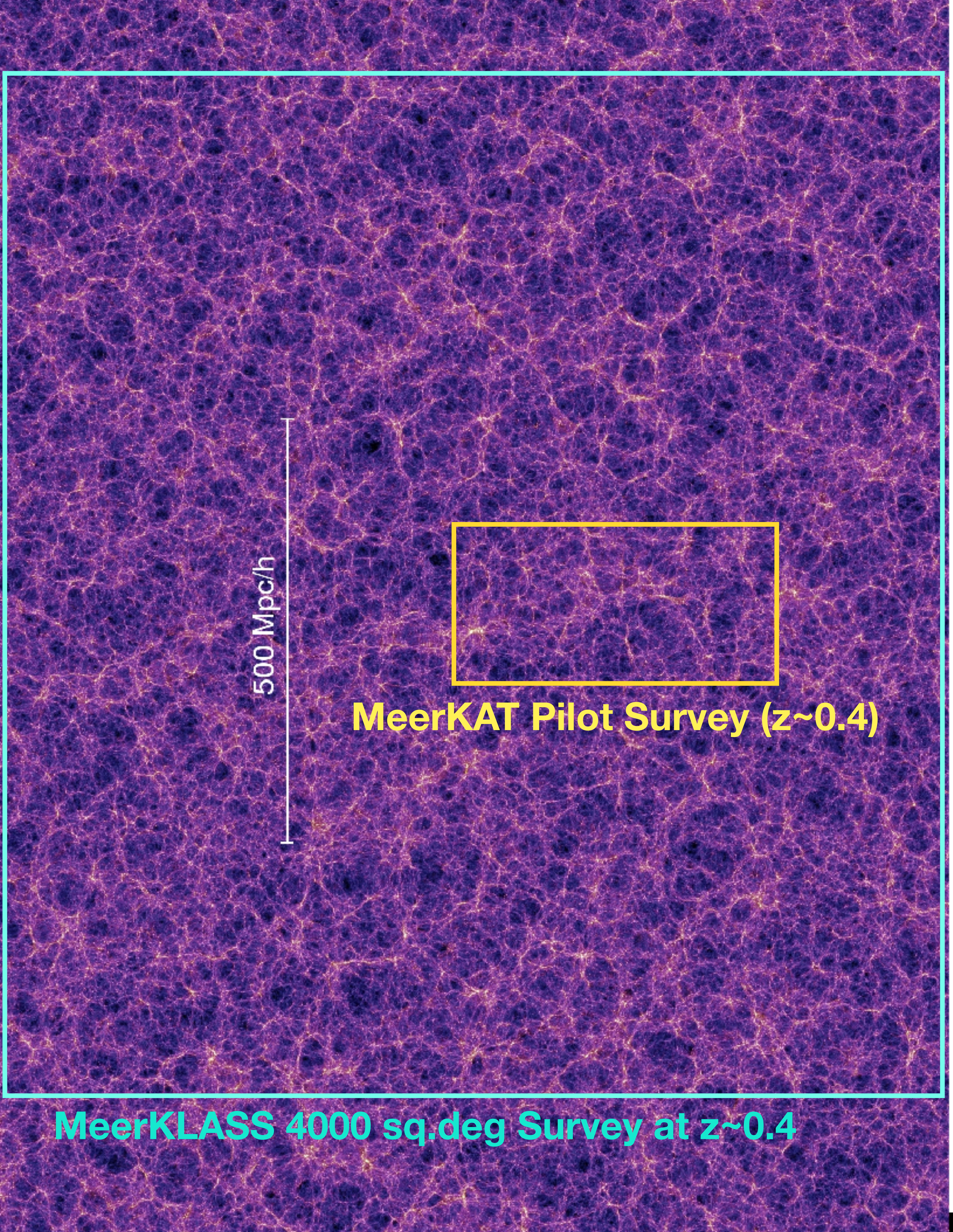
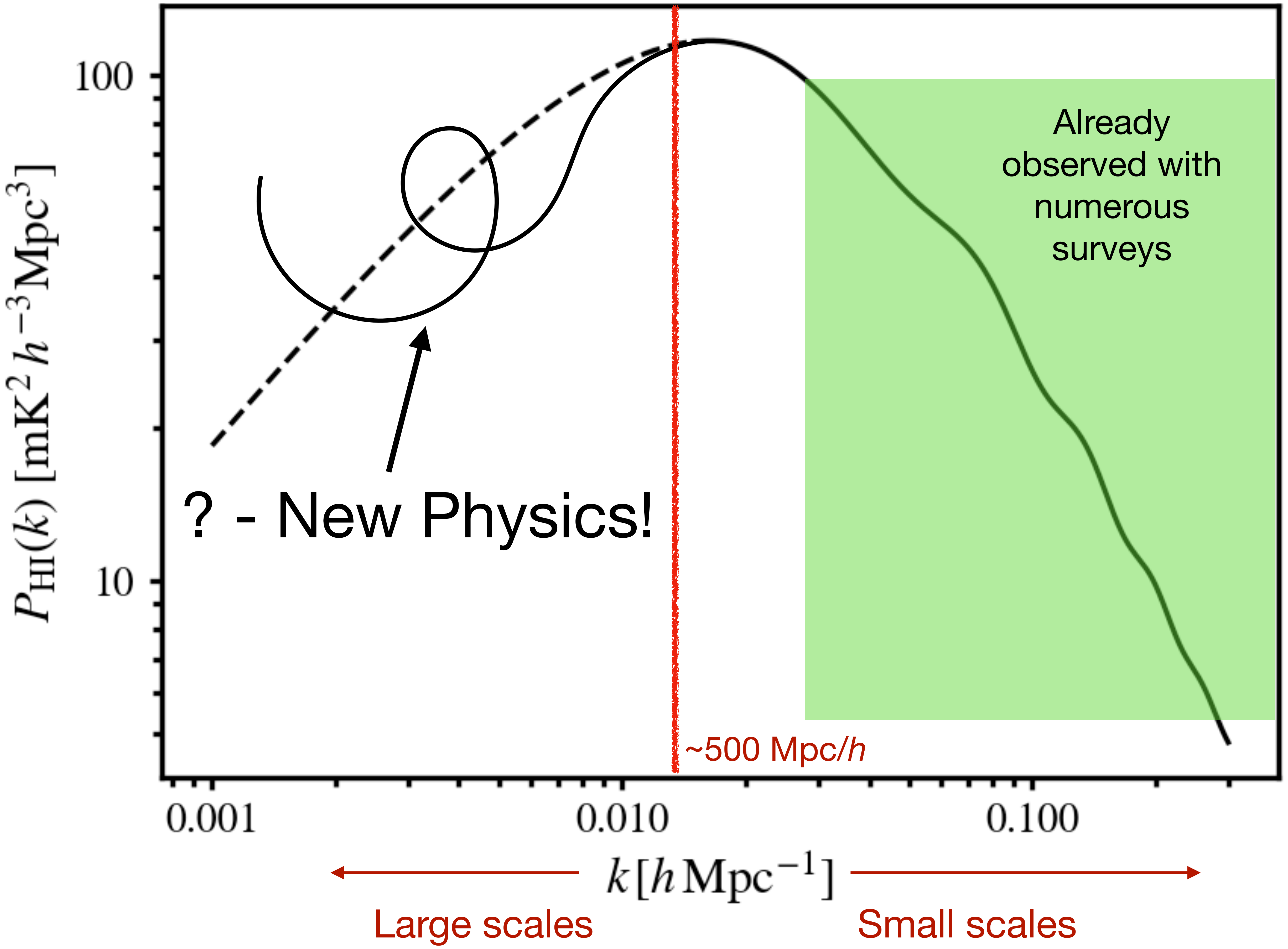
Future Prospects

Extending to “ultra-large” scales



Credit: The Millennium Simulation Project



Large scales could host evidence for:

- Primordial non-Gaussianity
- Relativistic effects

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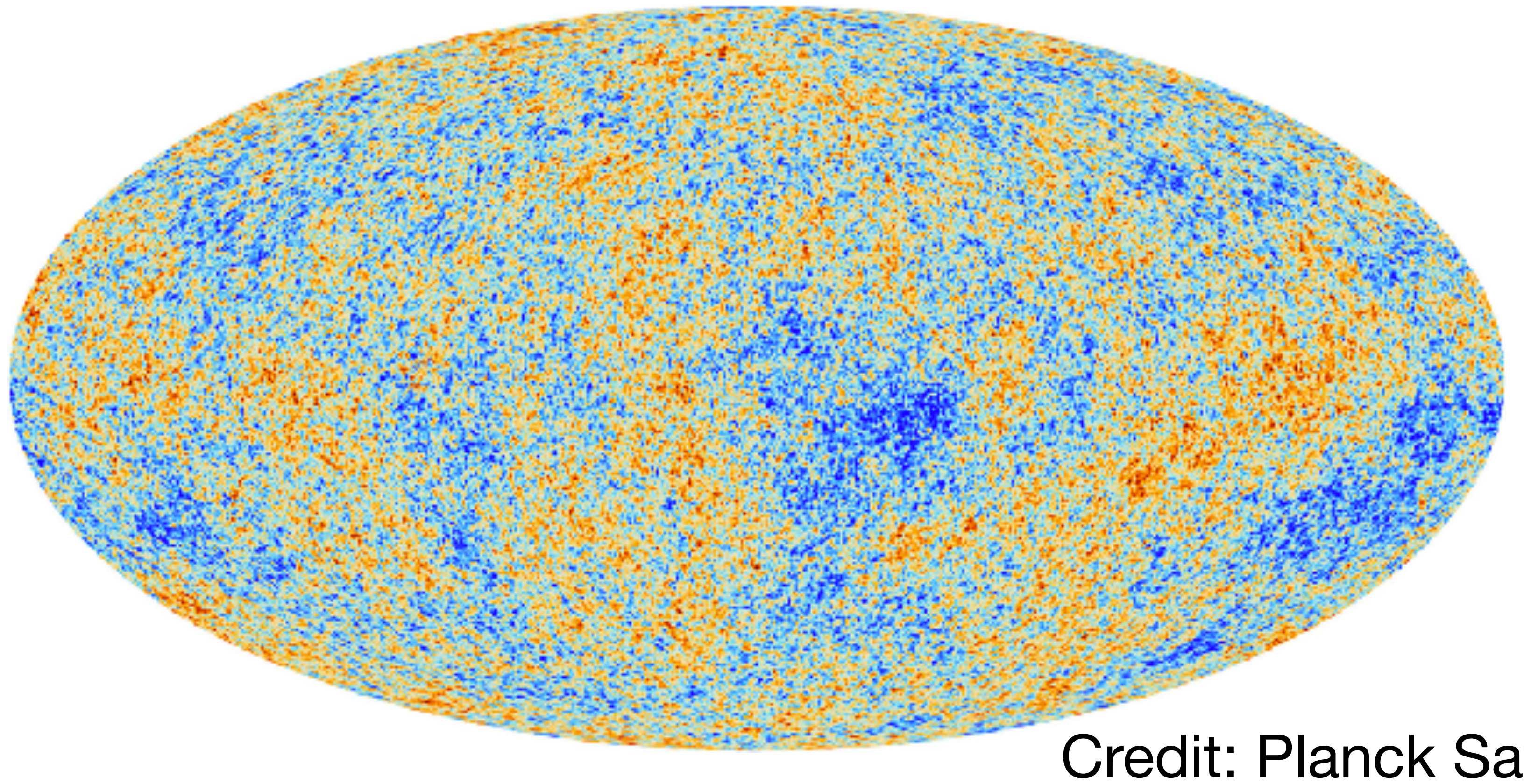
Why the largest scales?

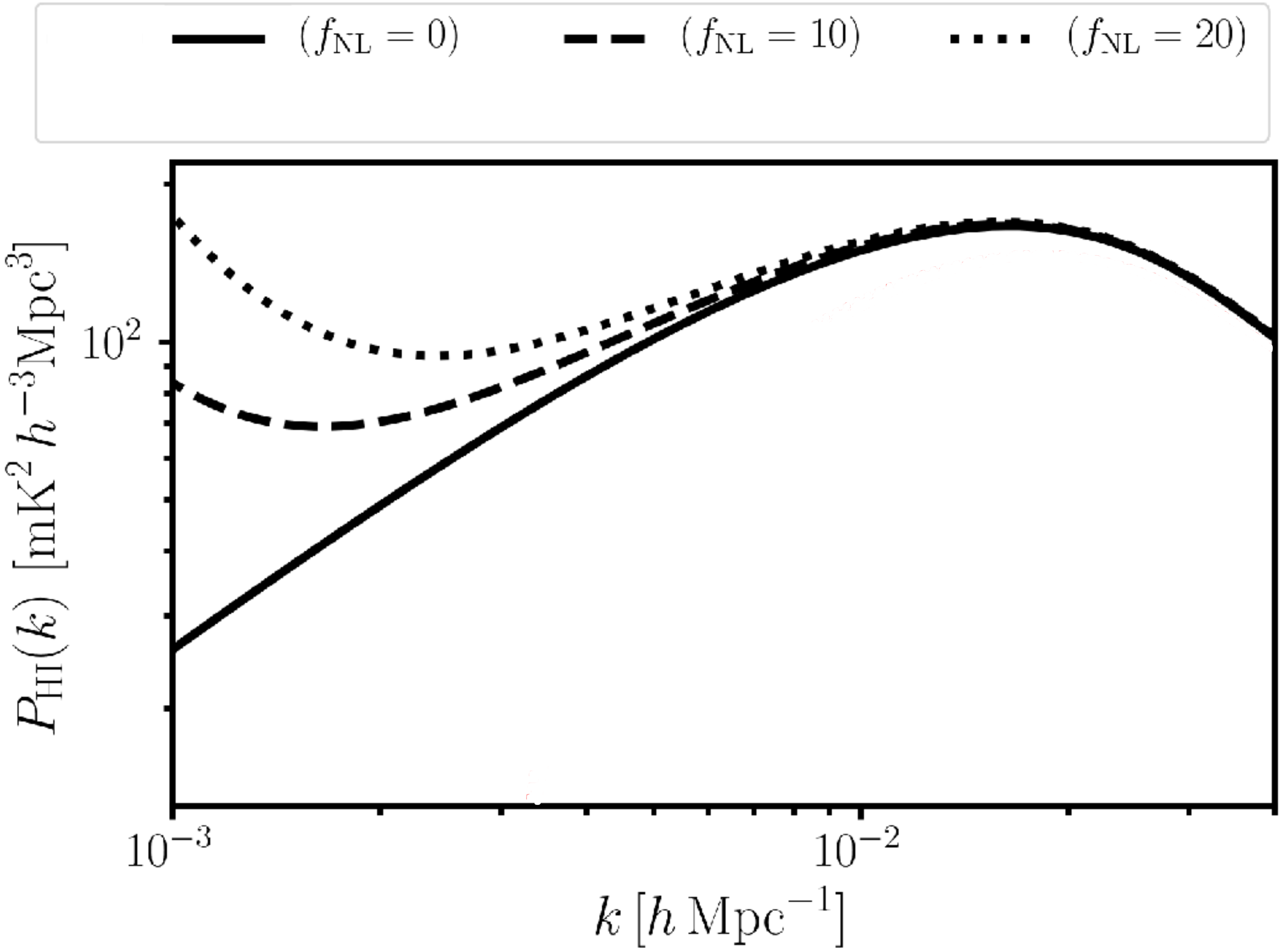


Credit: Planck Satellite

Q) Is the early Universe perturbation field Gaussian?

$$\Phi = \Phi_{\rm G} + f_{\rm NL}\left(\Phi_{\rm G}^2 - \langle\Phi_{\rm G}^2\rangle\right)$$

- $f_{\rm NL}$ parameterises **primordial non-Gaussianity** and we can use LSS surveys to probe it



S.Cunnington+20 [arXiv:2007.12126]

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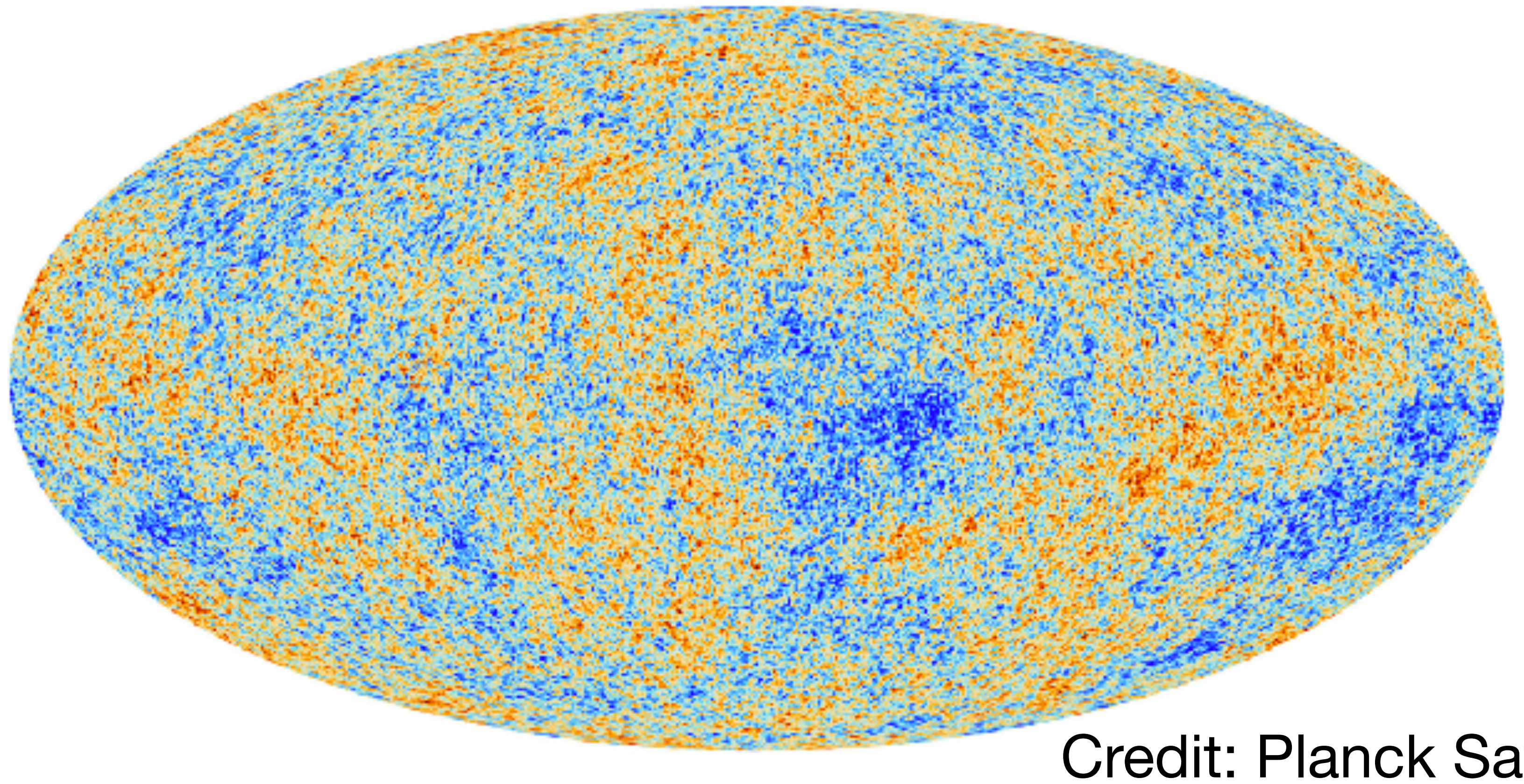

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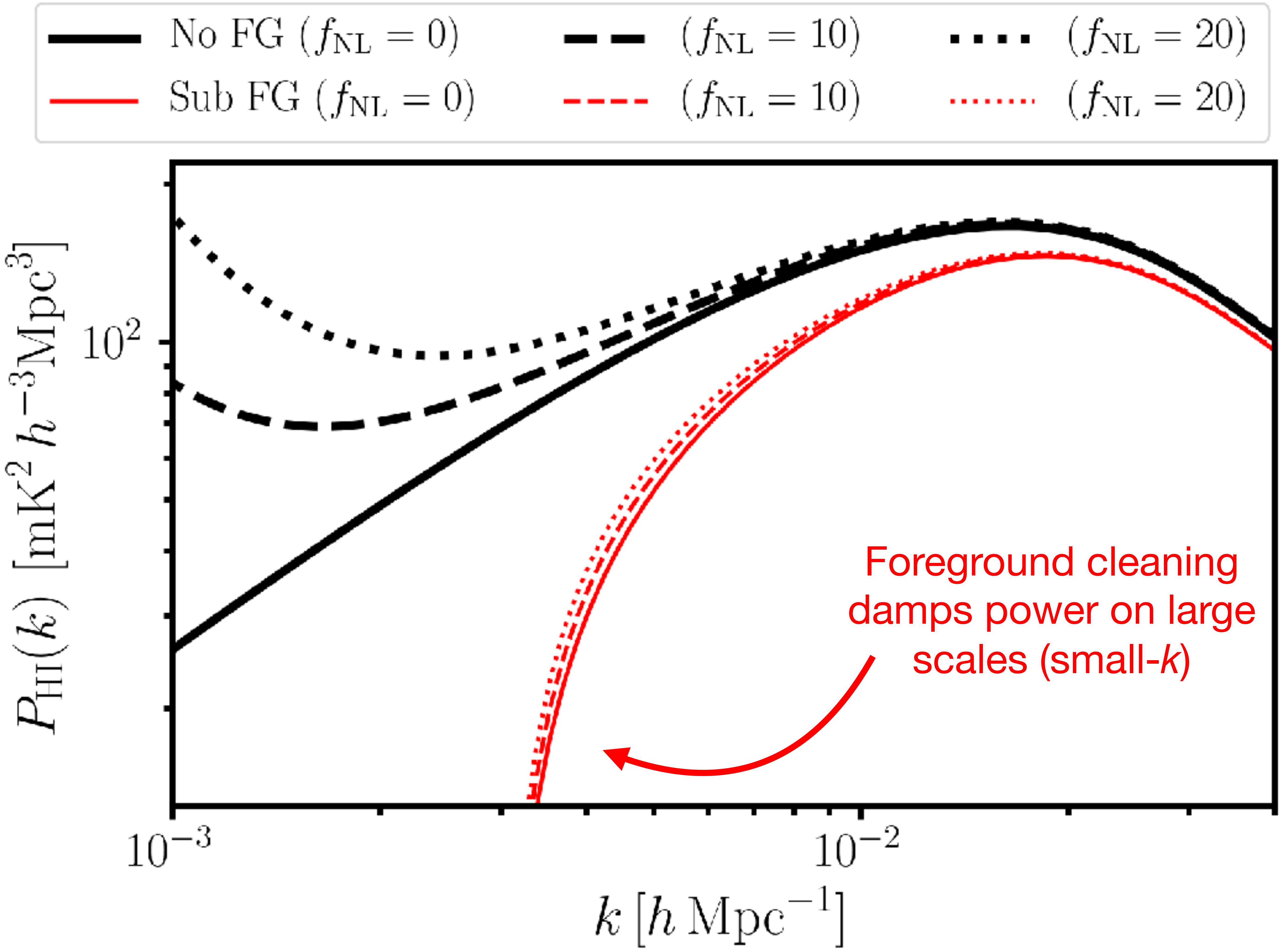
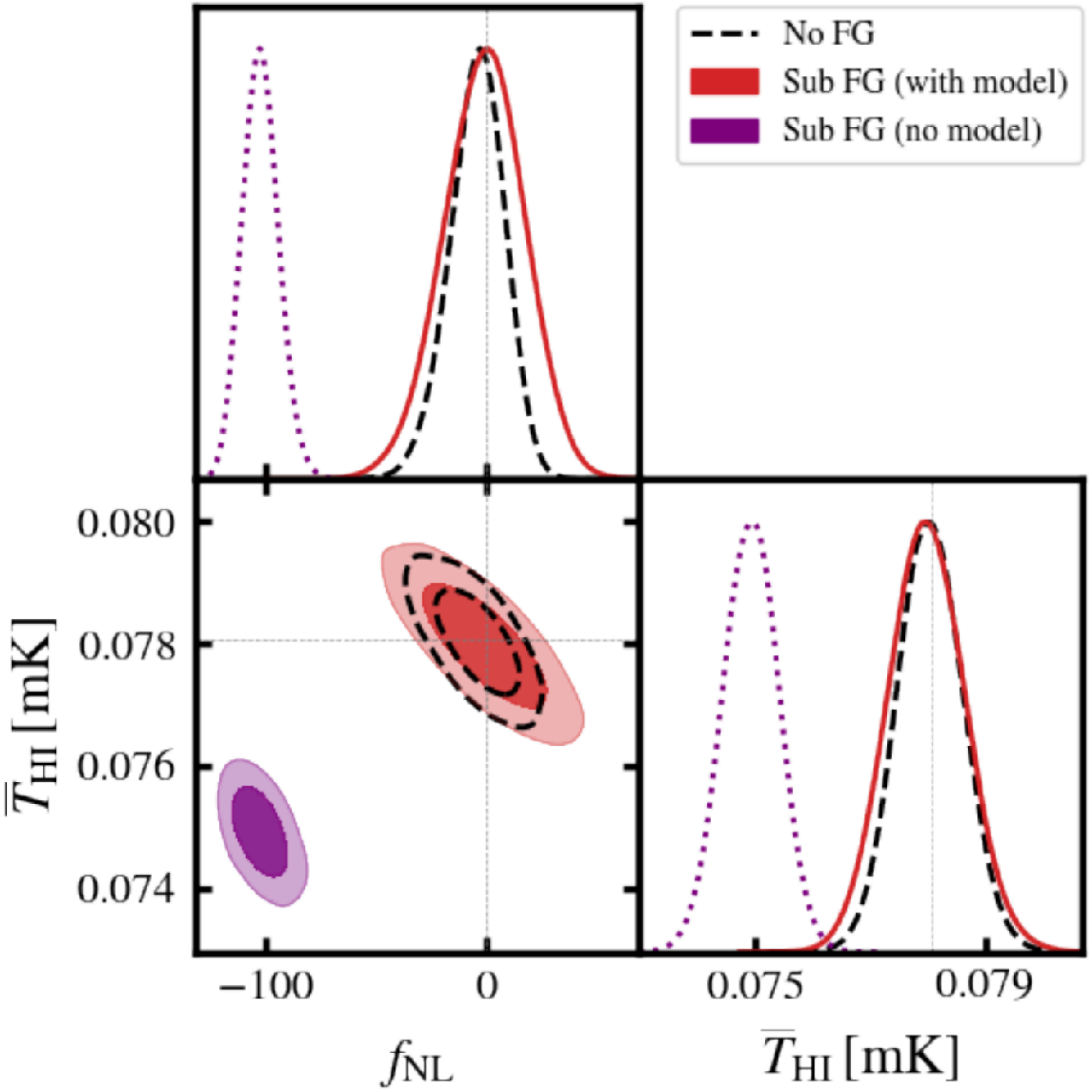
S.Cunnington+20 [arXiv:2007.12126]



Foreground cleaning damps power on large scales (small-*k*)

Effects from foregrounds on cosmology and correcting them



S.Cunnington+20 [arXiv:2007.12126]

Why 21cm HI (neutral hydrogen)?

Credit: Kovetz+17 [arXiv:1709.09066]

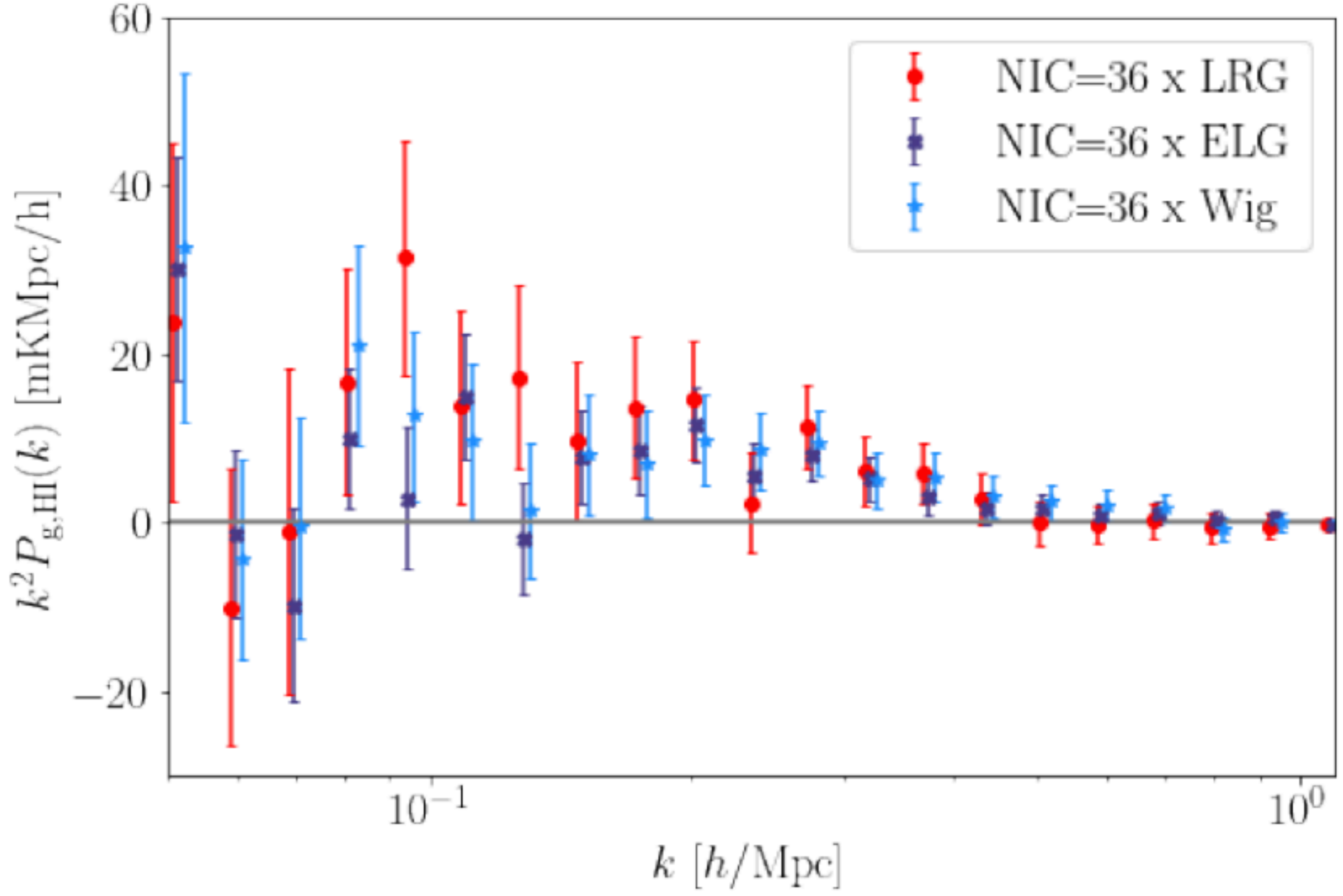
Steve Cunnington [steven.cunnington@manchester.ac.uk]

Operational single-dish intensity mapping experiments

1 - Parkes Observatory (Australia)
2 - Green Bank Telescope (USA)
3 - MeerKAT (South Africa)

Successful detections using HI intensity mapping

L.Wolz, …, SC+21 [arXiv:2102.04946]

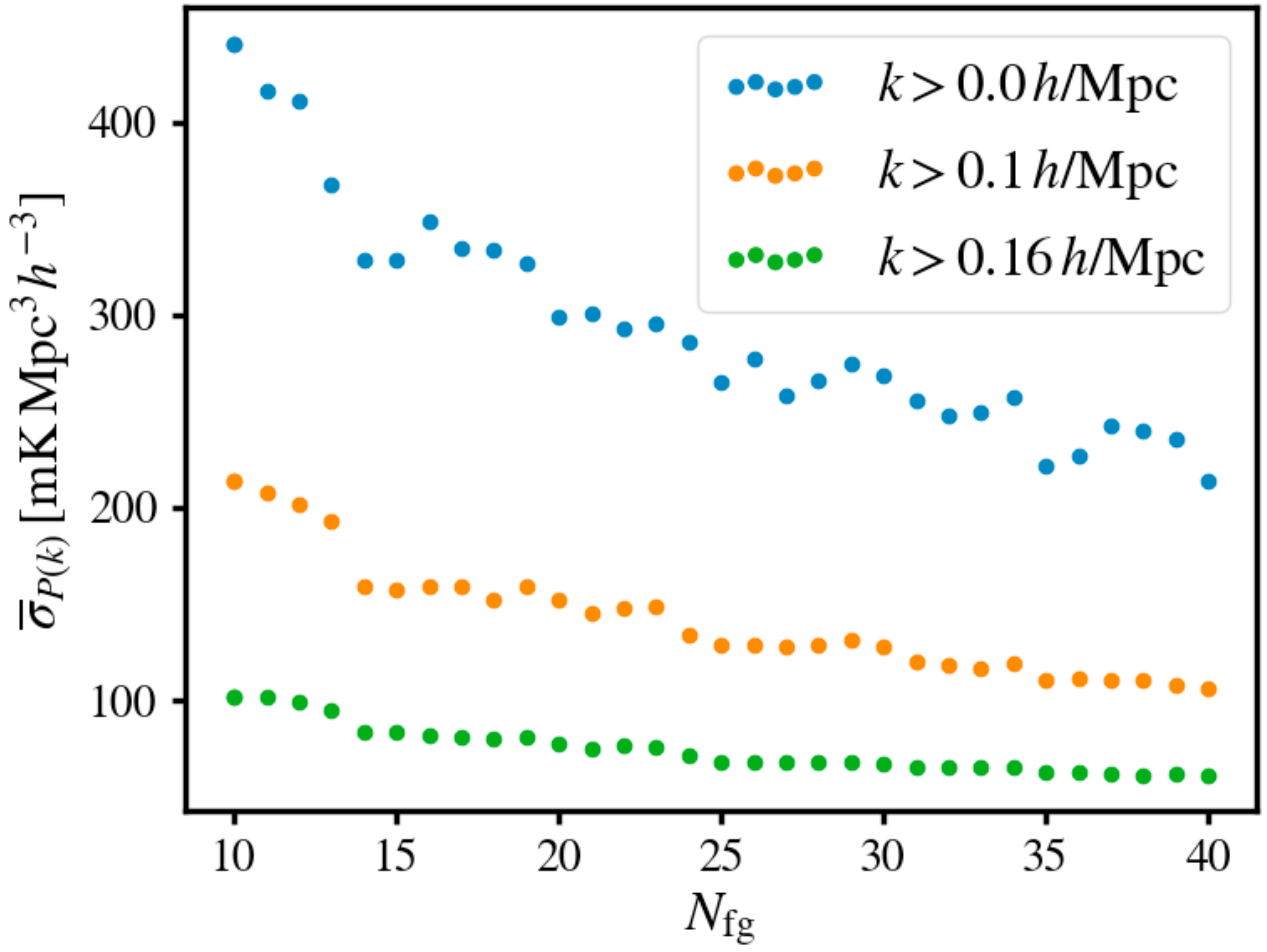


Using ~100 deg2 of GBT intensity map observations in **cross-correlation** with

- eBOSS Luminous Red Galaxies (LRG)
- eBOSS Emission Line Galaxies (ELG)
- WiggleZ Dark Energy Survey Sample

Error estimation

$$\hat{\sigma}_{\mathrm{HI,g}}(k)=\frac{1}{\sqrt{2N_{\mathrm{modes}}(k)}}\sqrt{\hat{P}^2_{\mathrm{HI,g}}(k)+\hat{P}_{\mathrm{HI}}(k)\left(\hat{P}_{\mathrm{g}}(k)+\frac{1}{\bar{n}_{\mathrm{g}}}\right)}$$



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