Large scale radio cosmology with 21cm intensity mapping

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Department of Theoretical Physics Mumbai - 11th Feb 2022

Karoo Desert, South Africa

THE UNIVERSITY of EDINBURGH

UK Research and Innovation

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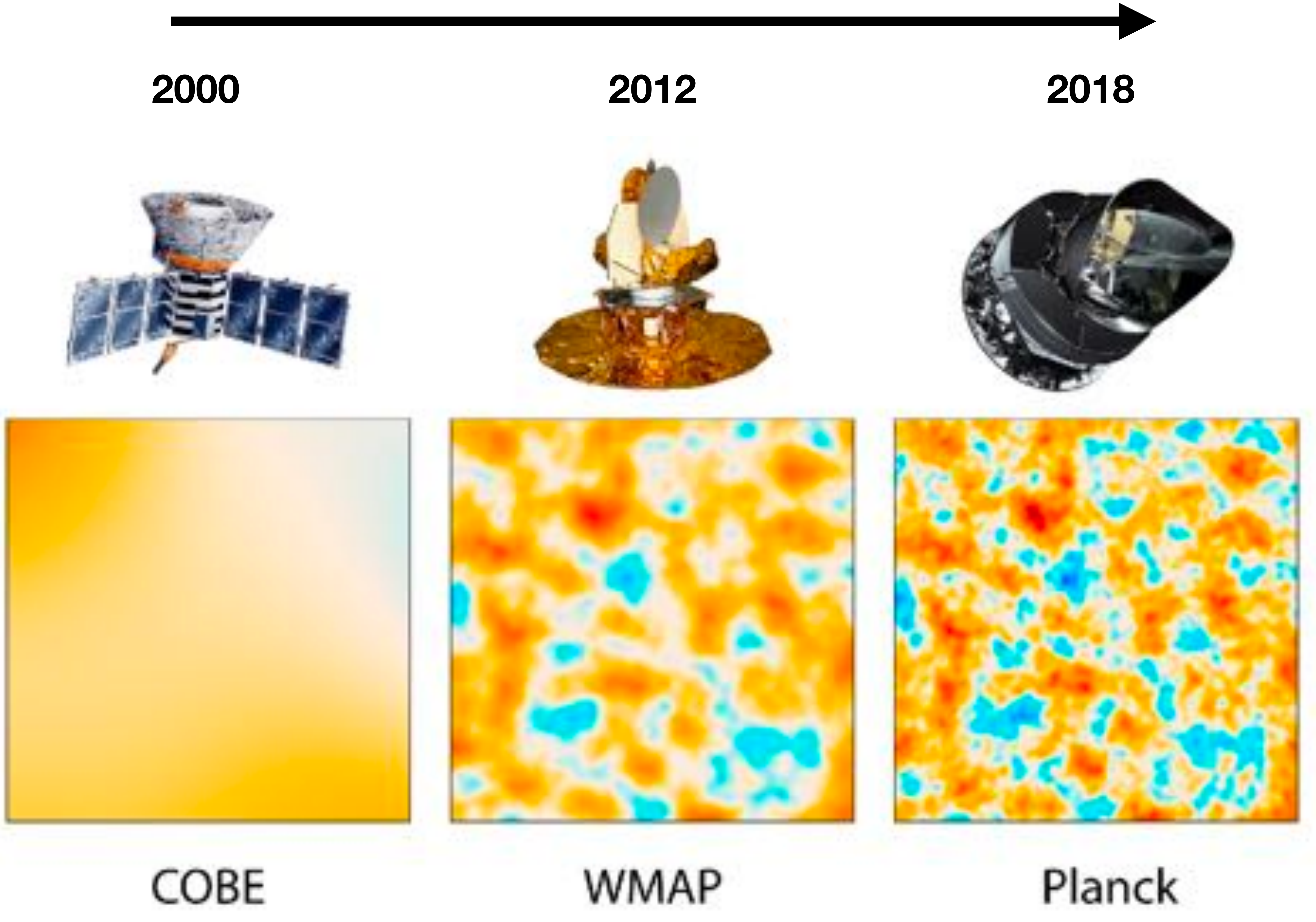
What I will talk about …

- Cosmology - a precision science(?)
- Why study **large-scale cosmic structure**?
- What is **intensity mapping**?
- Why HI 21cm (neutral hydrogen)?
- **Challenges** to overcome
- HI intensity mapping pathfinder survey **data**
- What the future holds?

Cosmology - a precision science(?)



Experiments to probe the Cosmic Microwave Background (CMB) - source: Wikipedia

Parameter	*Planck* alone
$\Omega_b h^2$	0.02237 ± 0.00015
$\Omega_c h^2$	0.1200 ± 0.0012
$100\theta_{MC}$	1.04092 ± 0.00031
τ	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.044 ± 0.014
n_s	0.9649 ± 0.0042
H_0	67.36 ± 0.54
Ω_Λ	0.6847 ± 0.0073
Ω_m	0.3153 ± 0.0073
$\Omega_m h^2$	0.1430 ± 0.0011
$\Omega_m h^3$	0.09633 ± 0.00030
σ_8	0.8111 ± 0.0060
$\sigma_8(\Omega_m/0.3)^{0.5}$	0.832 ± 0.013
z_{re}	7.67 ± 0.73
Age[Gyr]	13.797 ± 0.023
r_*[Mpc]	144.43 ± 0.26
$100\theta_*$	1.04110 ± 0.00031
r_{drag}[Mpc]	147.09 ± 0.26
z_{eq}	3402 ± 26
k_{eq}[Mpc^{-1}]	0.010384 ± 0.000081
Ω_K	-0.0096 ± 0.0061
Σm_ν [eV]	< 0.241
N_{eff}	$2.89^{+0.36}_{-0.38}$
$r_{0.002}$	< 0.101

within 1% precision (first six parameters)

Planck Collaboration 2018 [arXiv:1807.06205]

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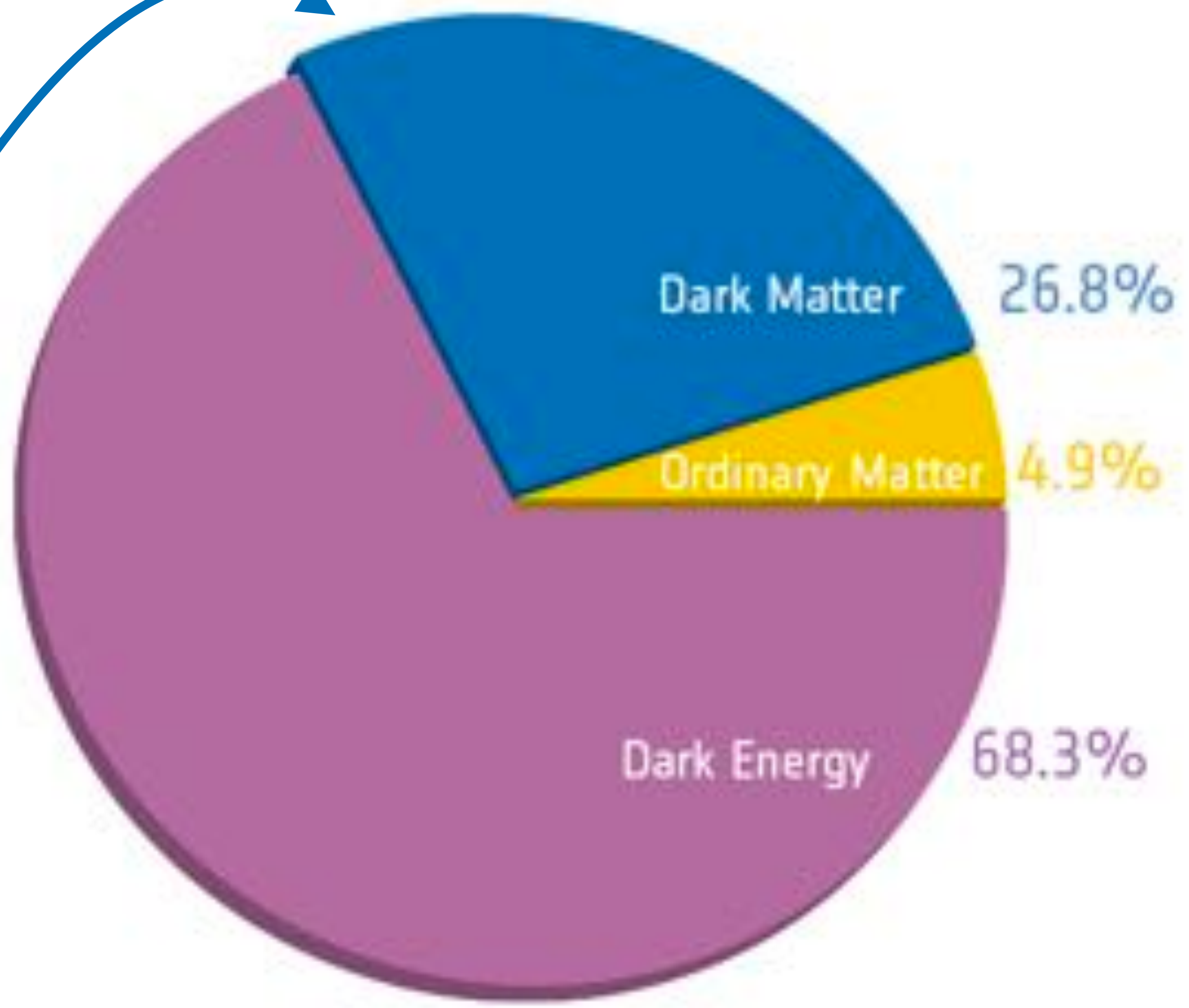
Cosmology - a precision science(?)

Standard Model of Cosmology: ΛCDM



Still plenty of unanswered questions:

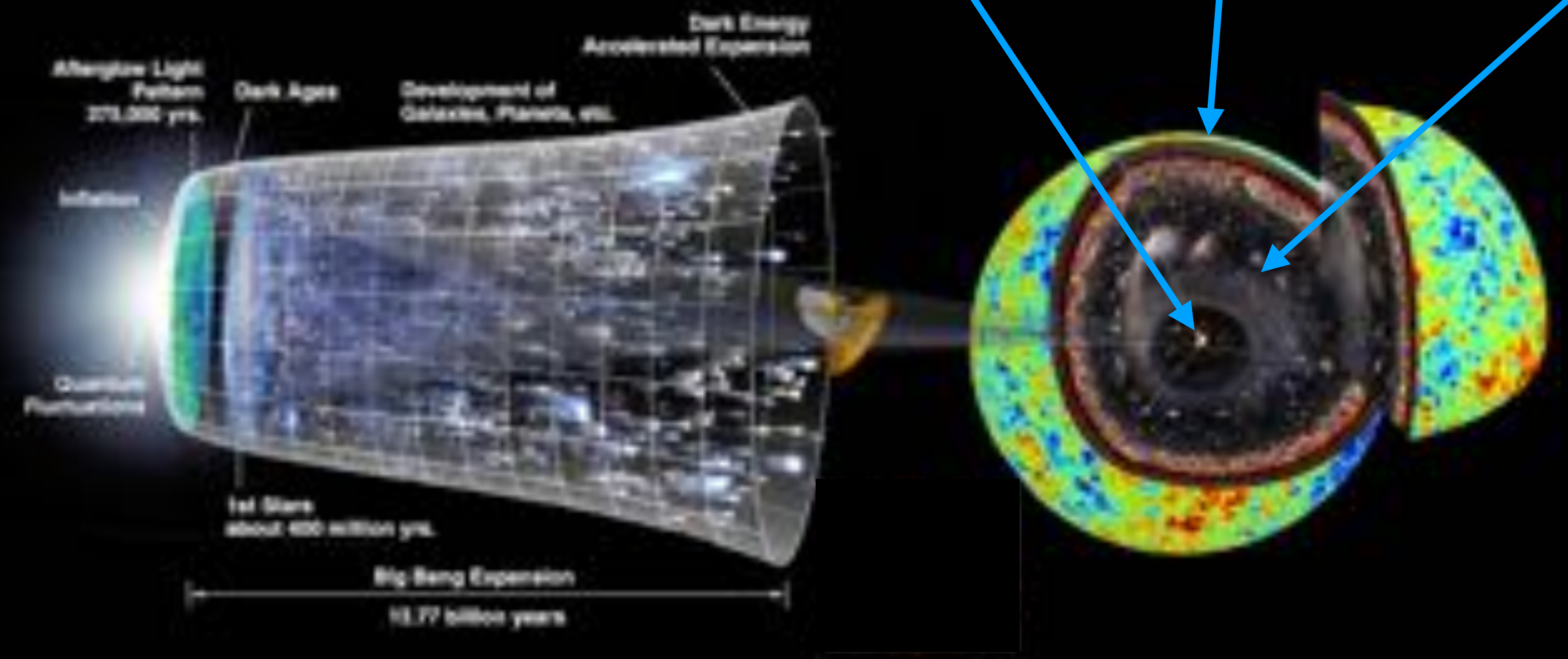
- Nature of dark matter
- Nature of dark energy
- Conditions and processes during the early universe
- Theory of gravity consistent with QFT
- ??????

Why study large-scale cosmic structure?

Observer

CMB “outer-shell”

In between will mostly contain large-scale structure



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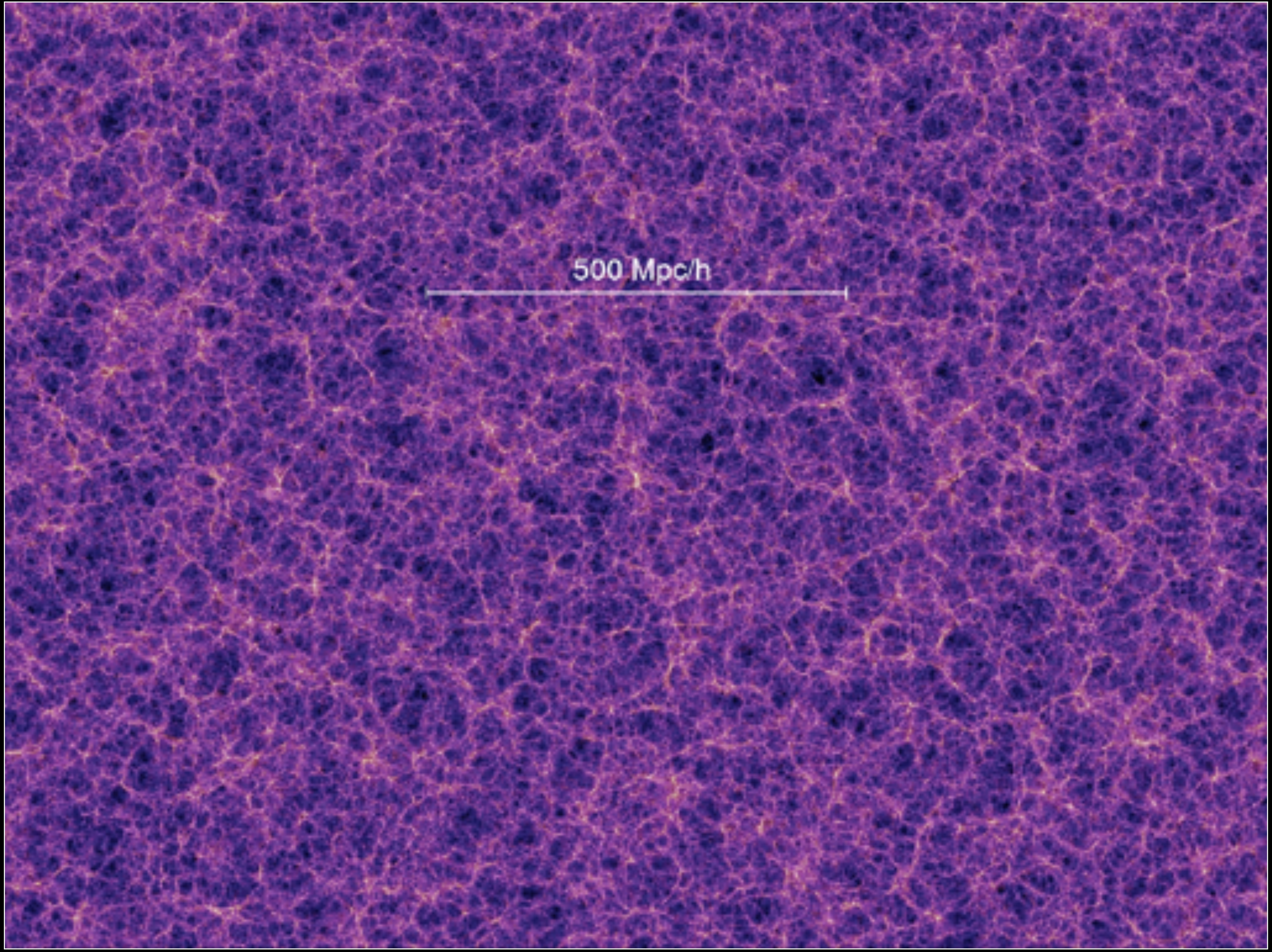
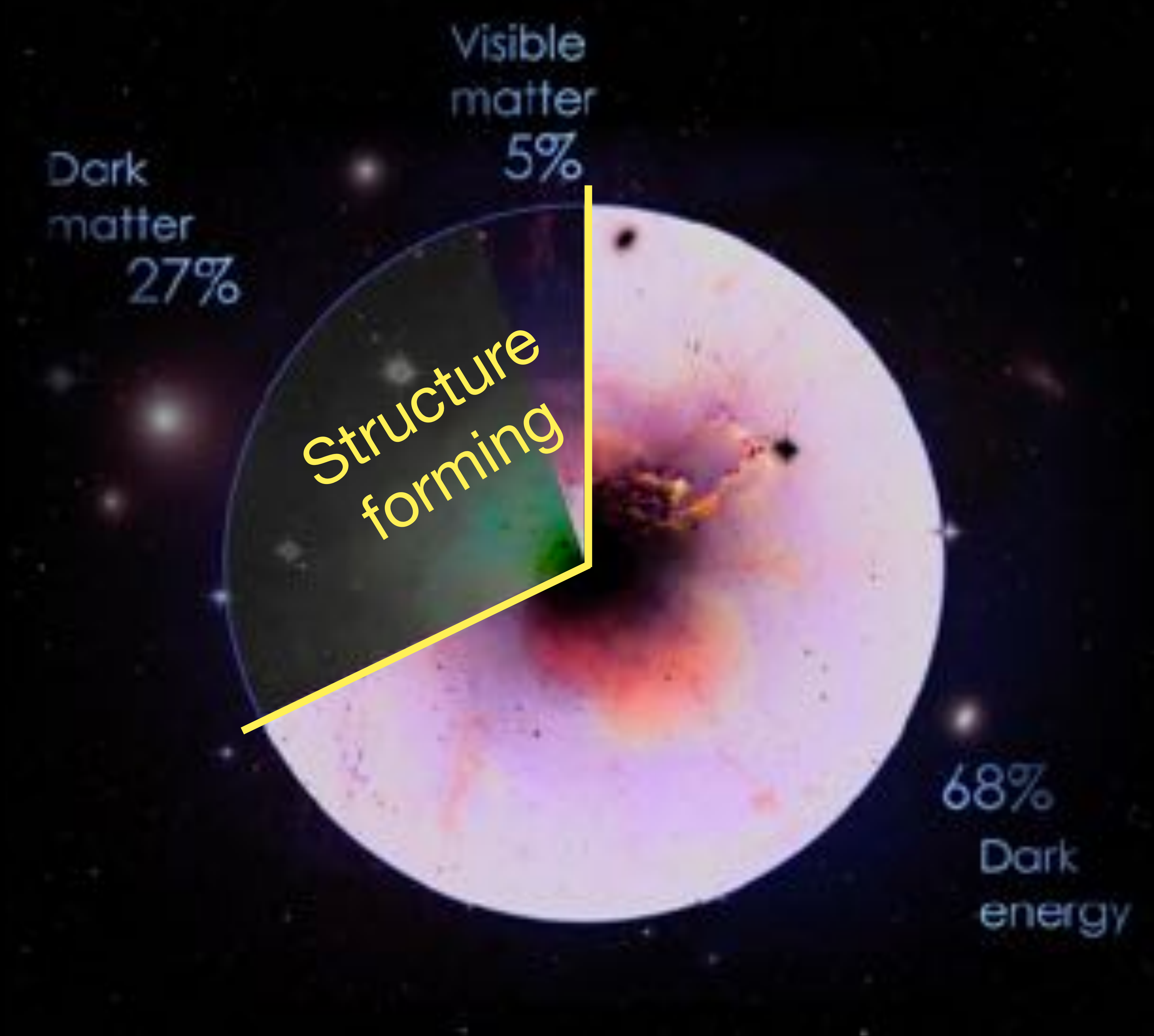
Why study large-scale cosmic structure?





The Millennium
Simulation Project

[a dark matter simulation]

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

Electrical lighting is a *biased* tracer of population

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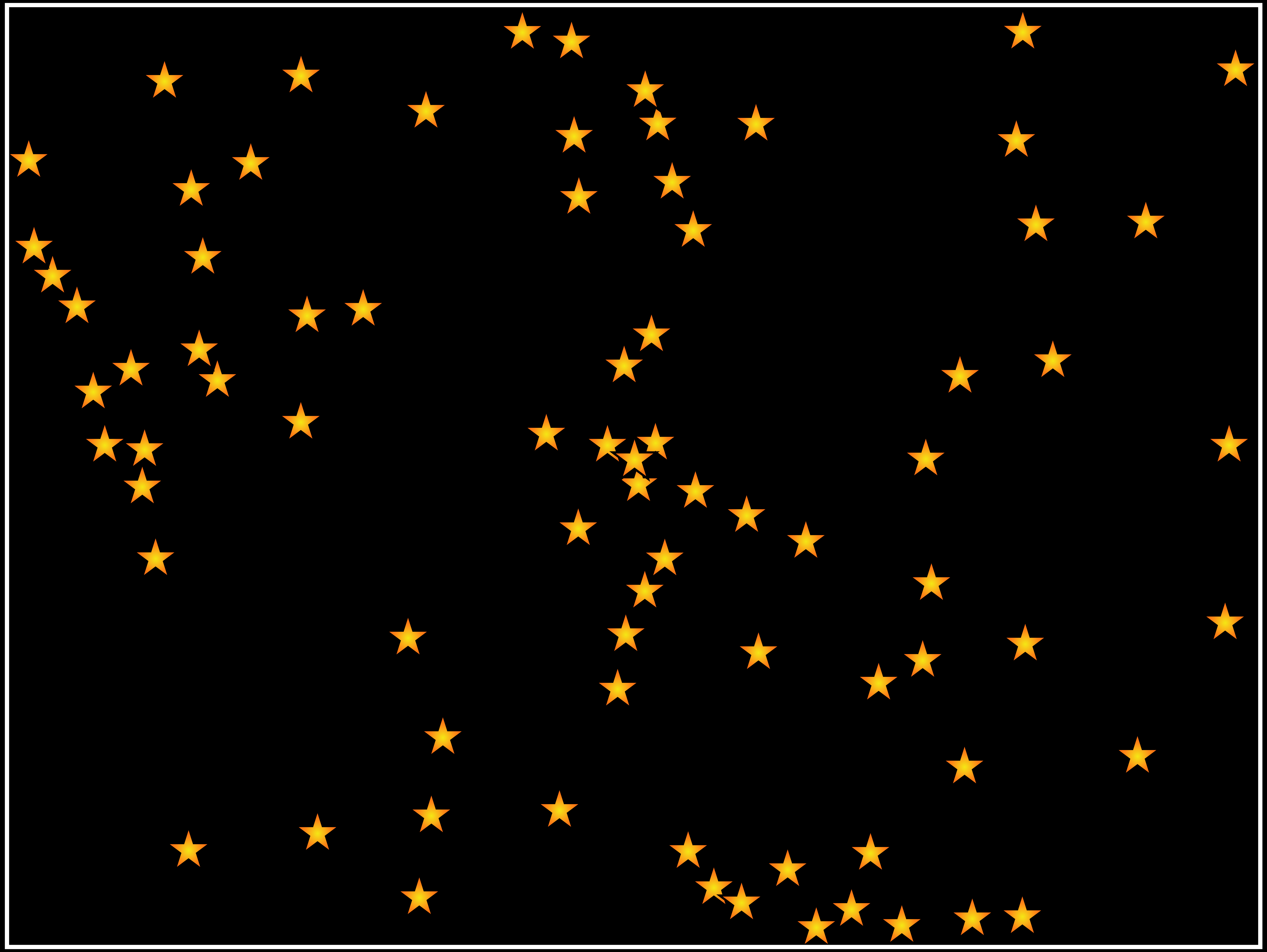
Why study large-scale cosmic structure?



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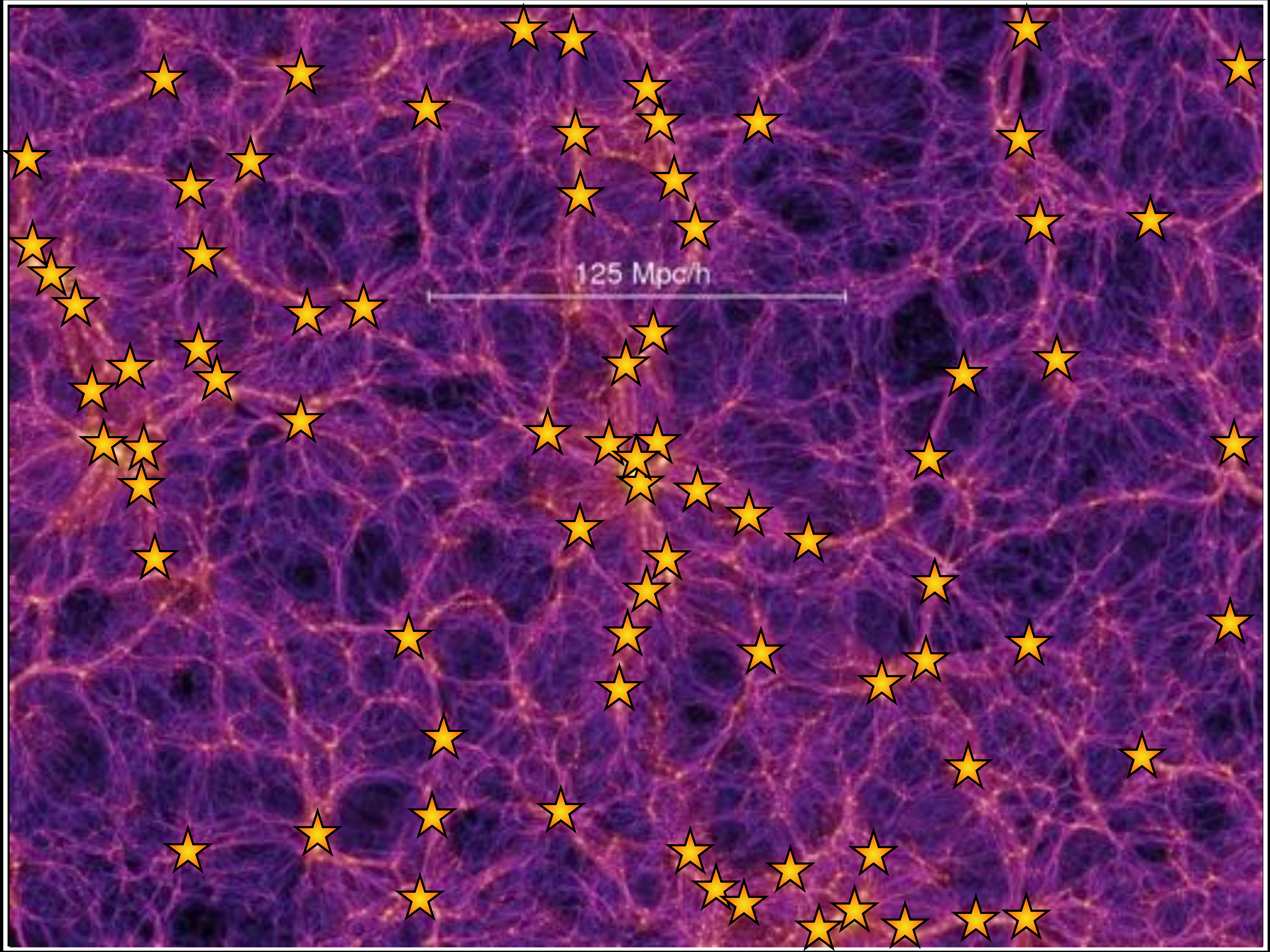
Why study large-scale cosmic structure?



The Millennium Simulation Project

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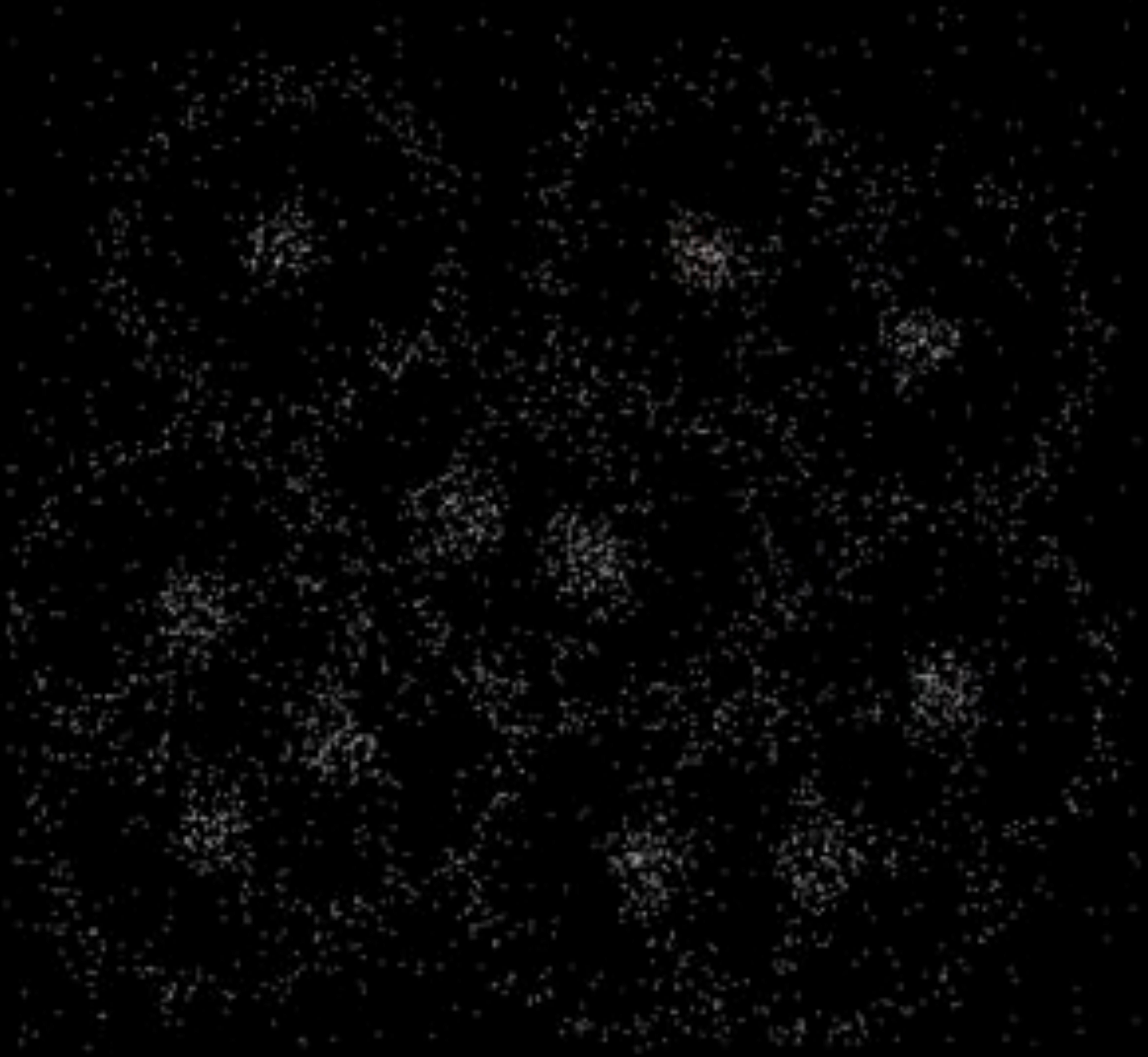
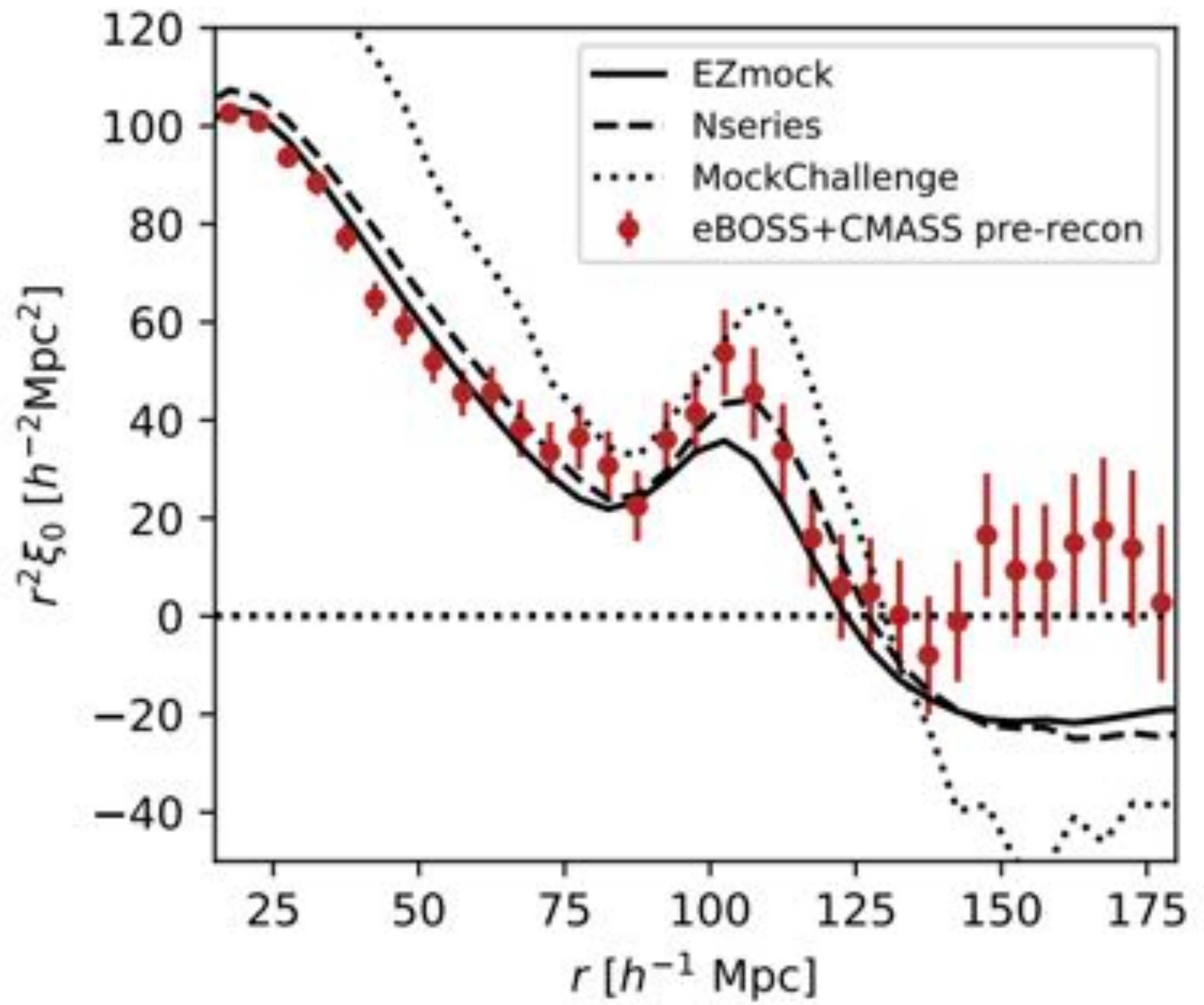


A real data example:

eBOSS measured correlation function from ~375,000 galaxies

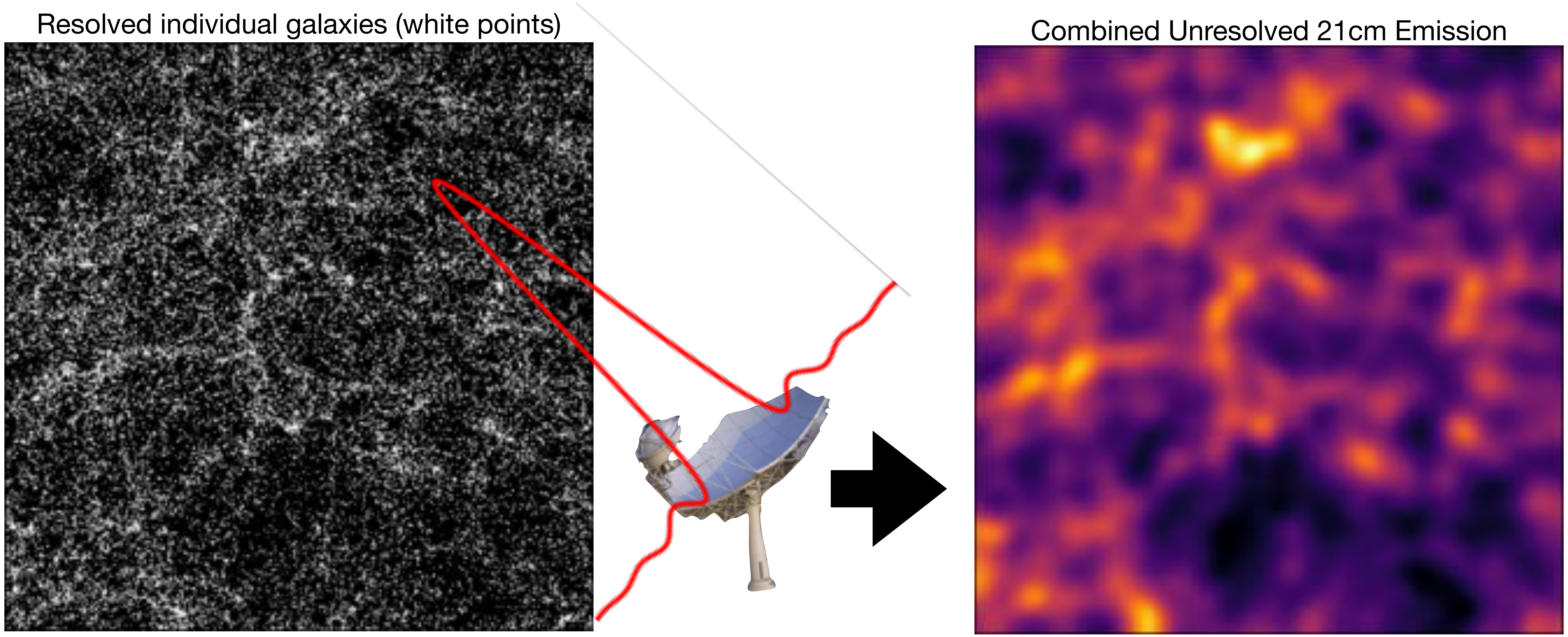


Credit: Bautista+20 [arXiv:2007.08993]

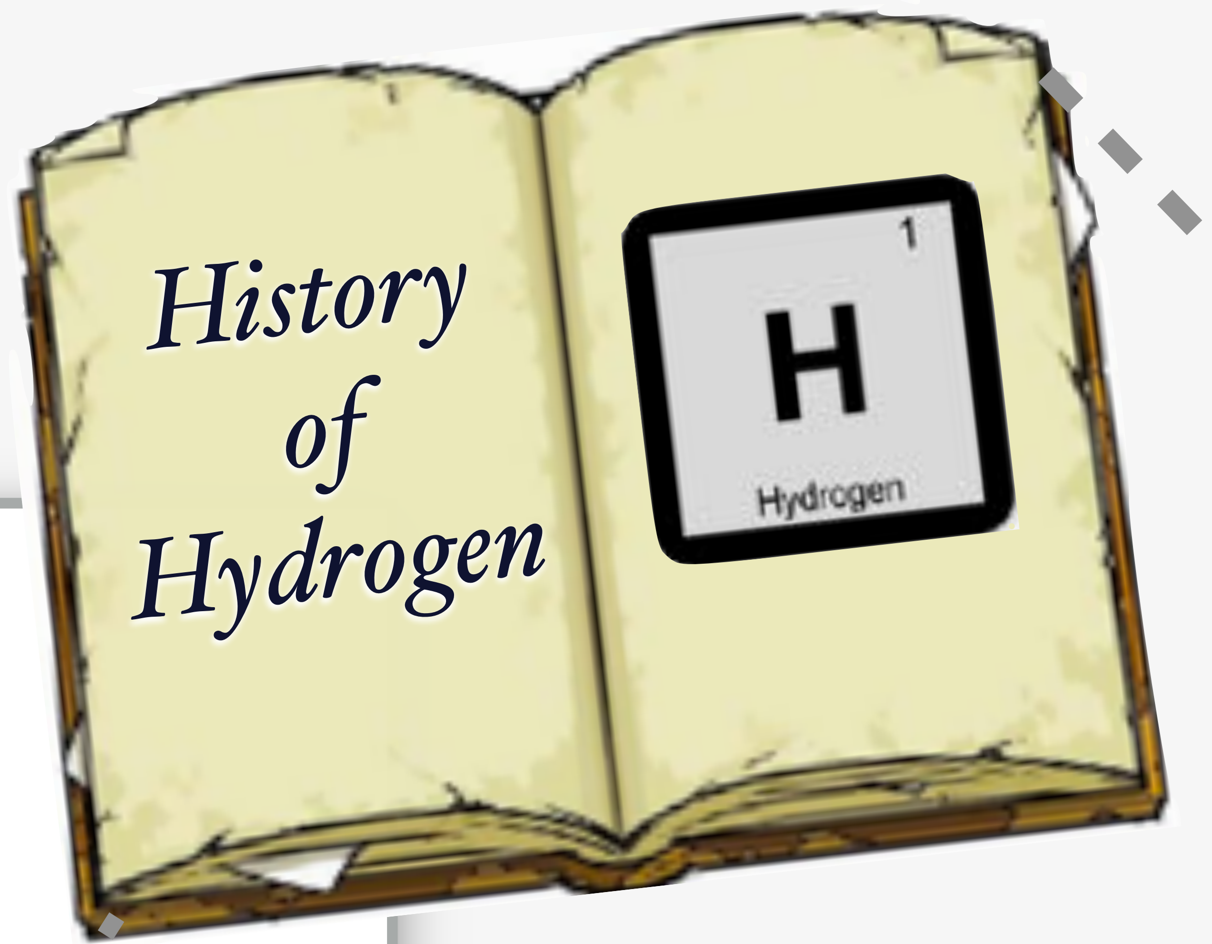
Other ways to map large-scale structure?

- 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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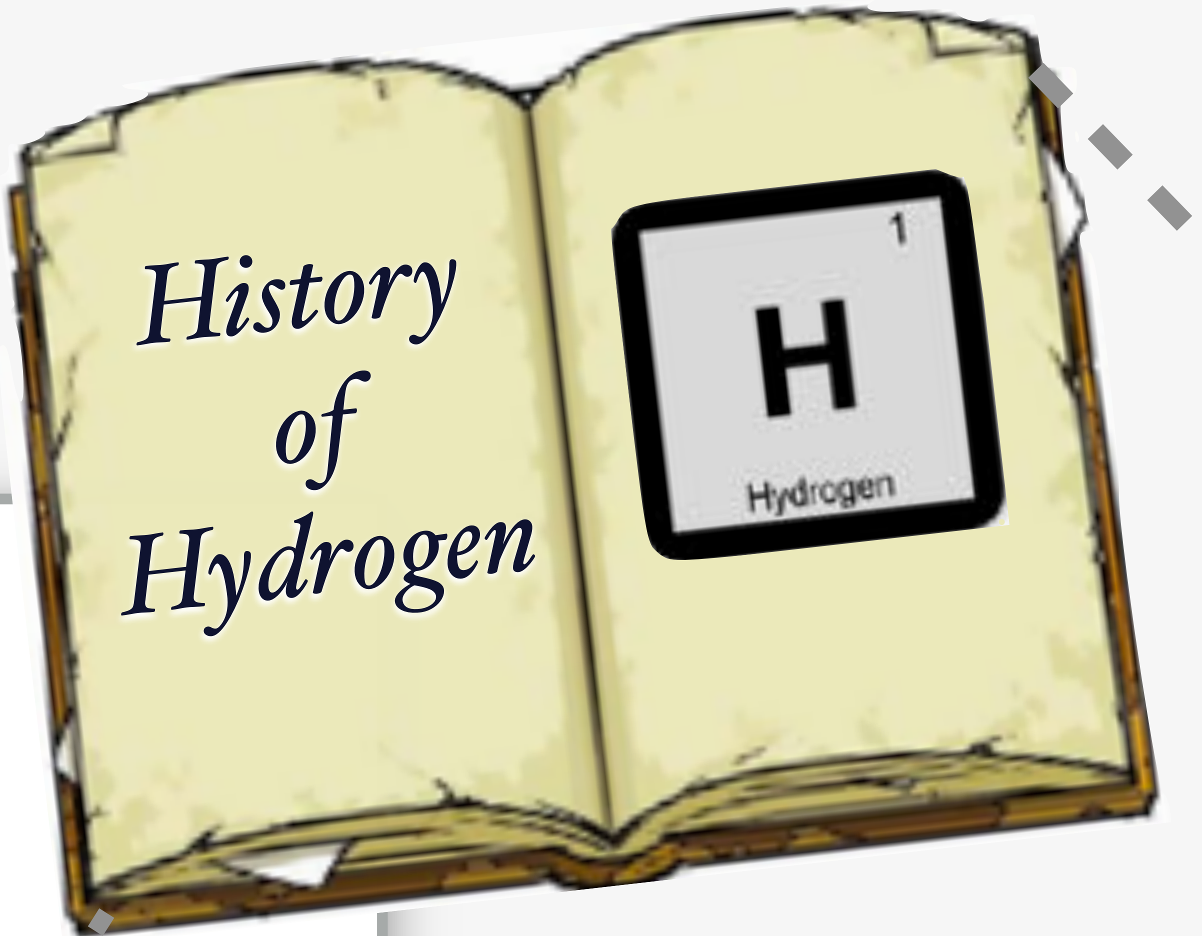
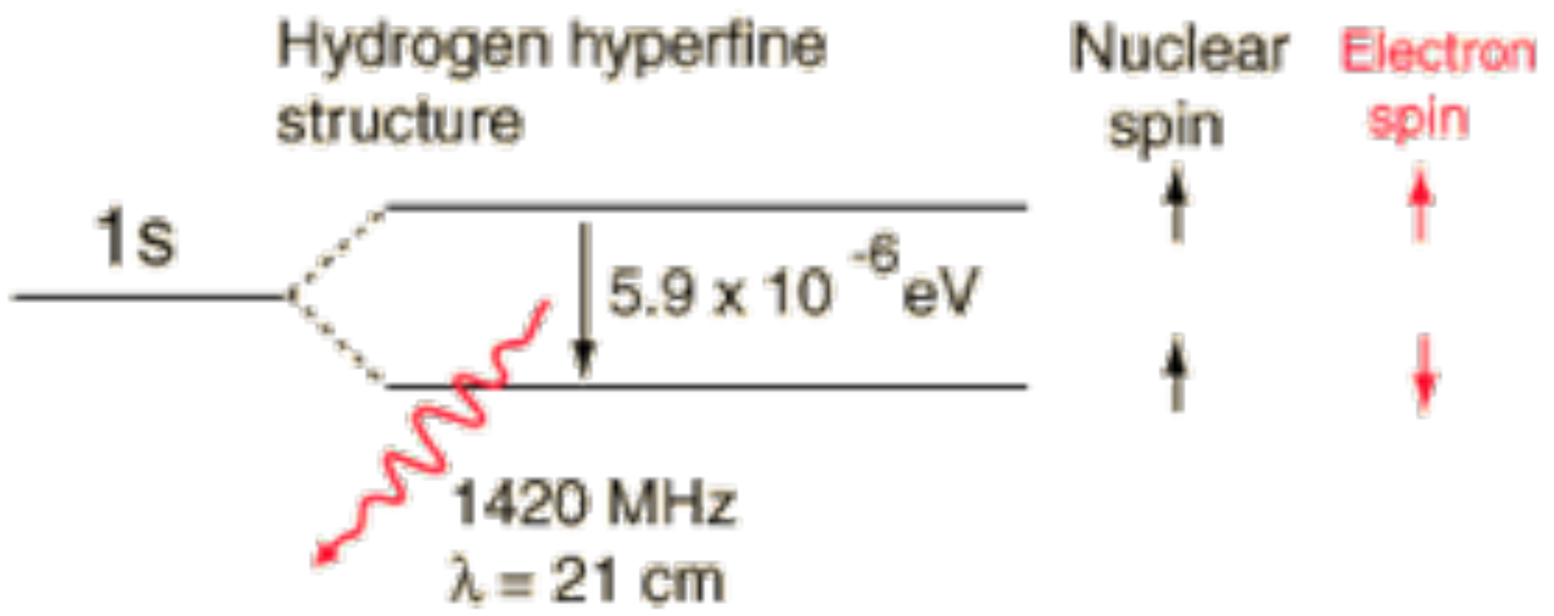
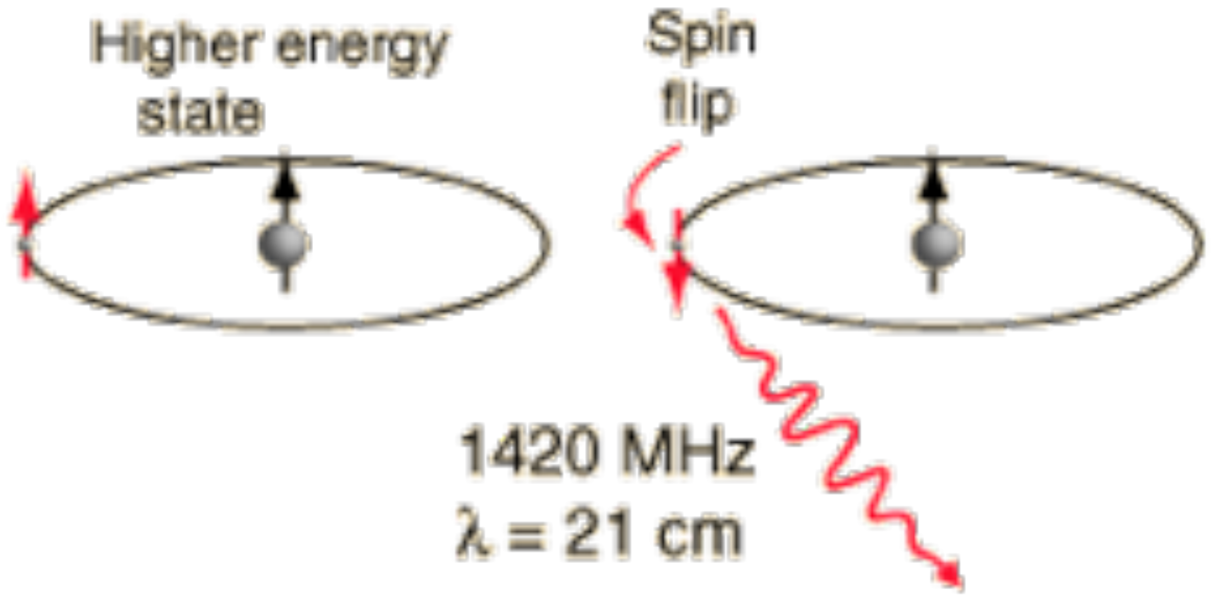
Why 21cm HI (neutral hydrogen)?



HI ground state has hyperfine structure





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

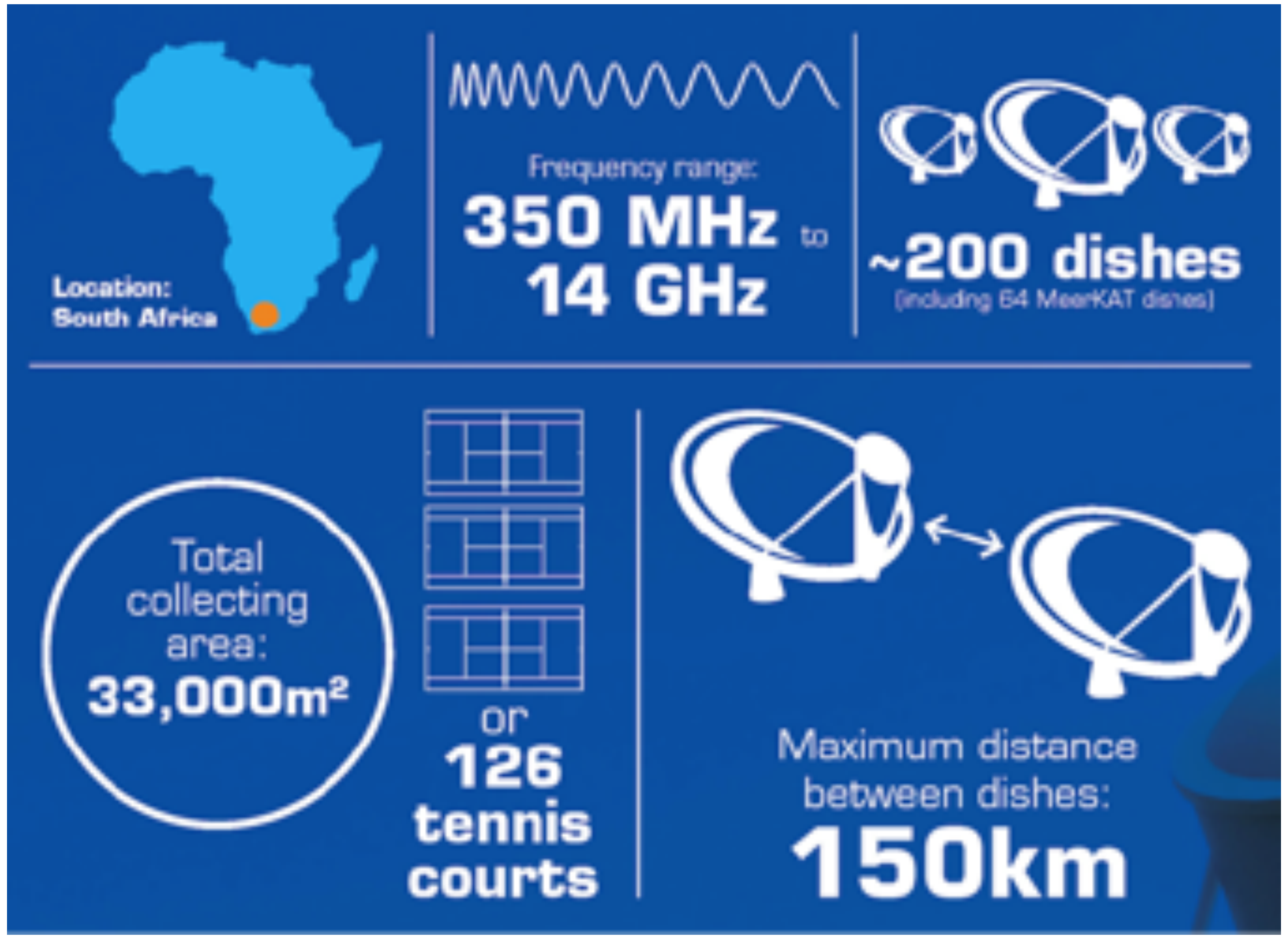
This emits a photon with small amount of energy and consequently a large (radio) wavelength of **21cm**


CAASTRO

21cm intensity mapping experiments

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

SKA1 - MID (South Africa)



- Redshift range: $0 < z < 3$

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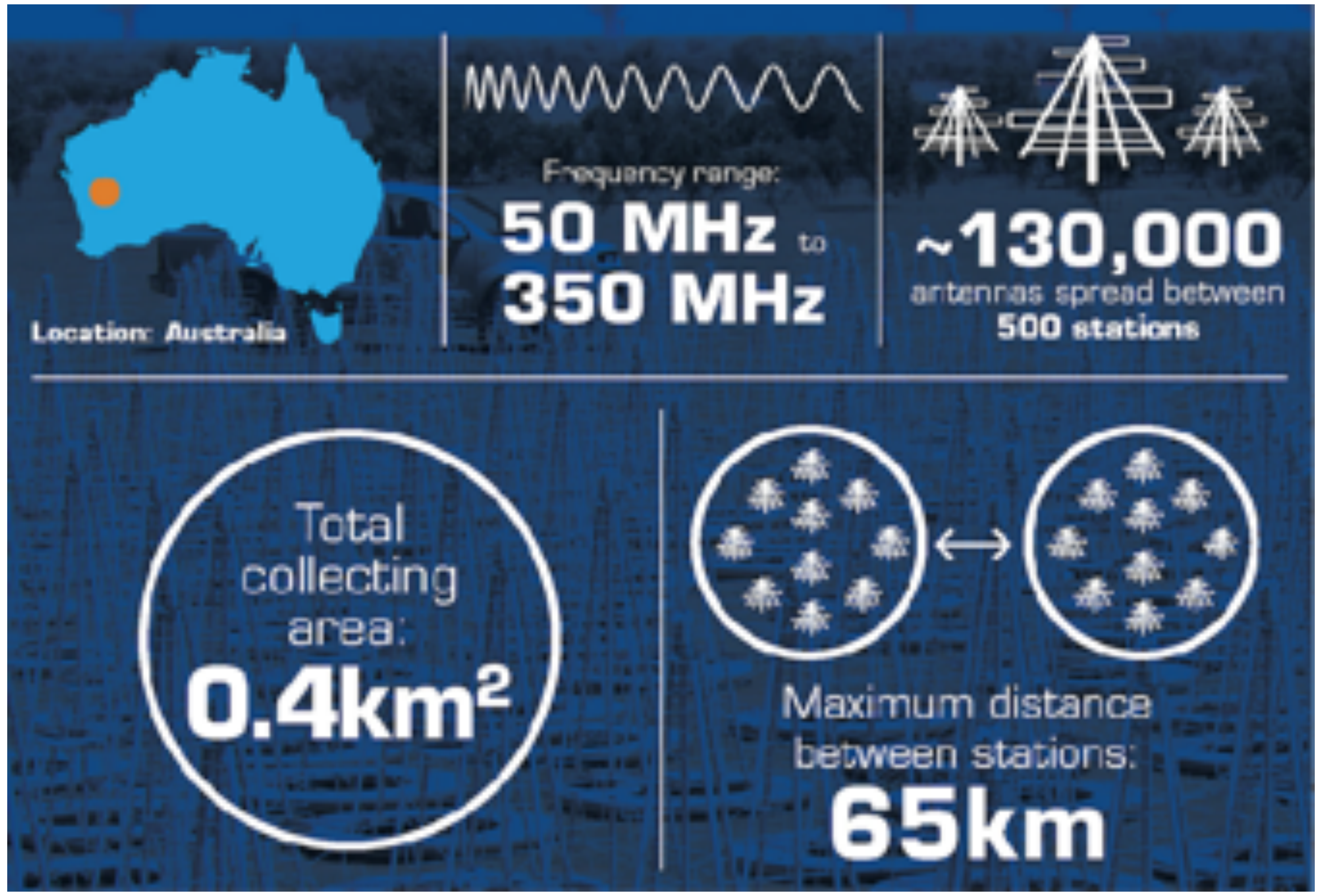
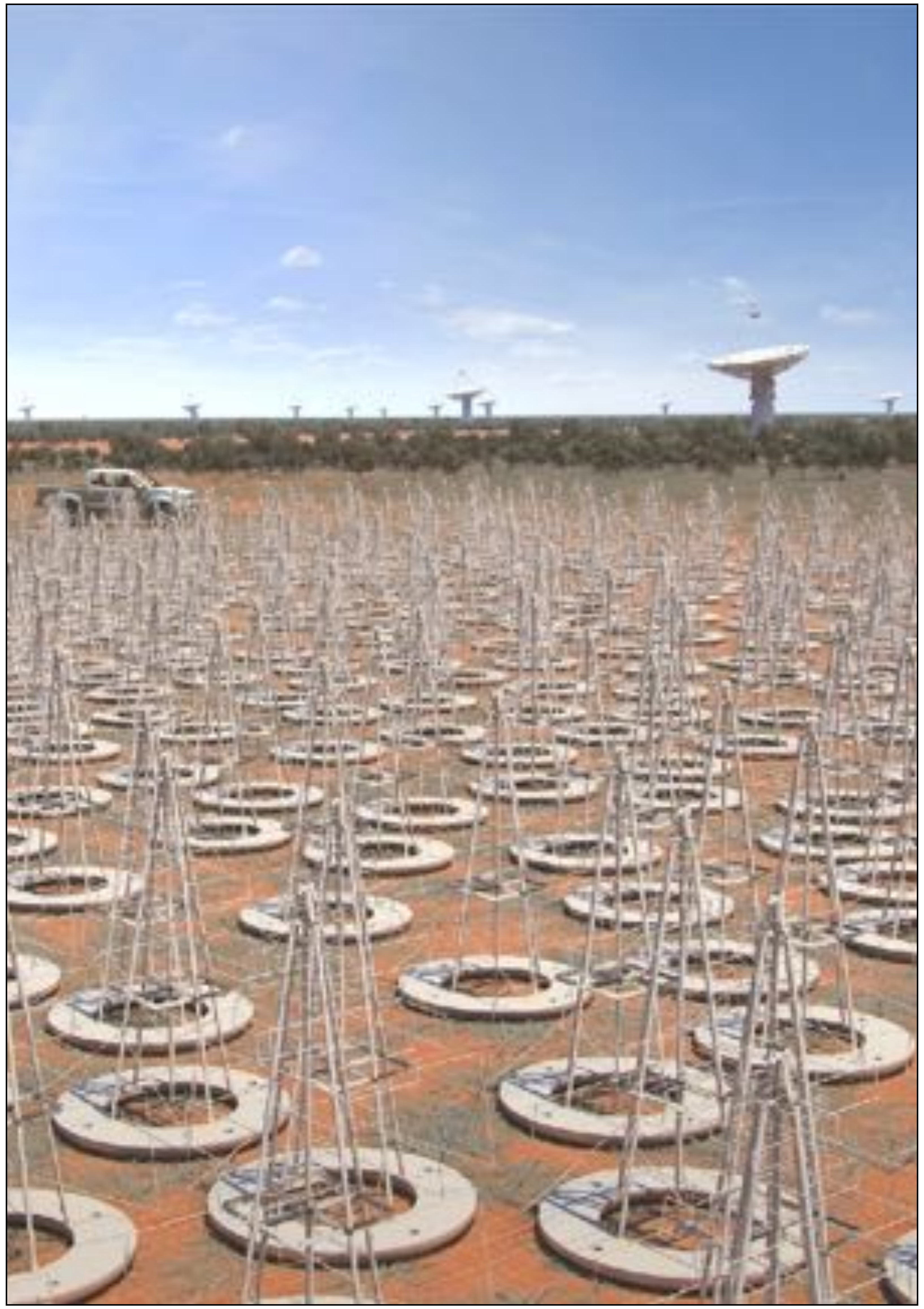
21cm intensity mapping experiments

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

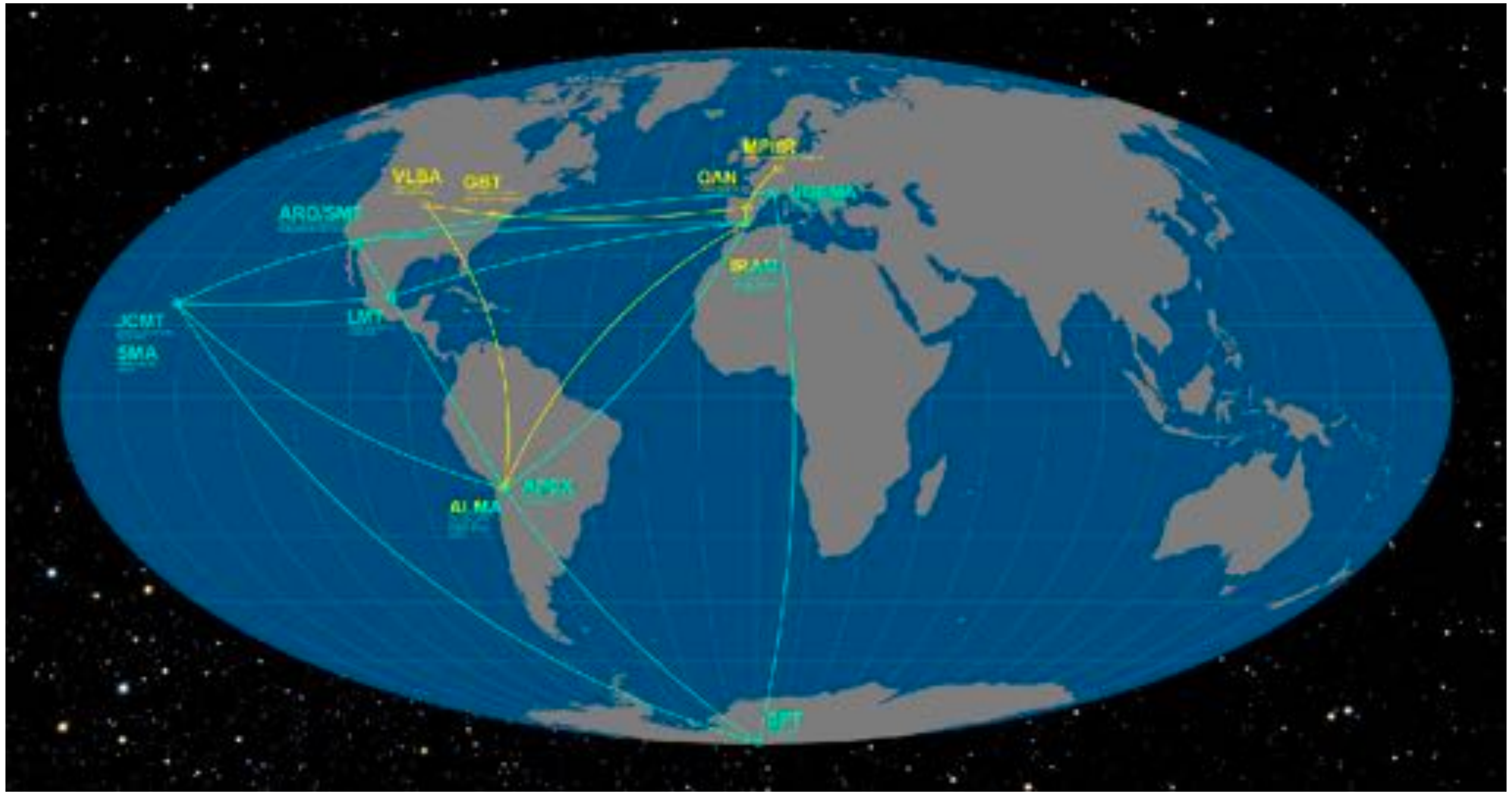
SKA1 - LOW (Australia)

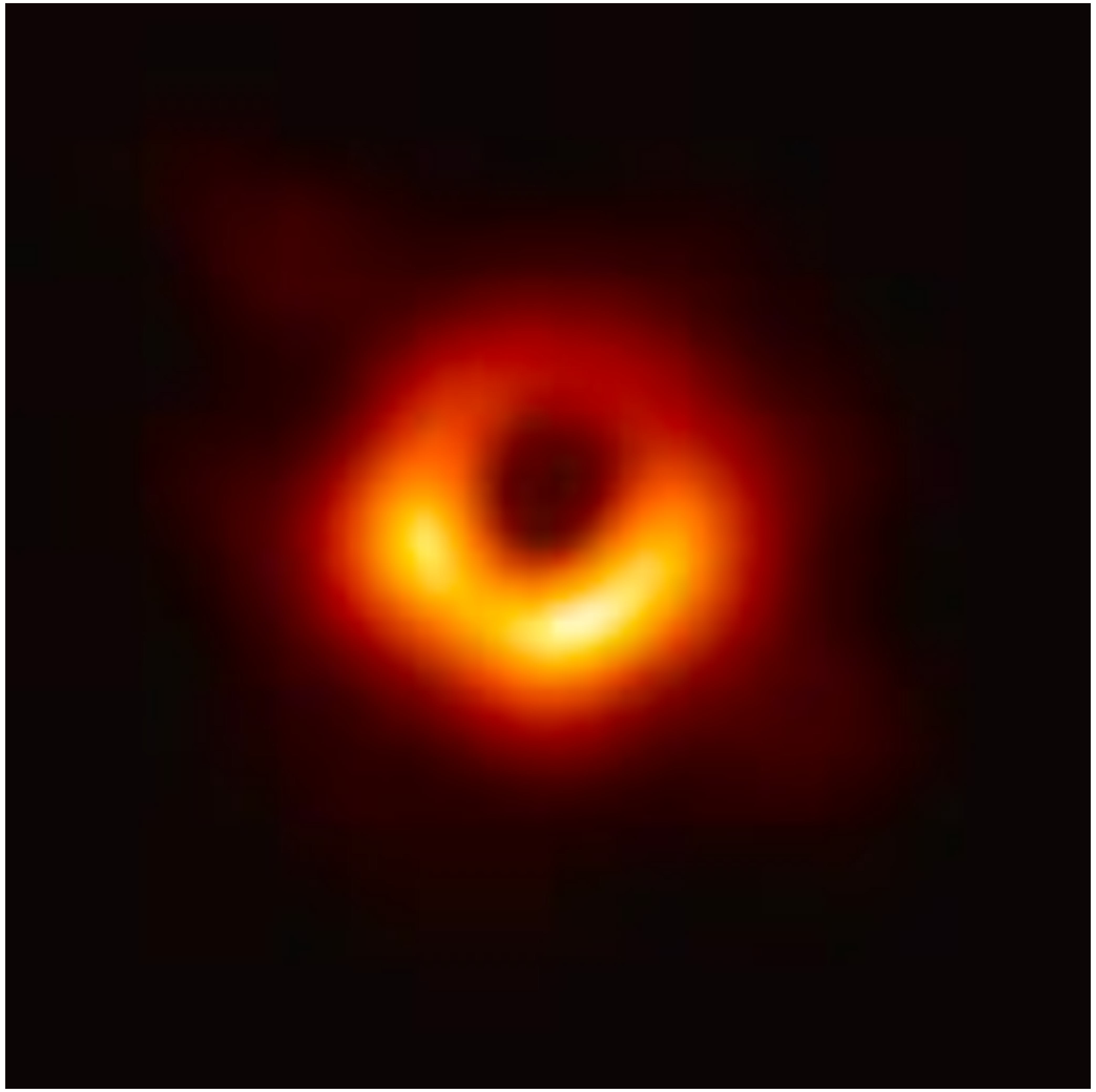




- Redshift range: $z > 3$

Interferometers:
multiple-dish arrays acting as one telescope





Black hole imaged by the Event Horizon Telescope

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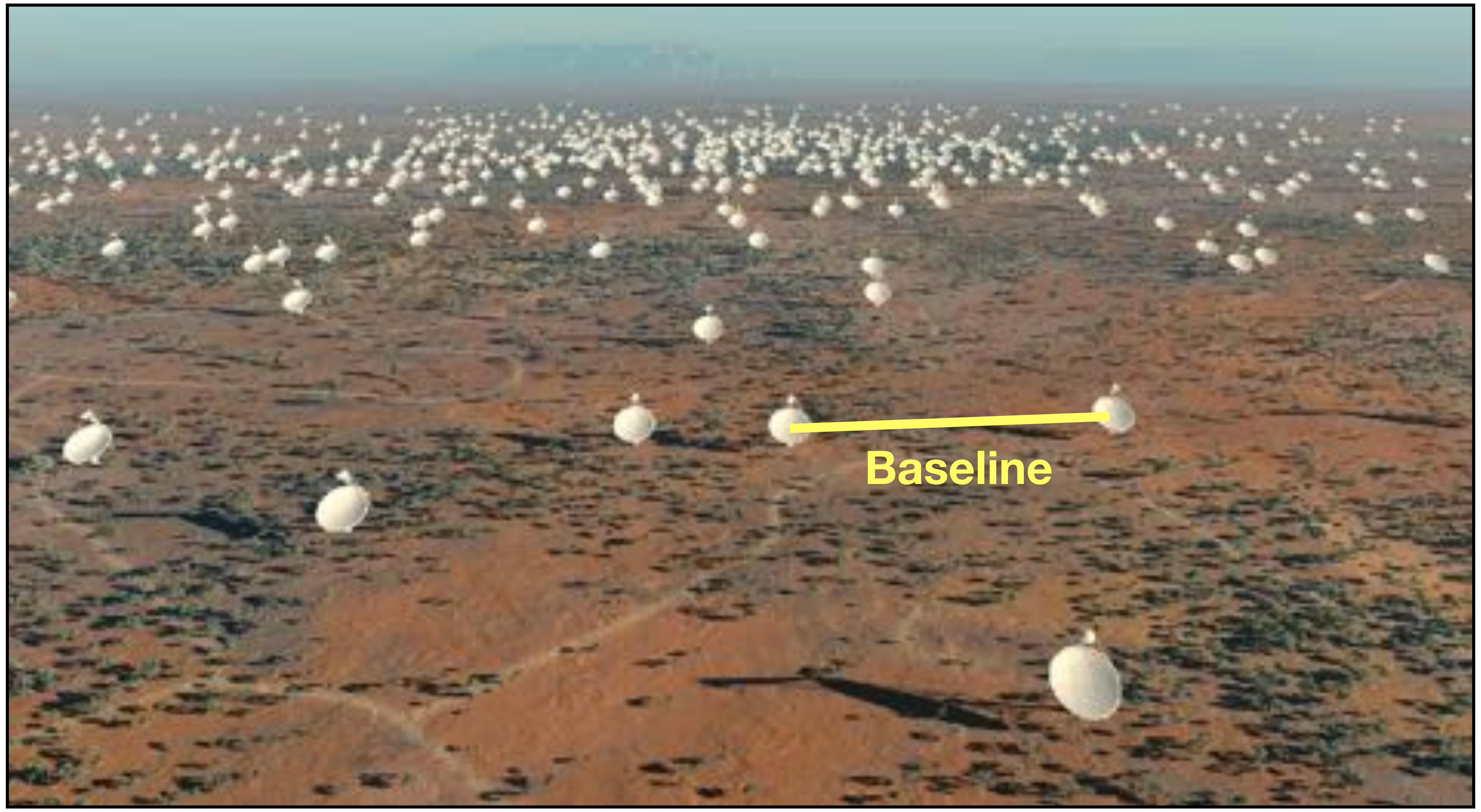
Interferometer has limitations for large-scale cosmology



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_{dish}

SKAO Pathfinders: 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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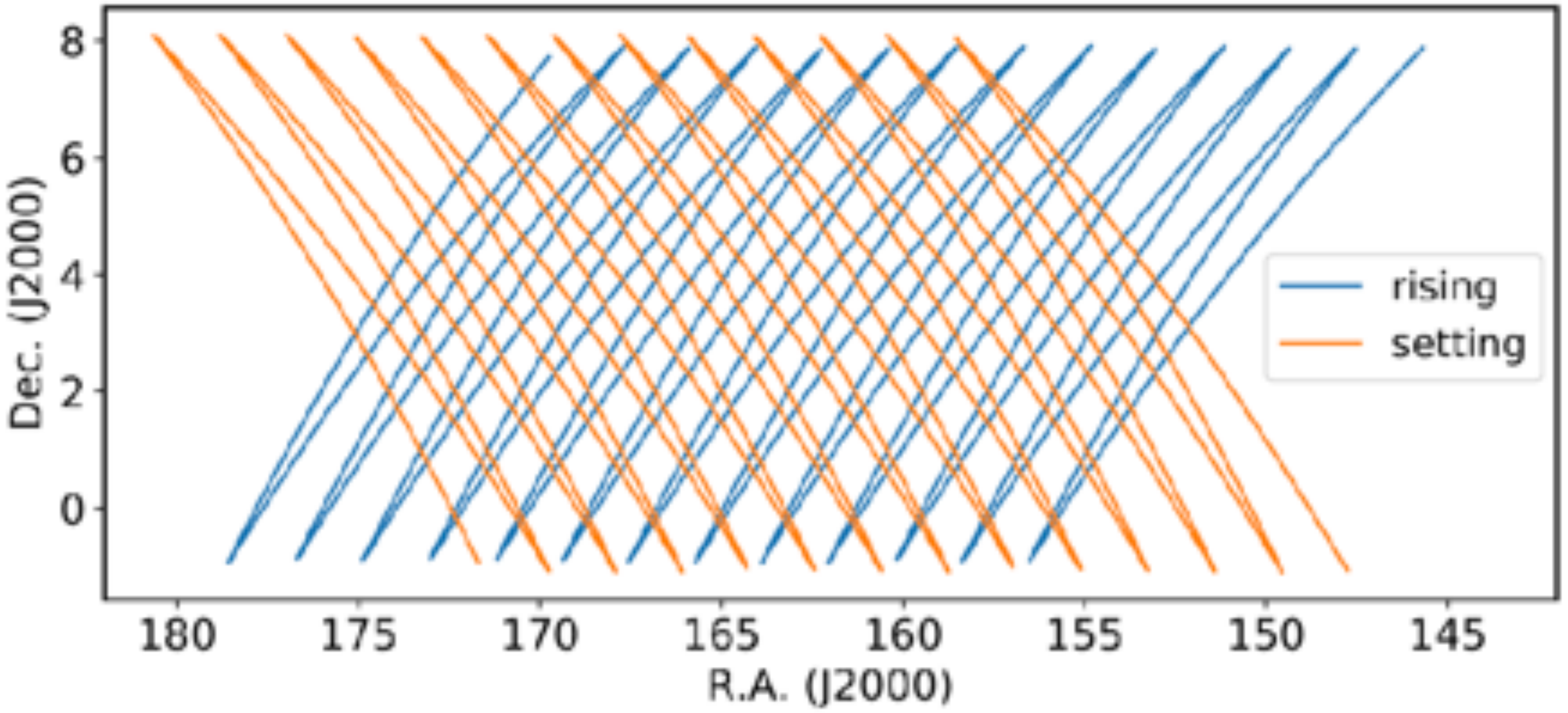
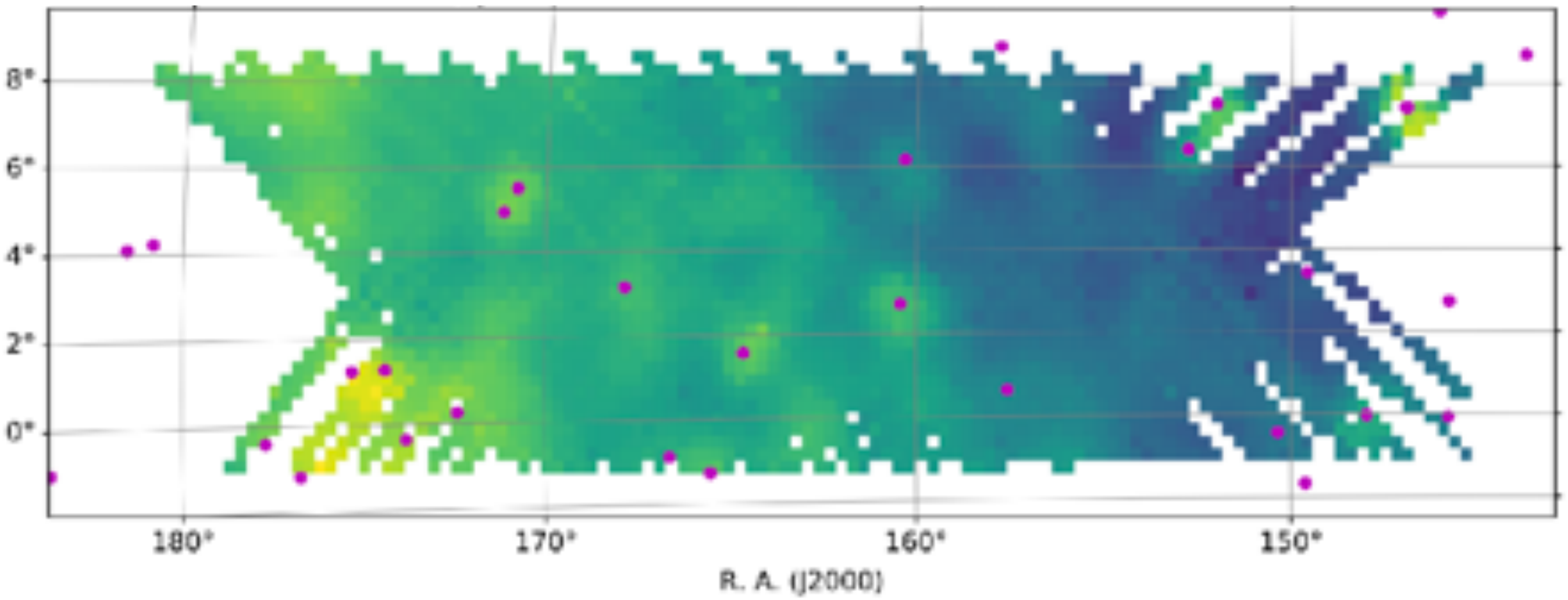
Conducting single-dish intensity mapping observations with MeerKAT

J.Wang, …, SC+21 [arXiv:2011.13789]





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Challenges to overcome with intensity mapping

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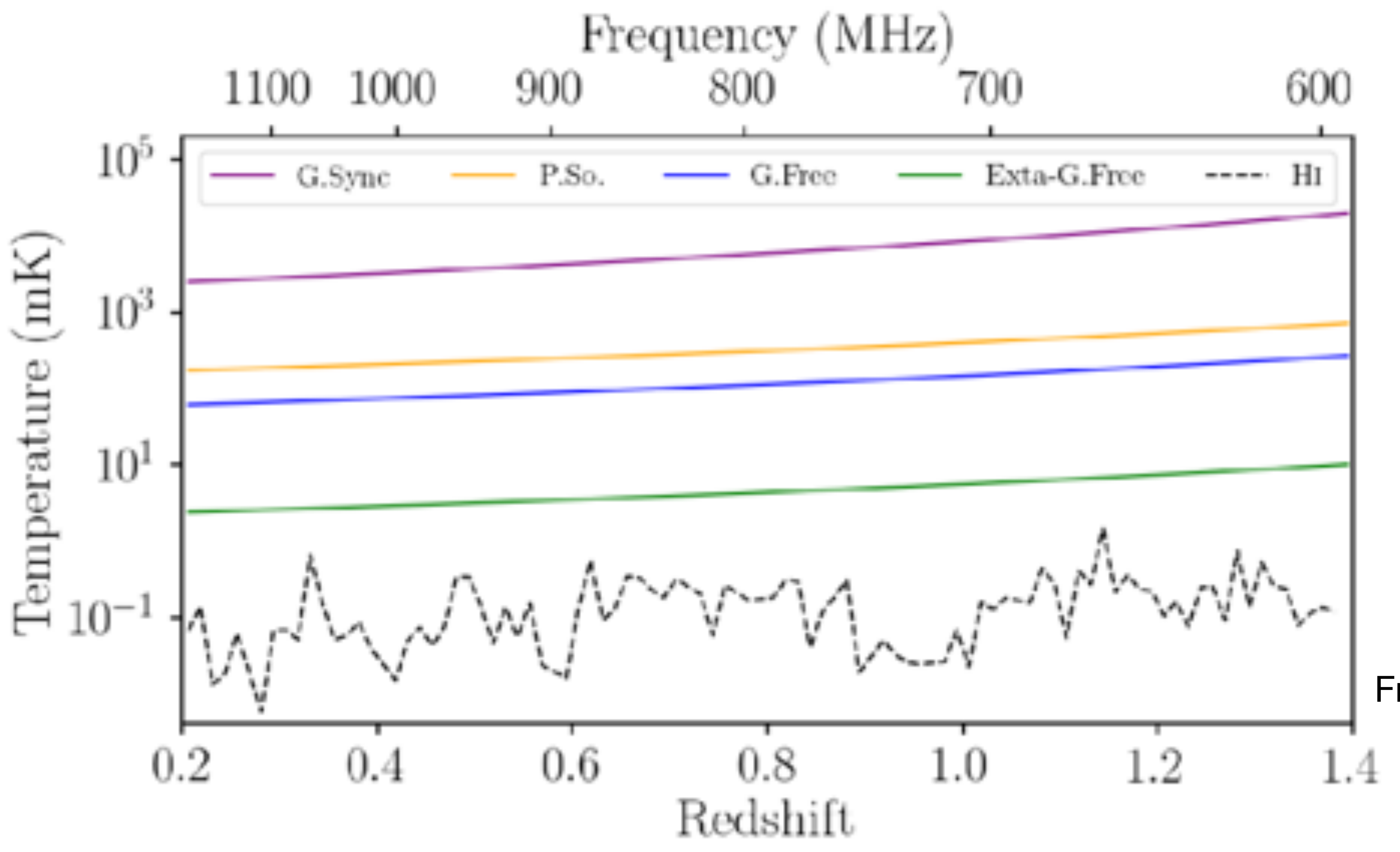
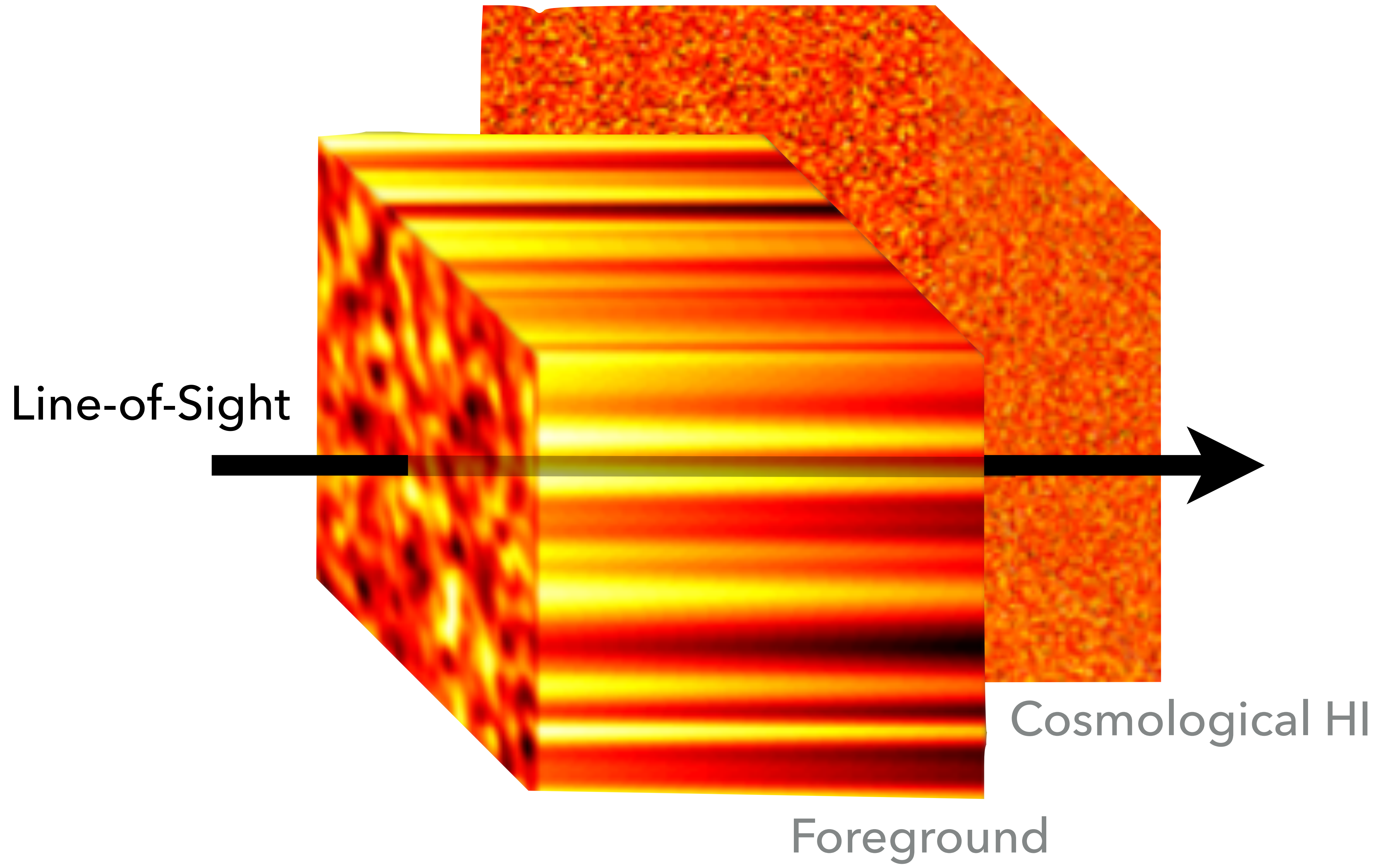
Challenges to overcome with intensity mapping

- Foreground cleaning

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



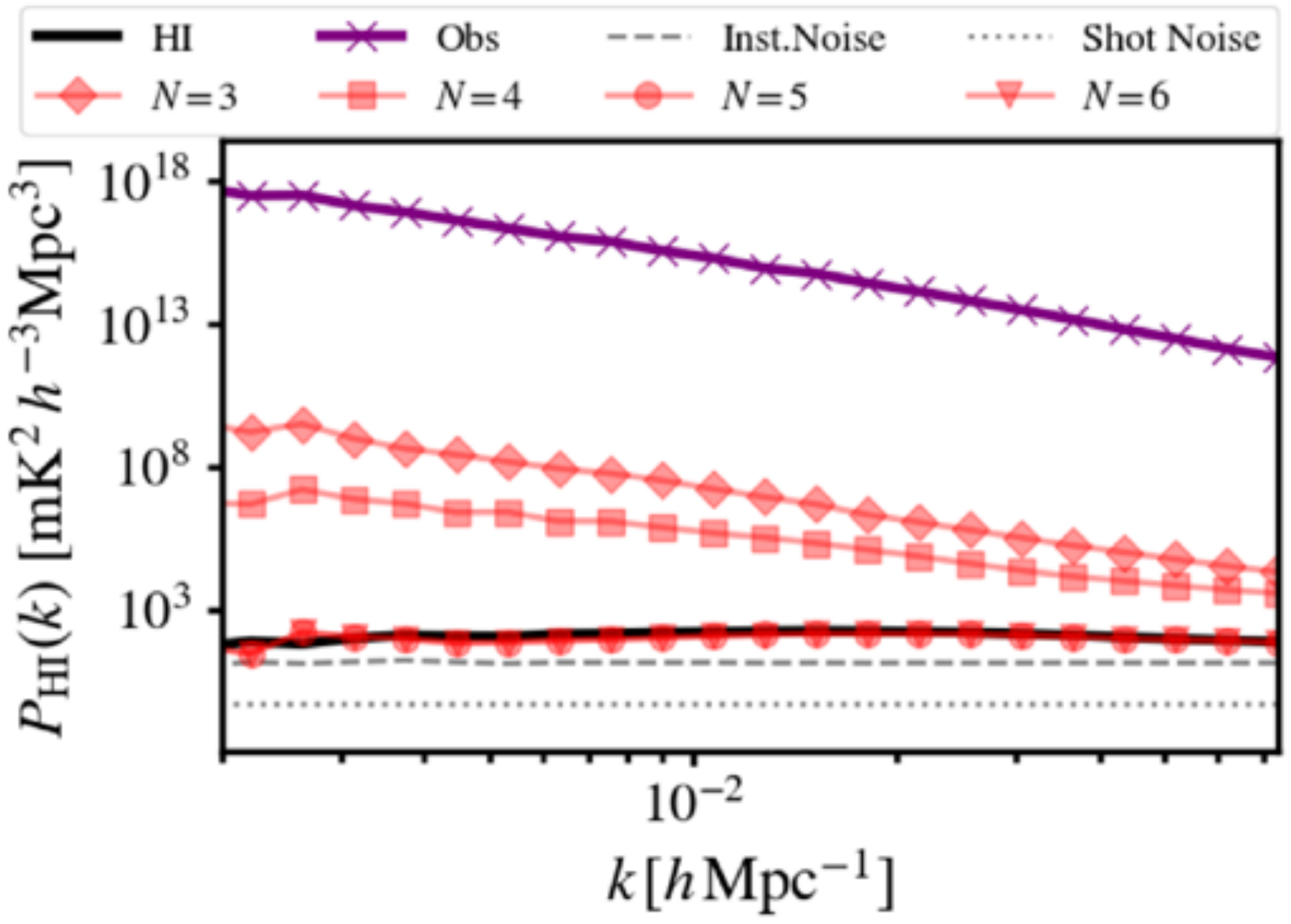


From S.Cunnington+19 [arXiv:1904.01479]

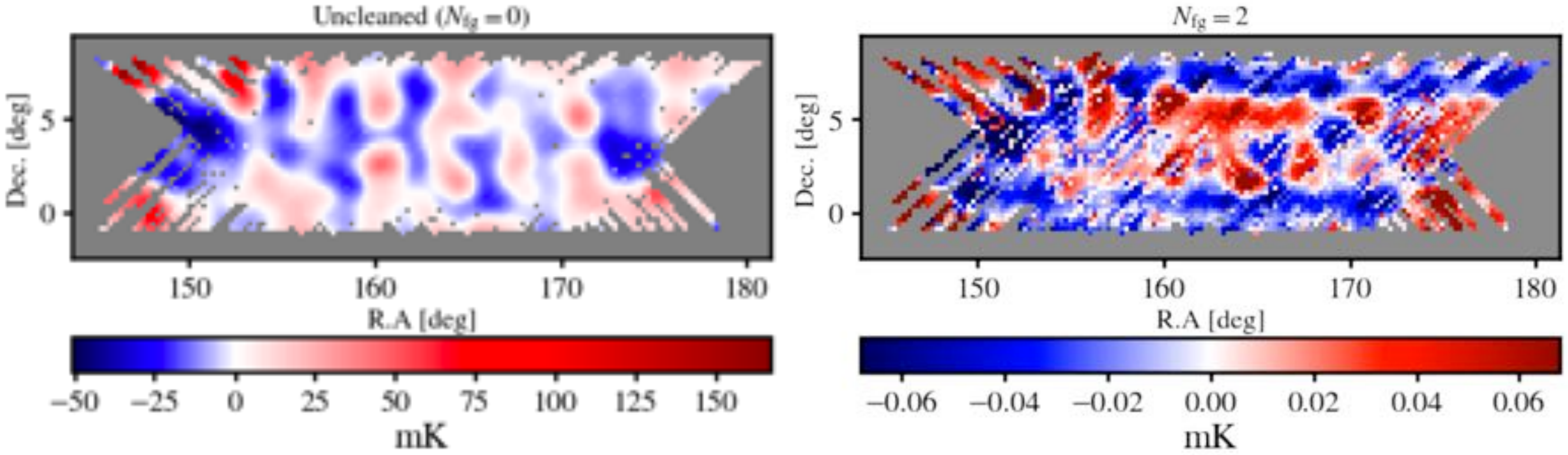
How we do foreground cleaning

S.Cunnington+20 [arXiv:2007.12126]

- Blind methods can remove foregrounds e.g. **Principal Component Analysis** (PCA)
- Foregrounds are **dominant** and **correlated** in frequency
- Therefore, they're contained in just a few dominant **Eigenmodes**
- By removing these we perform an effective foreground clean

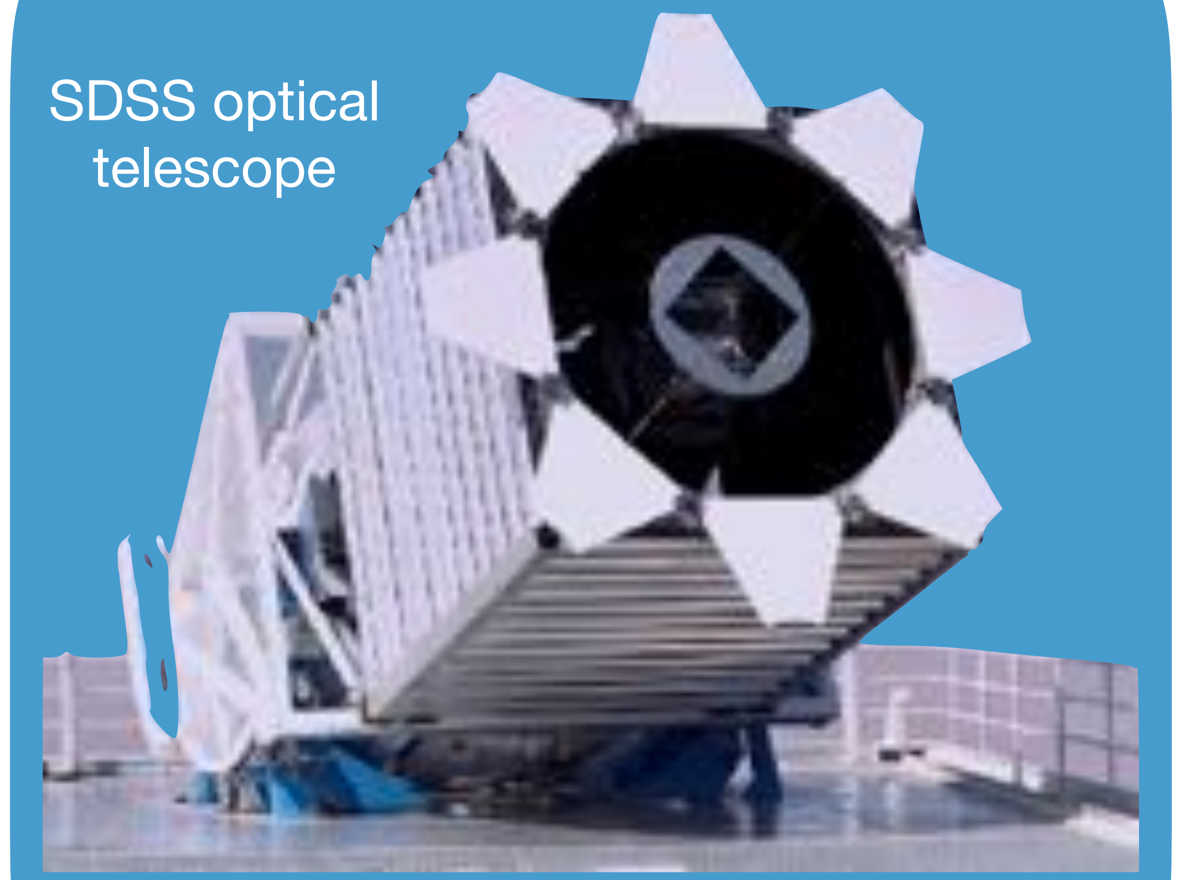


Foreground cleaning MeerKAT HI intensity maps



Cross-correlations mitigate systematics

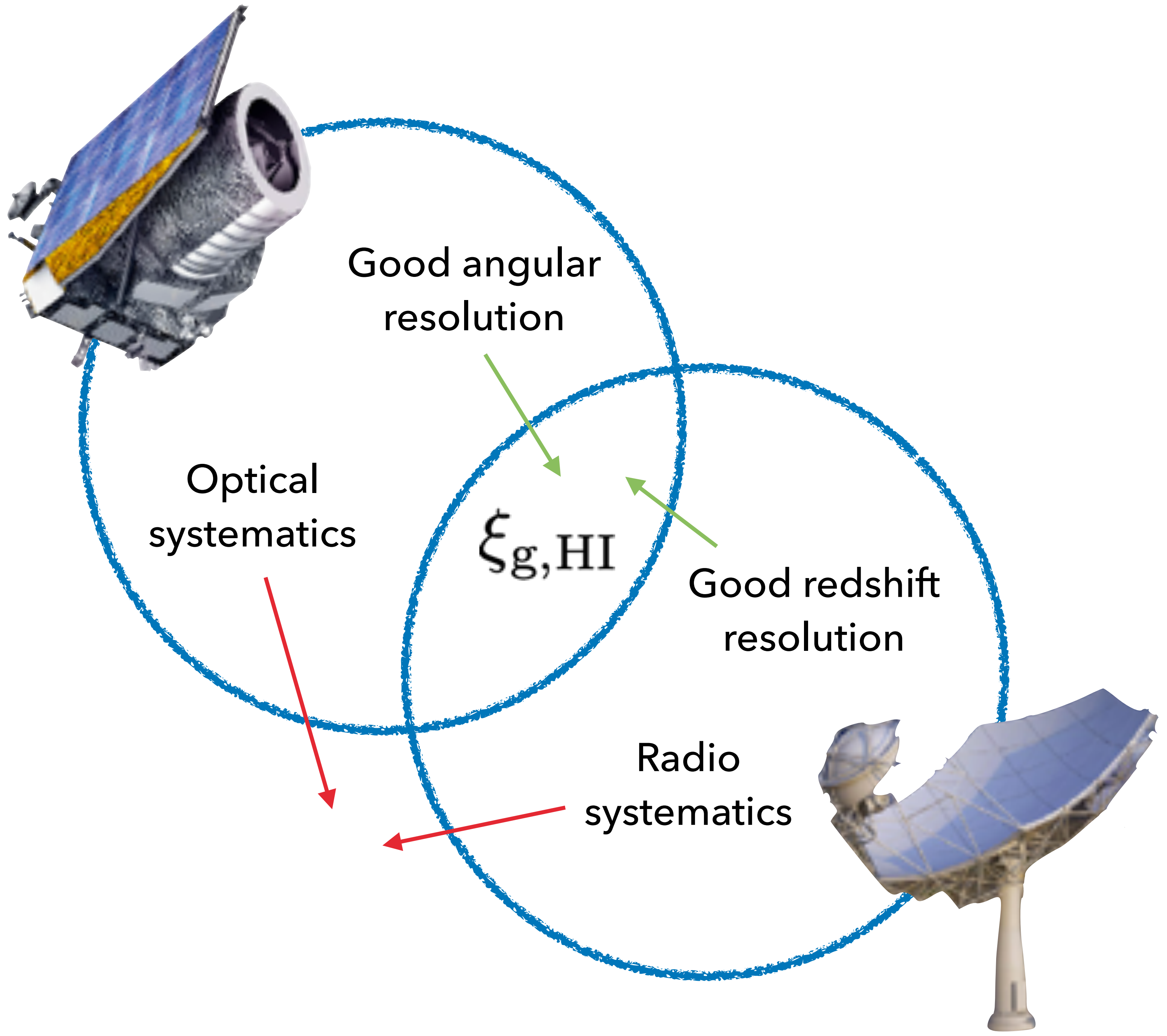
Optical



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

Radio

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



Auto Correlation:

uncorrelated

$$\langle \mathbf{X}_{\mathrm{opt}}\mathbf{X}_{\mathrm{opt}} \rangle = \langle \mathbf{S}_{\mathrm{opt}}\mathbf{S}_{\mathrm{opt}} \rangle + \cancel{2\langle \mathbf{S}_{\mathrm{opt}}\mathbf{N}_{\mathrm{opt}} \rangle} + \langle \mathbf{N}_{\mathrm{opt}}\mathbf{N}_{\mathrm{opt}} \rangle$$

$$\langle \mathbf{X}_{\mathrm{opt}}\mathbf{X}_{\mathrm{opt}} \rangle = \langle \mathbf{S}_{\mathrm{opt}}\mathbf{S}_{\mathrm{opt}} \rangle + \langle \mathbf{N}_{\mathrm{opt}}\mathbf{N}_{\mathrm{opt}} \rangle$$

signal you want *noise you don't want*

Cross Correlation:

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

Thus, 21cm intensity mapping offers enormous potential for future cross-correlations

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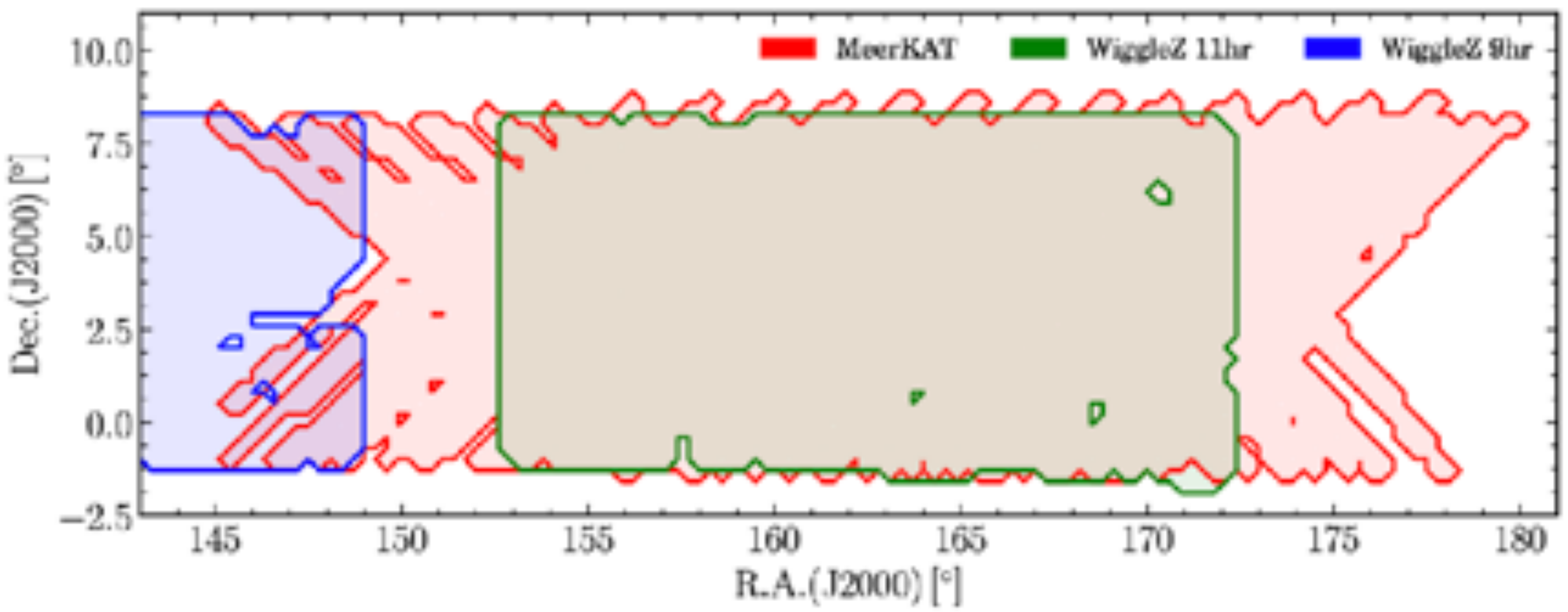
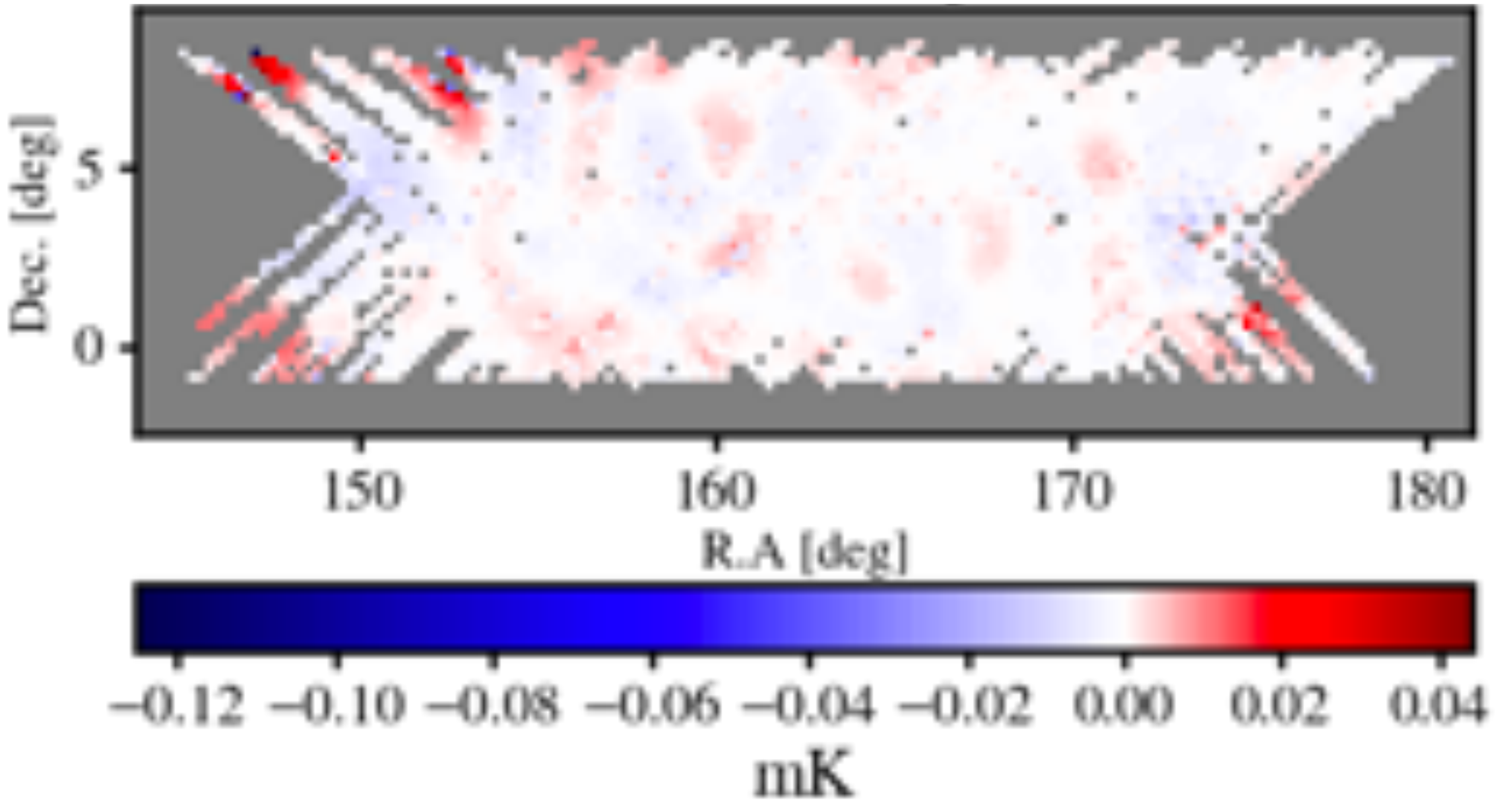
MeerKAT X Galaxies

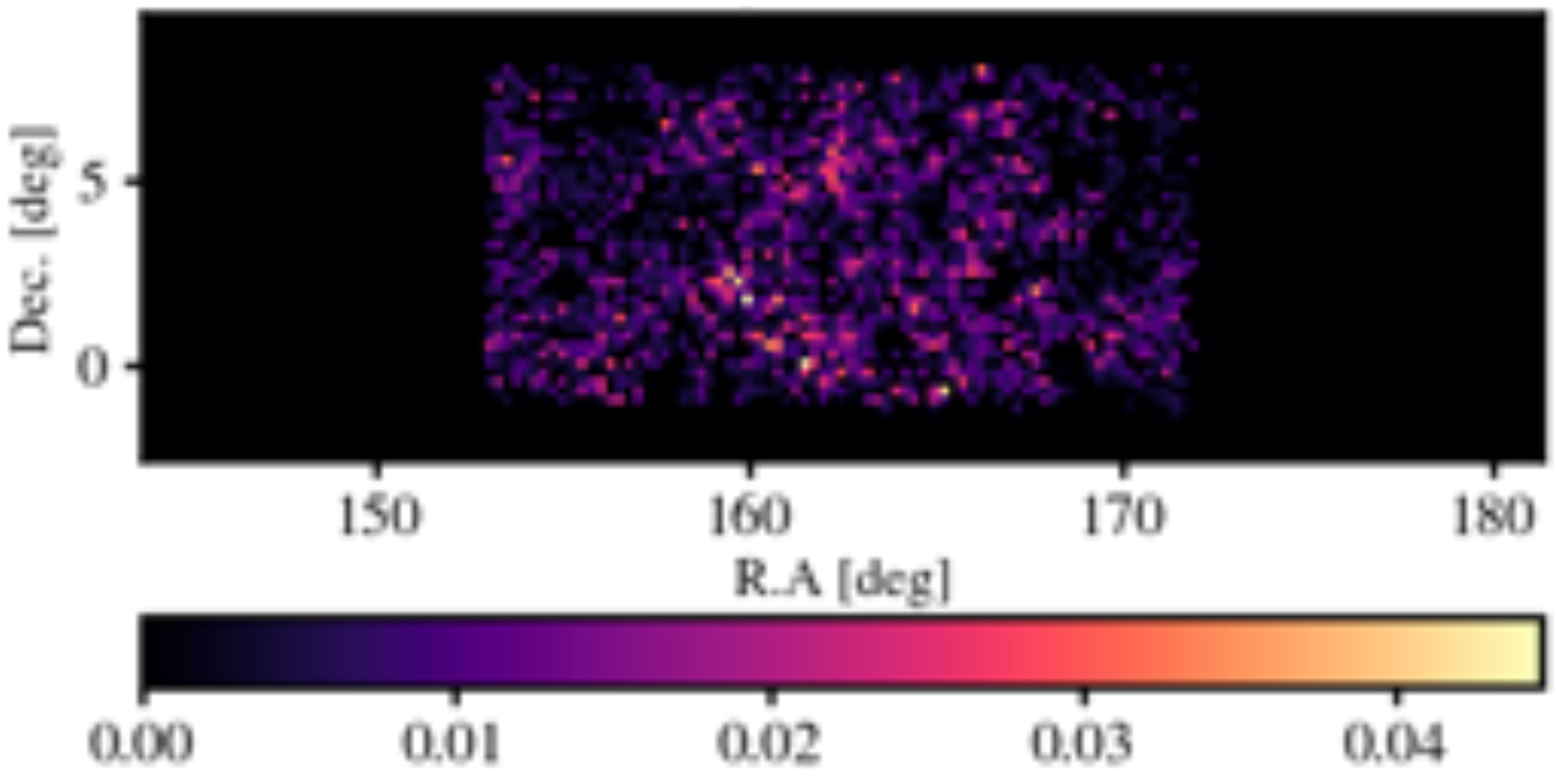
MeerKAT pilot observations conducted in WiggleZ 11hr field for the purpose of potential cross-correlations with a galaxy survey



Final foreground cleaned MeerKAT HI intensity map



WiggleZ Dark Energy Survey galaxies



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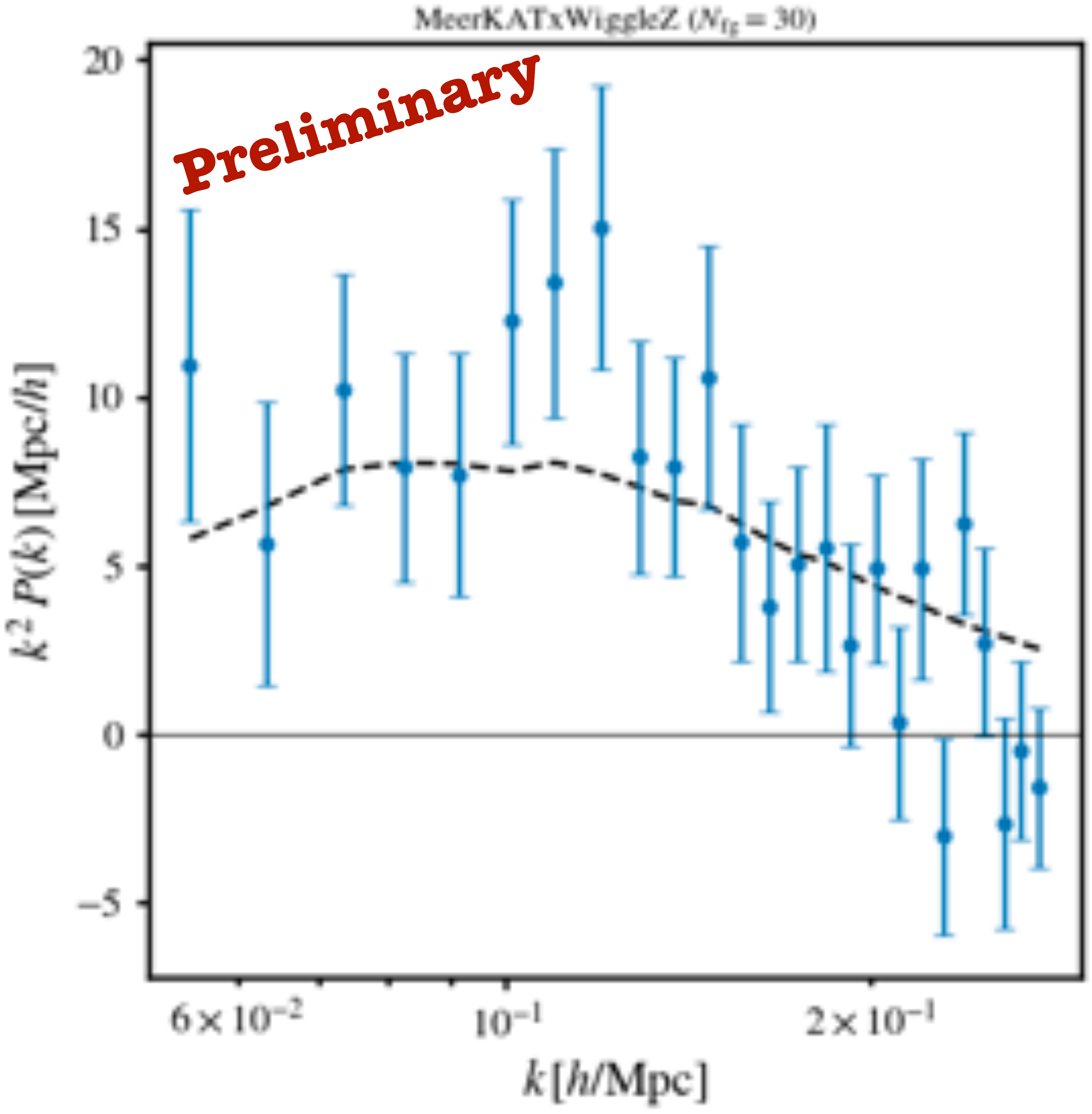
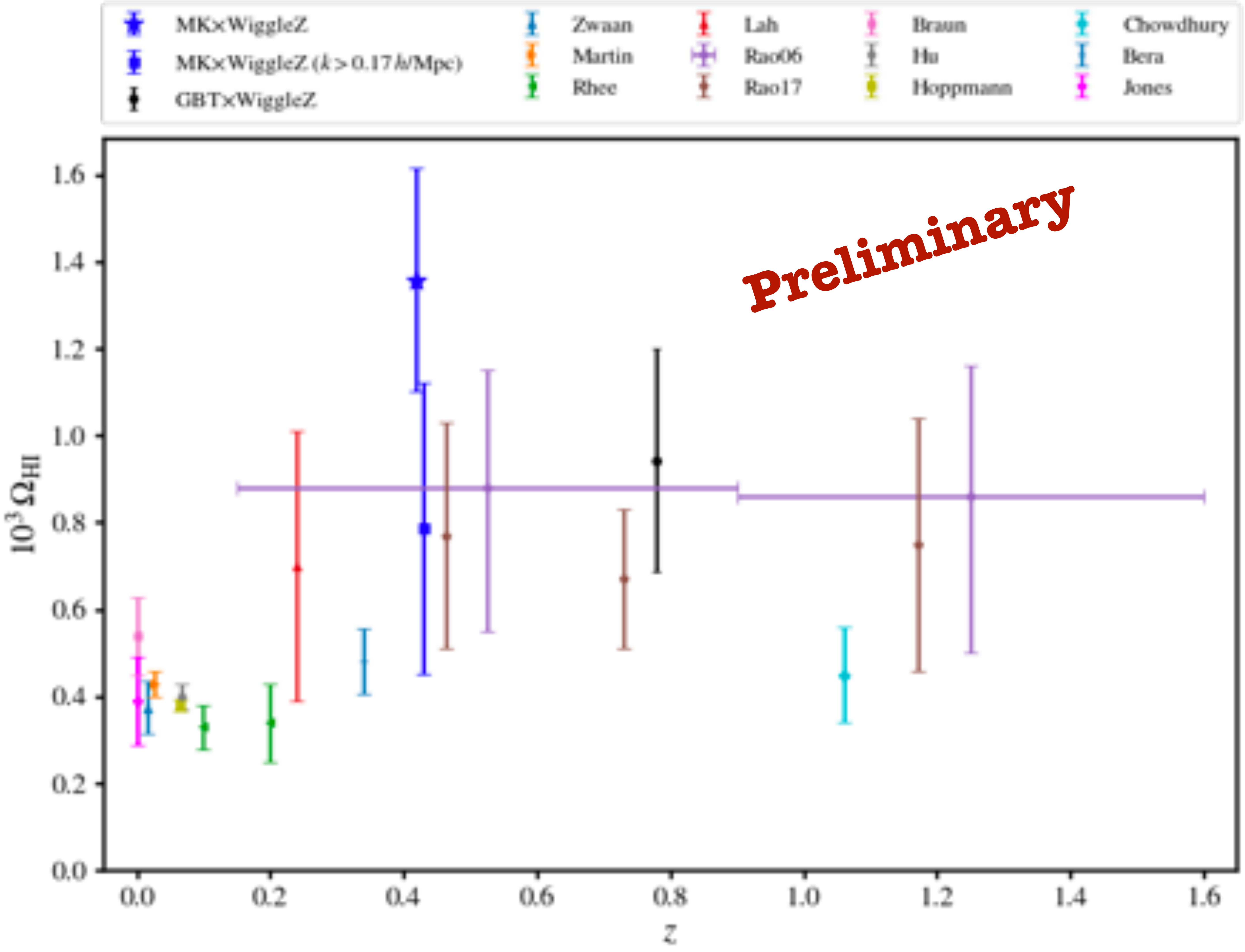
Detecting cosmological clustering in MeerKAT

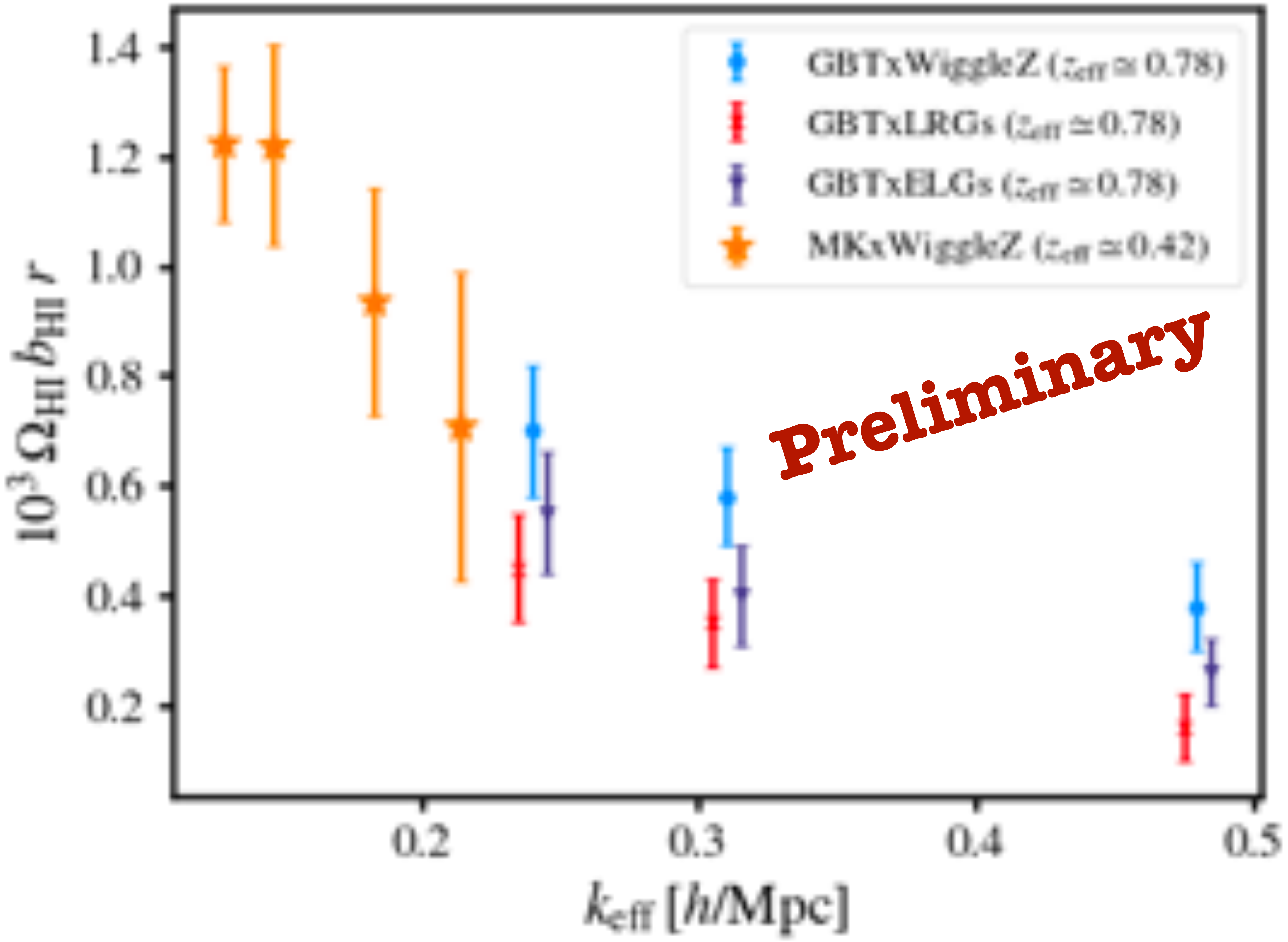
Results from MeerKAT large scale structure pilot survey

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

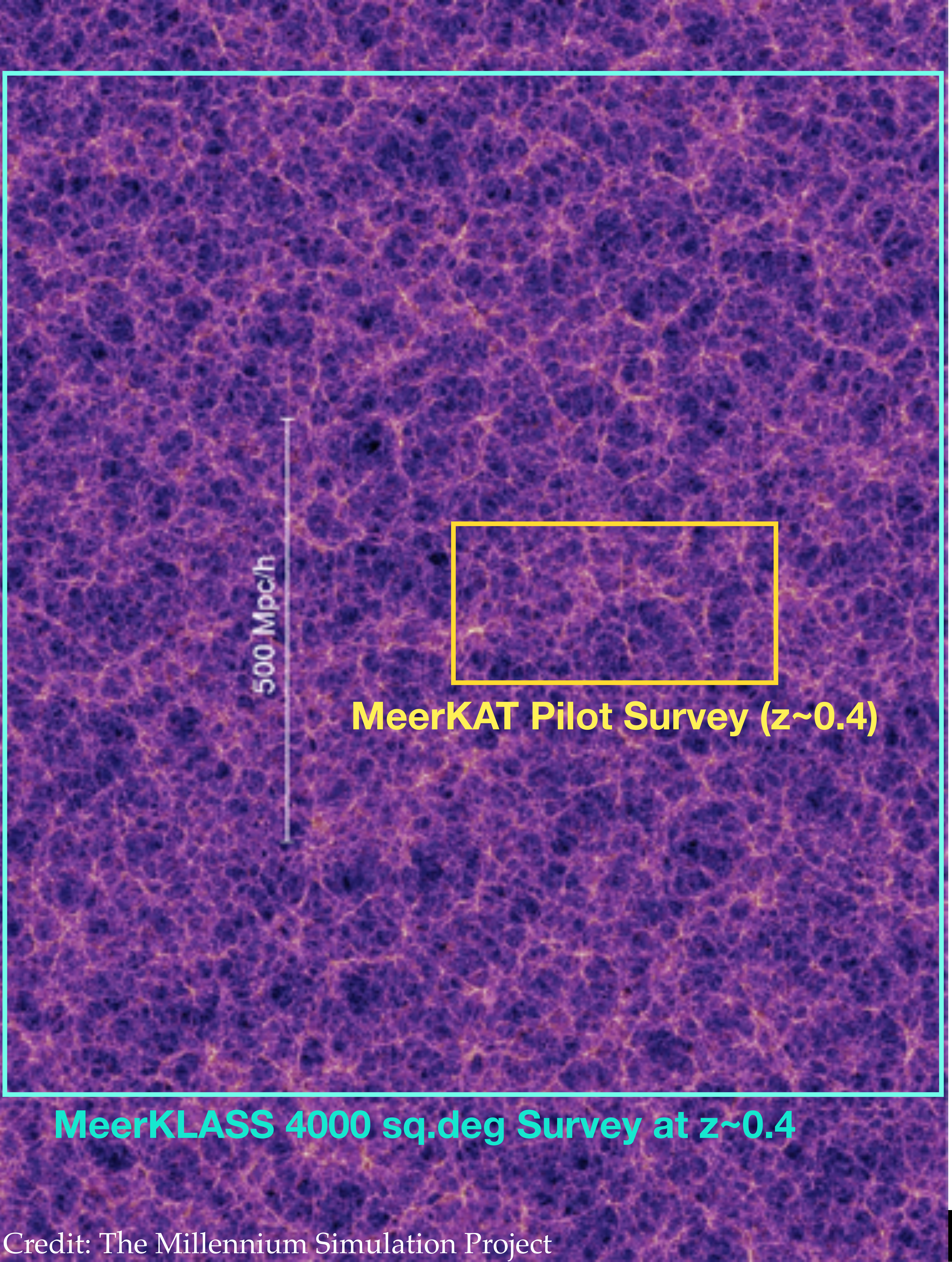


Constraining the HI abundance

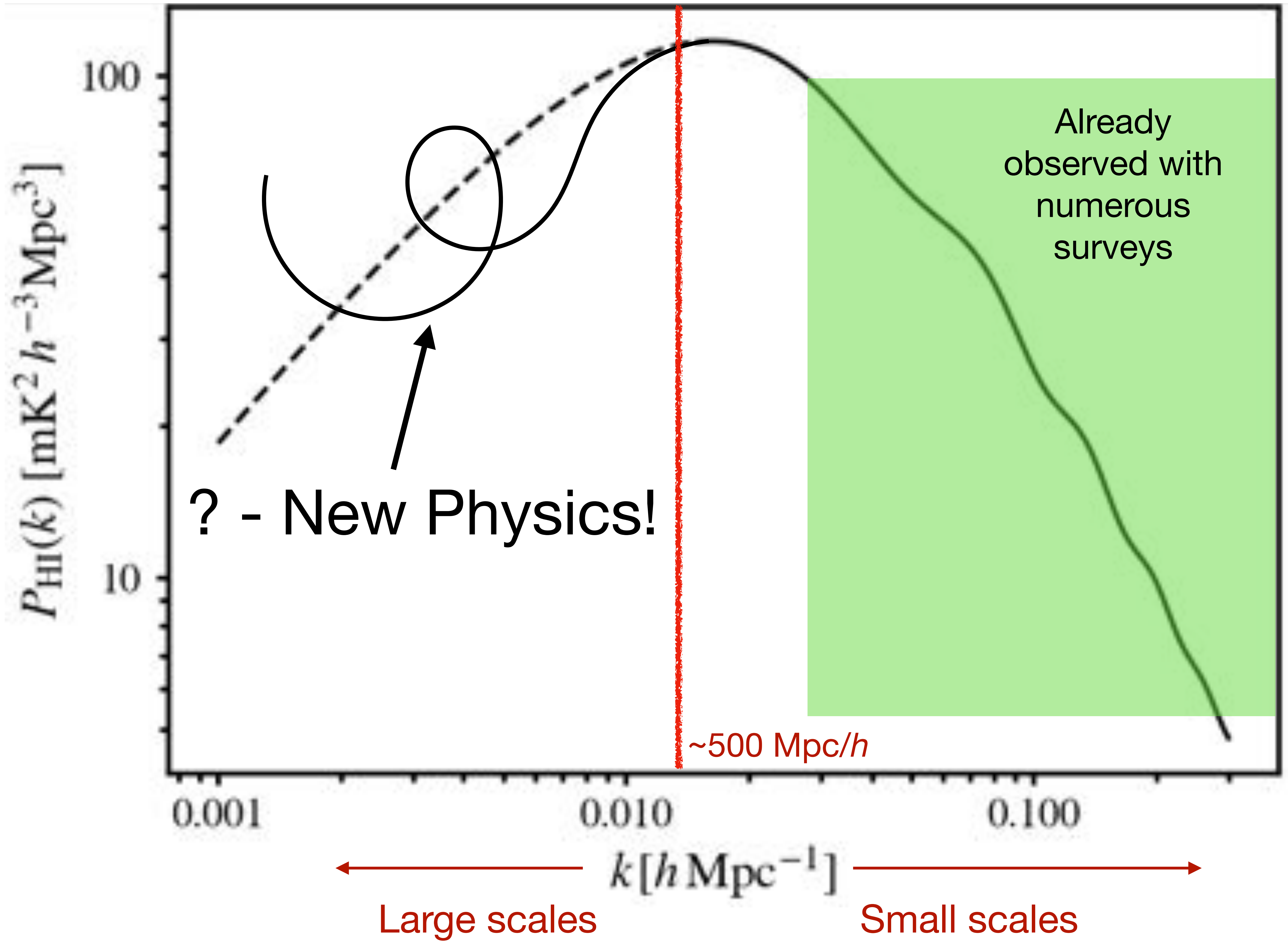




Future Prospects



Extending to "ultra-large" scales



Large scales could host evidence for:

- Primordial non-Gaussianity
- Relativistic effects

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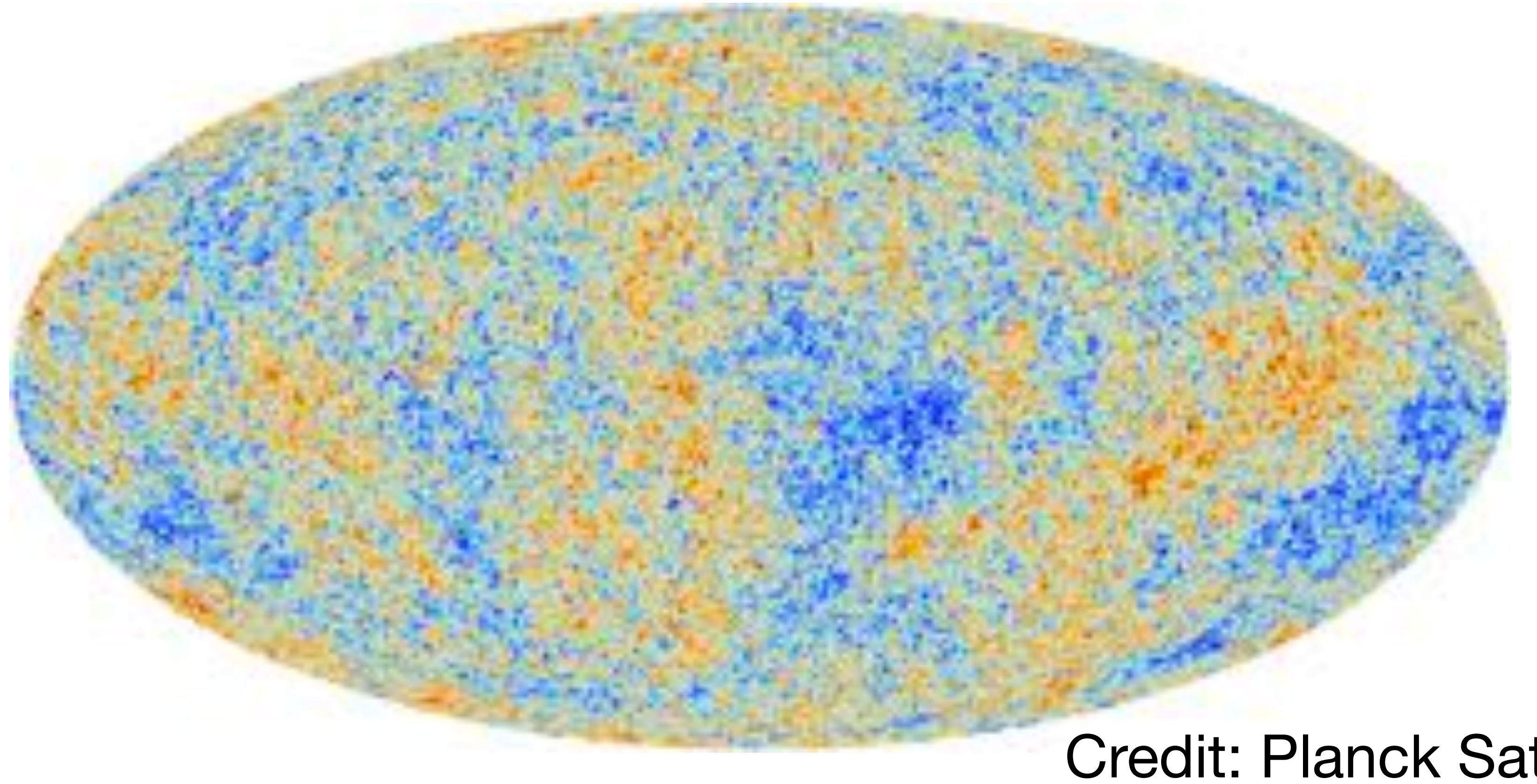
Why the largest scales?



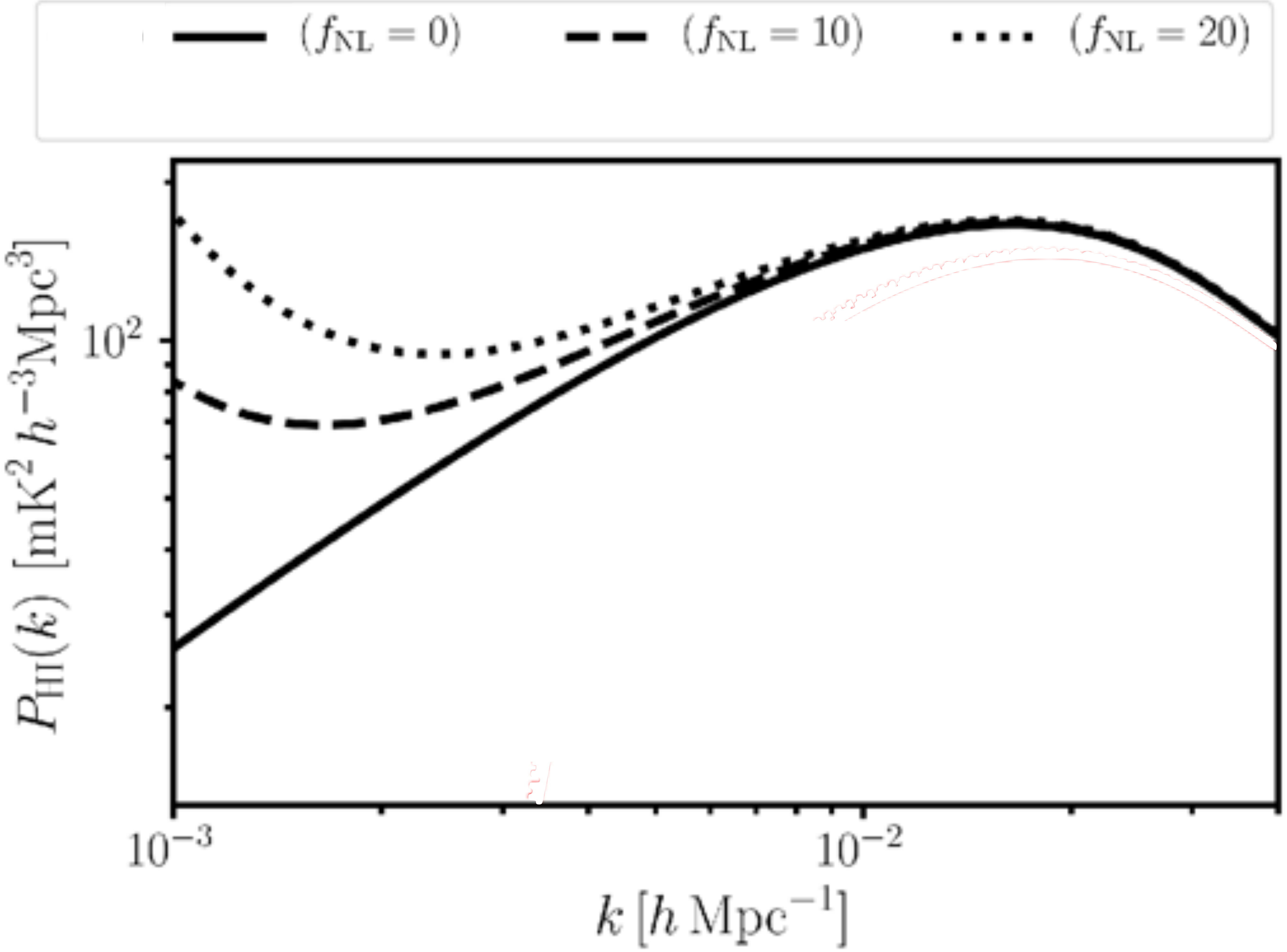
Credit: Planck Satellite

Q) Is the early Universe perturbation field Gaussian?

$$\Phi = \Phi_G + f_{NL}(\Phi_G^2 - \langle \Phi_G^2 \rangle)$$

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

S.Cunnington+20 [arXiv:2007.12126]



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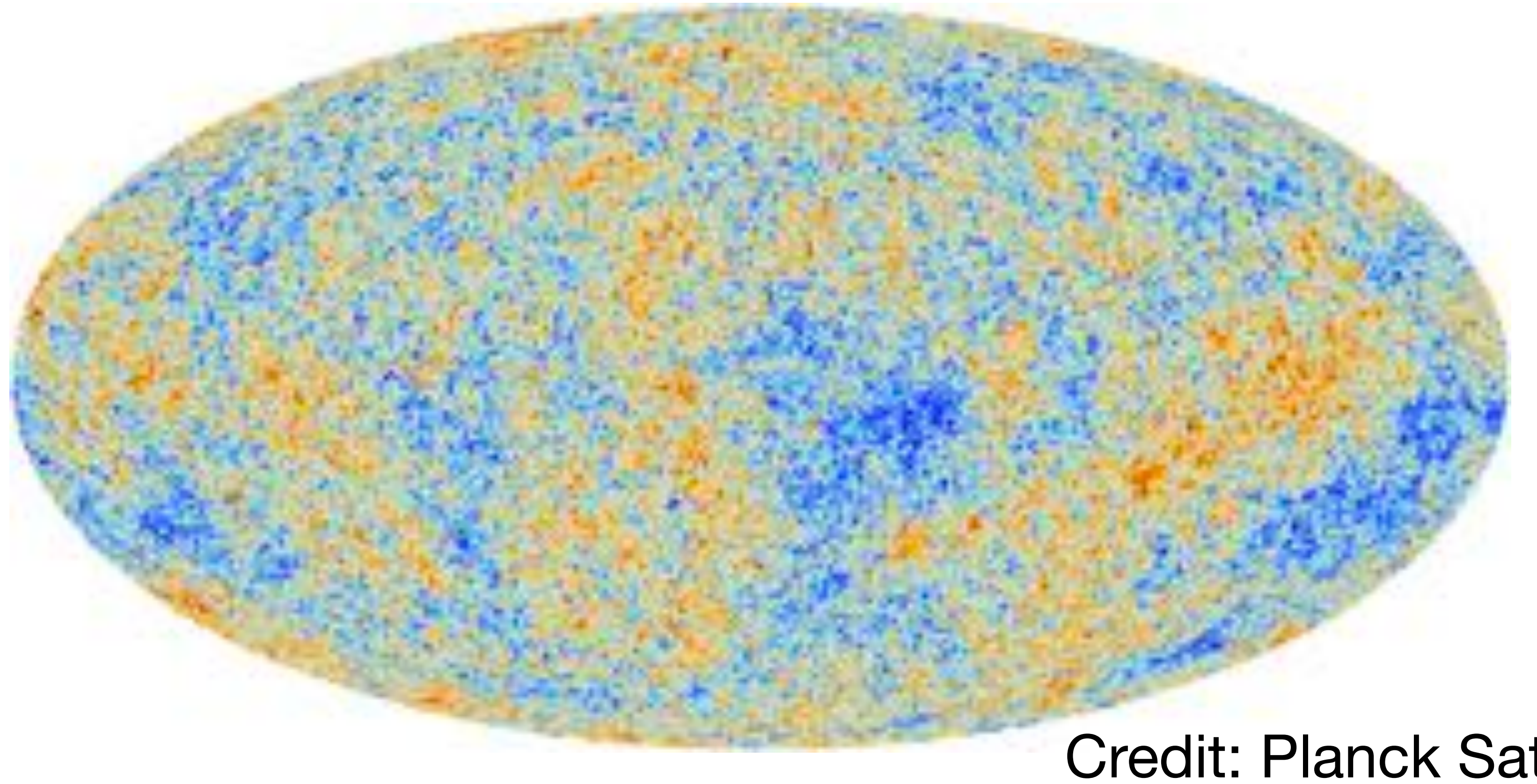

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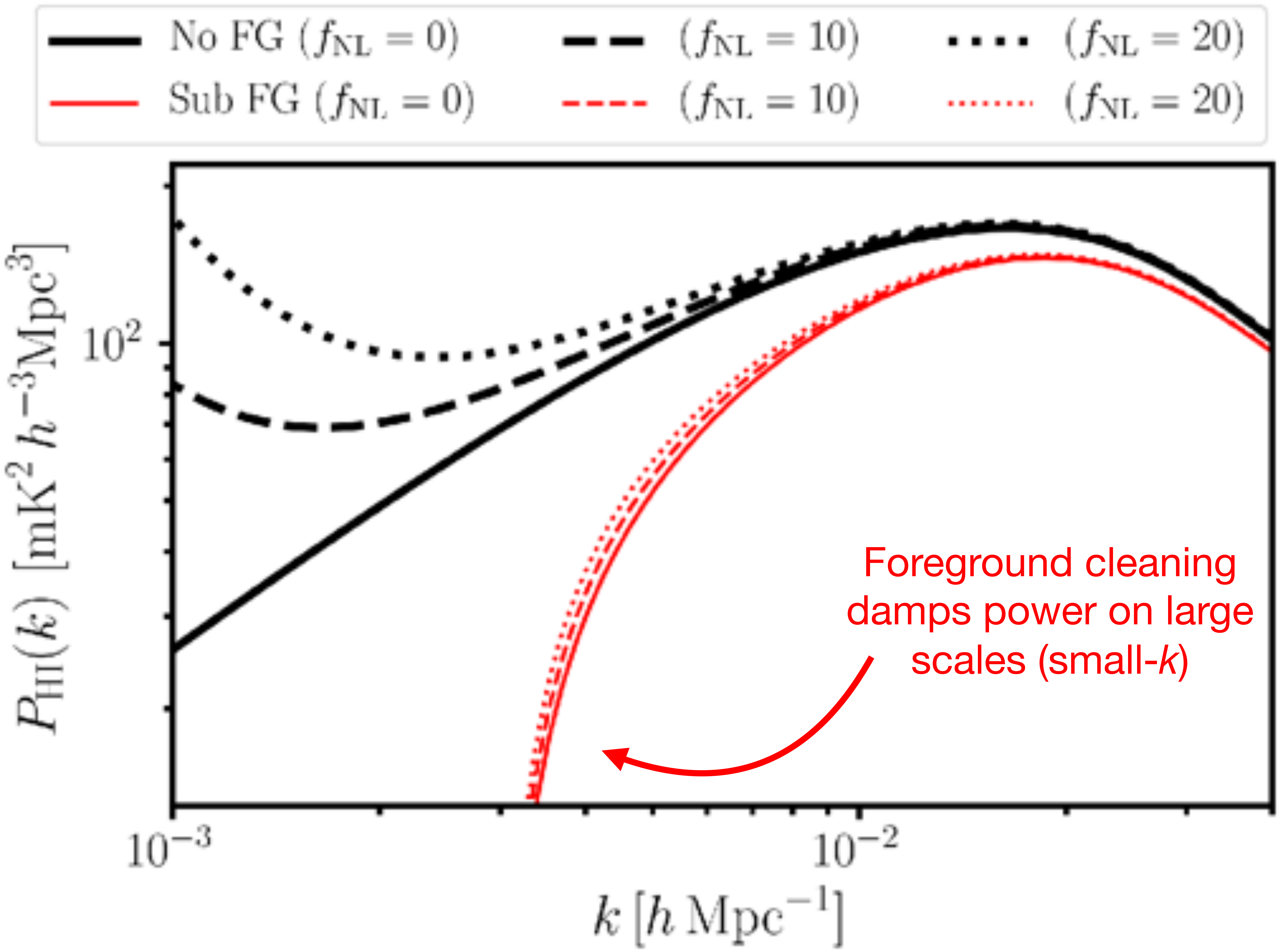
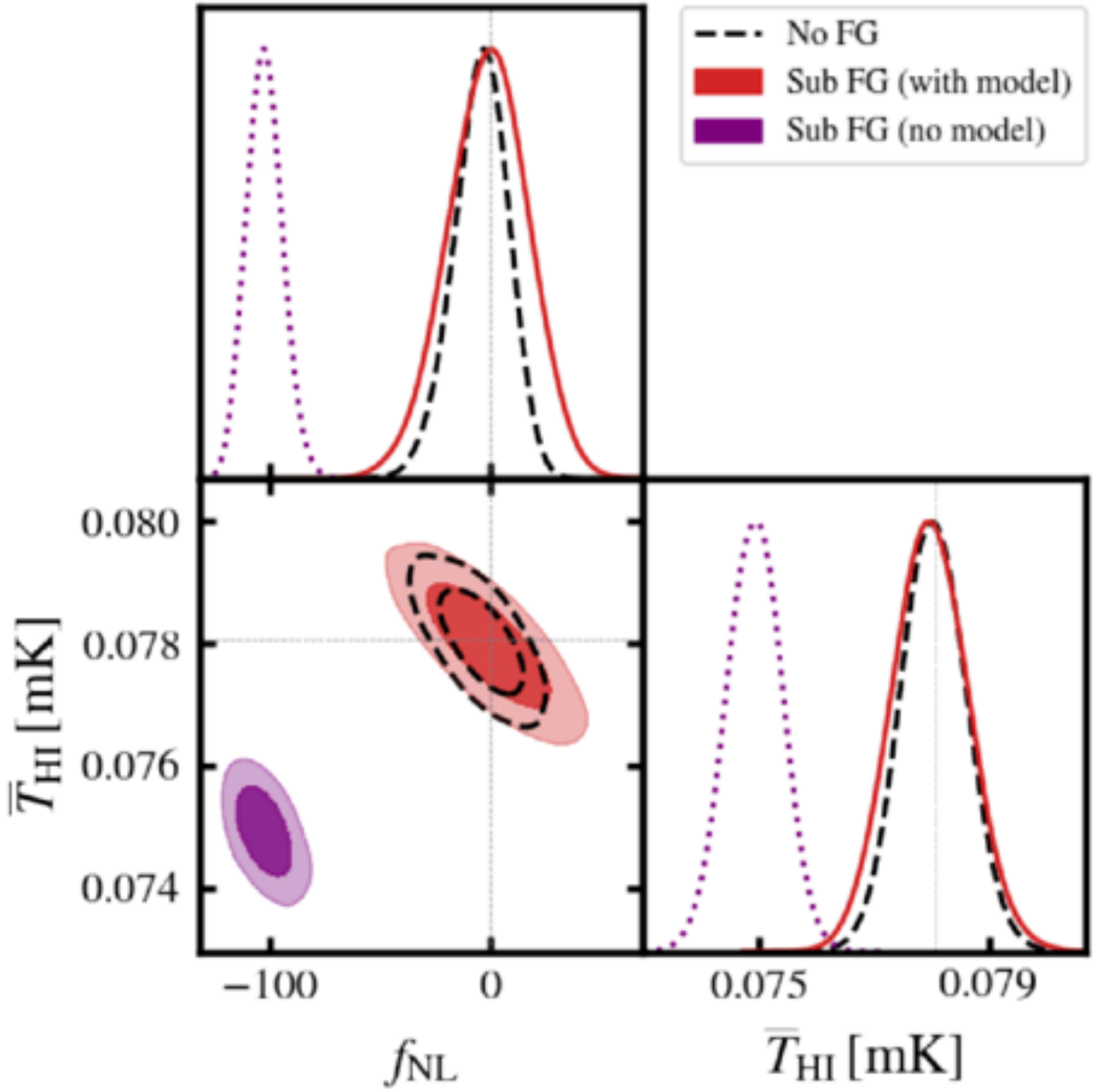
S.Cunnington+20 [arXiv:2007.12126]

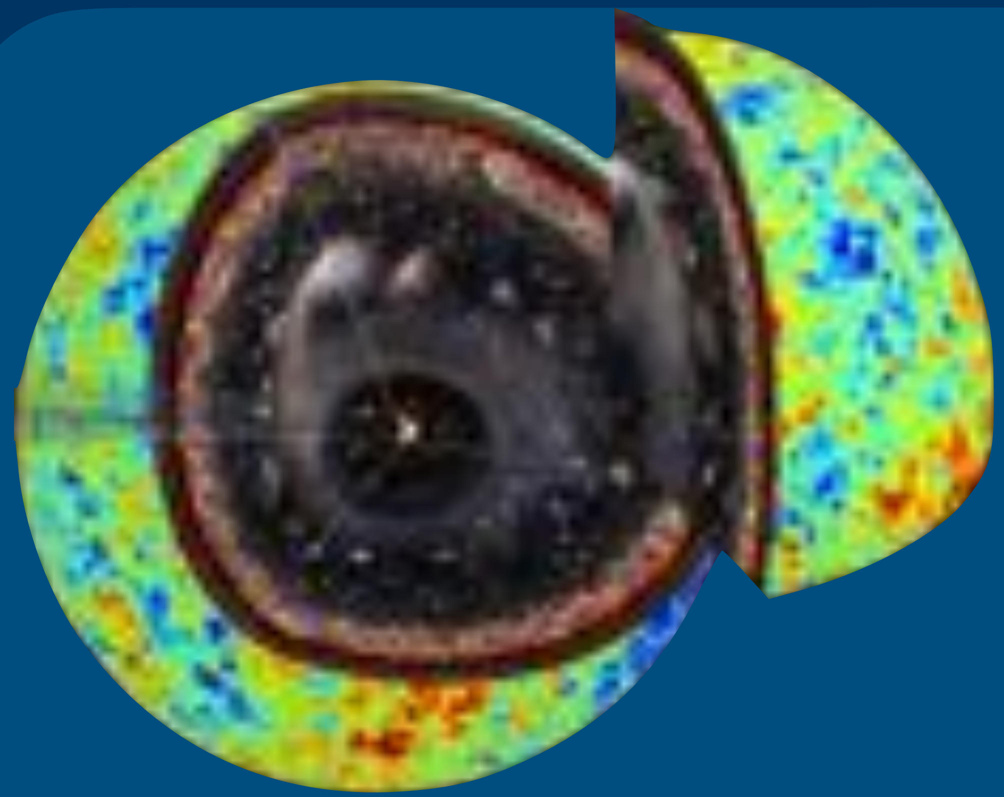


Effects from foregrounds on cosmology and correcting them

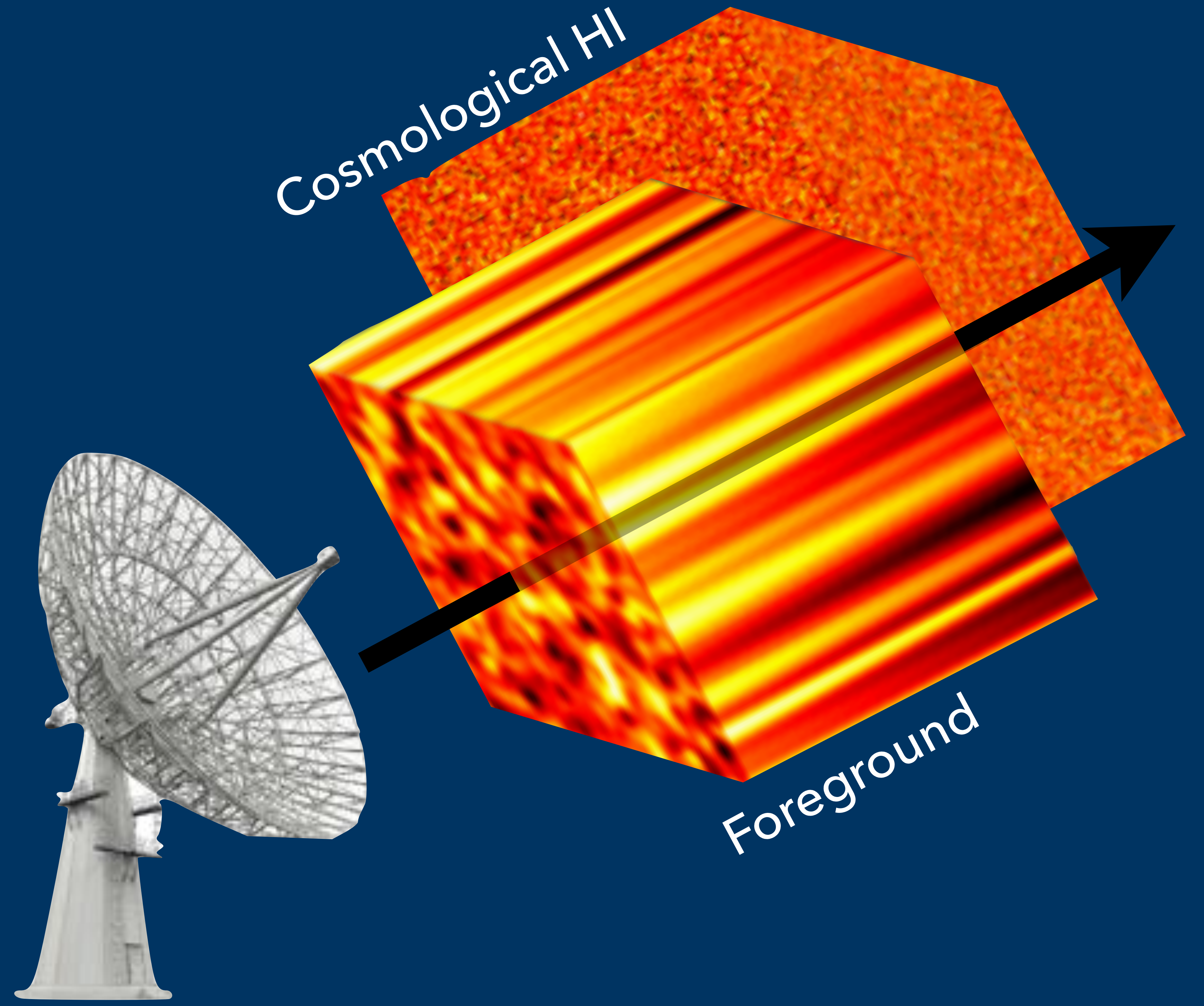


S.Cunnington+20 [arXiv:2007.12126]

In Summary…



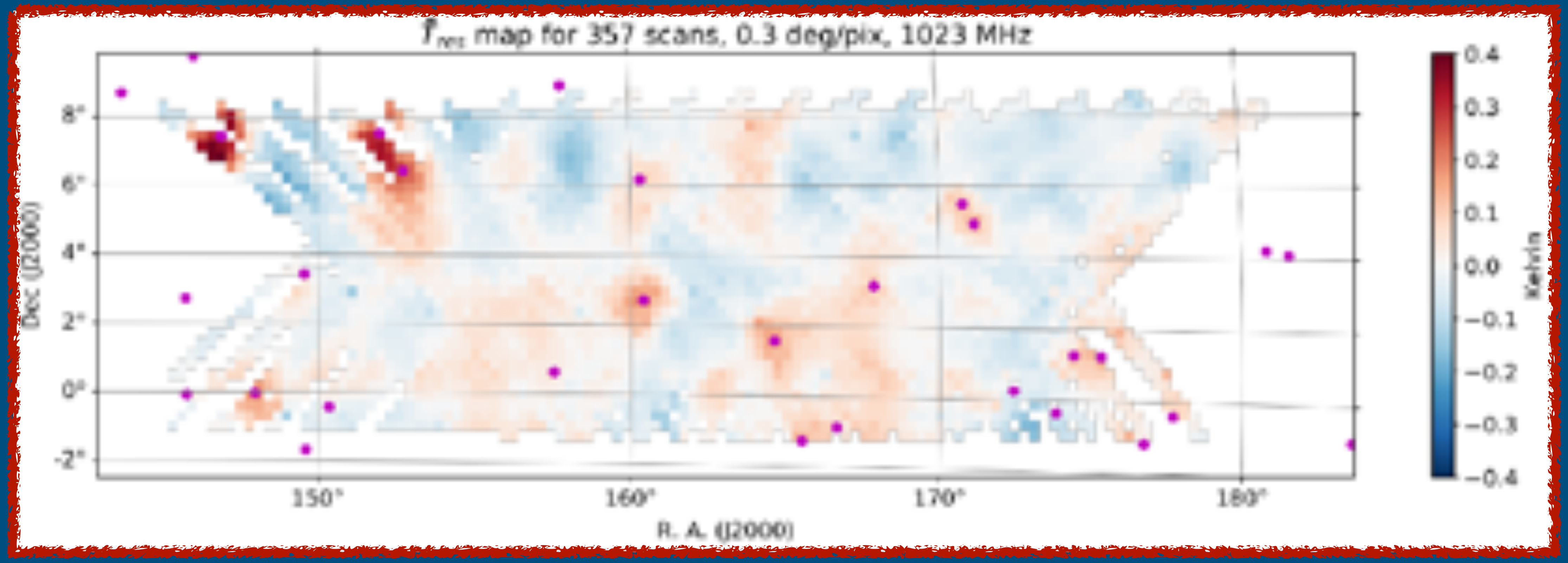
CMB allowed us to perform precision cosmology but **Large Scale Structure** allows us to probe Universe in 3D so will eventually provide better constraints



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

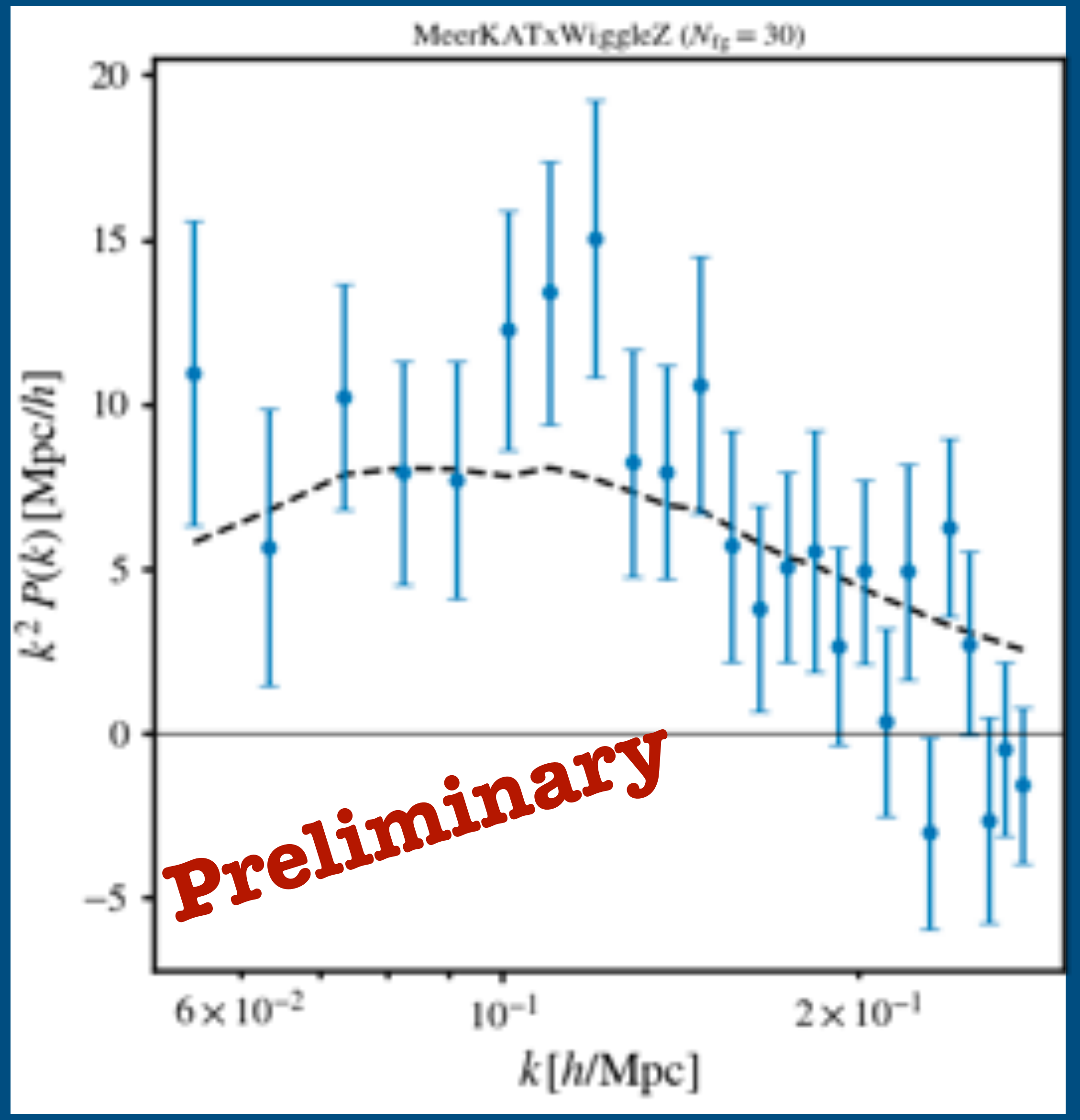
Numerous complications to overcome, perhaps most challenging is **foreground** contamination

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



MeerKAT's pilot survey data is showing signs of positive correlation with overlapping galaxy surveys

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



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Backup Slides

Why 21cm HI (neutral hydrogen)?

Credit: Kovetz+17 [arXiv:1709.09066]

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Operational single-dish intensity mapping experiments

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

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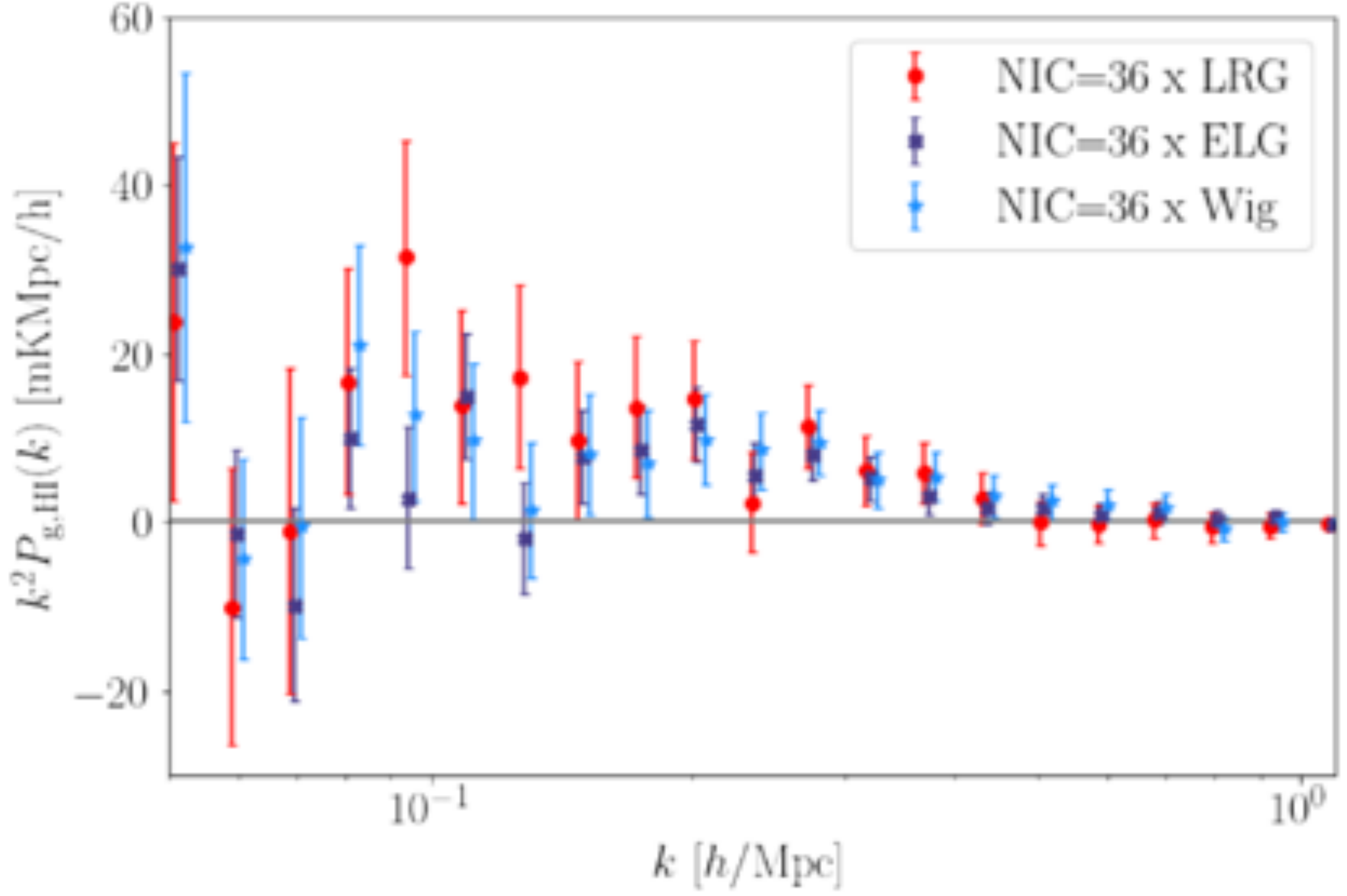
Successful detections using HI intensity mapping

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