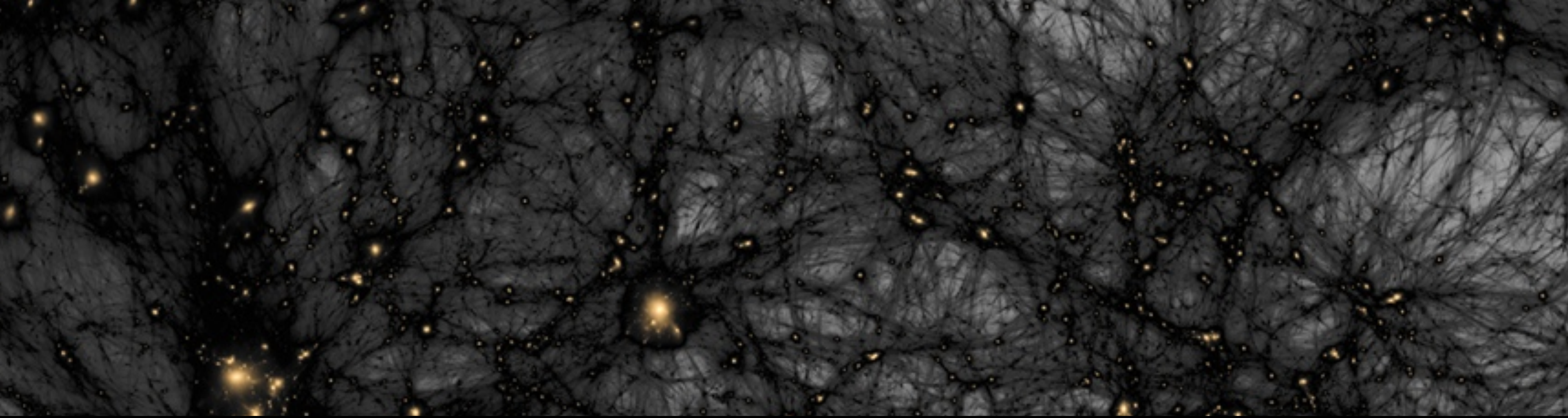


COSMOLOGY WITH NEUTRAL HYDROGEN INTENSITY MAPPING

Alkistis Pourtsidou
Higgs Centre & Institute for Astronomy

UK Research and Innovation

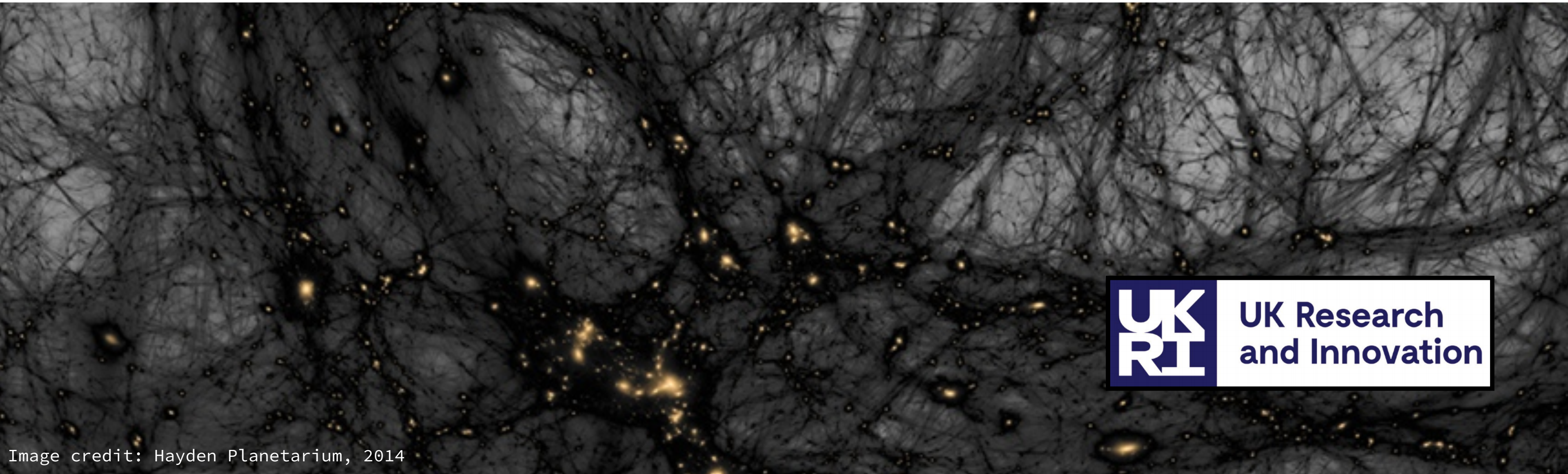


Image credit: Hayden Planetarium, 2014

RESOURCES

www.github.com/IntensityTools

Lectures Public
Relevant lecture notes and presentations
☆ 0 · GPL-3.0 · Forks 0 · Issues 0 · Pull requests 0 · Updated 20 hours ago

MultipoleExpansion Public
Multipole expansion for HI intensity mapping experiments
Jupyter Notebook · ☆ 5 · GPL-3.0 · Forks 1 · Issues 0 · Pull requests 0 · Updated on Jan 10, 2022

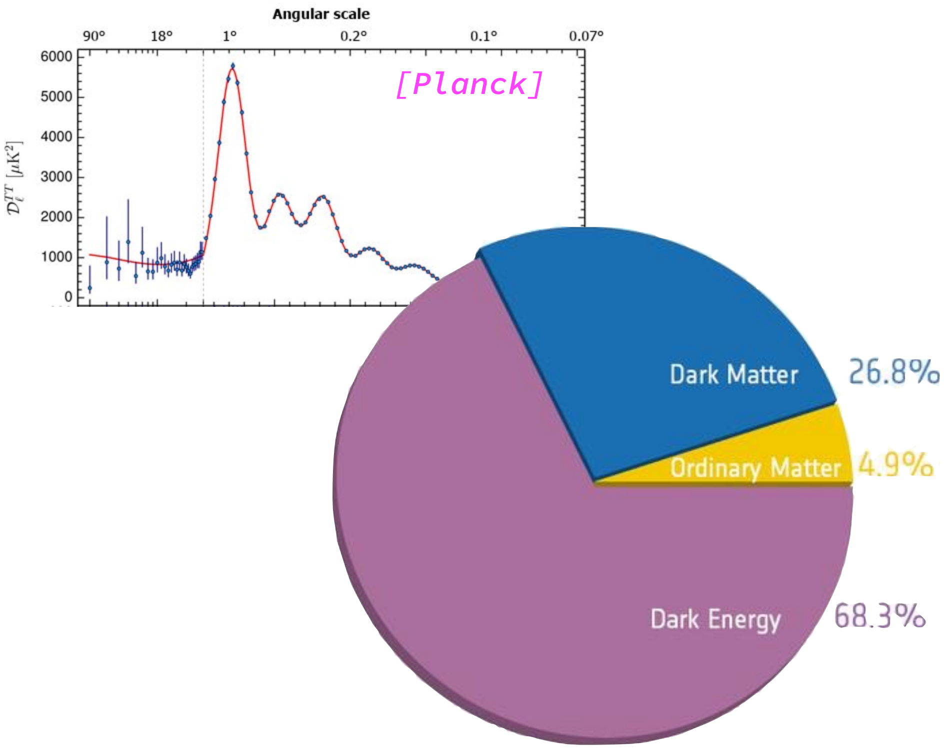
gpr4im Public
Using GPR as a foreground removal technique for single-dish 21cm intensity mapping.
Jupyter Notebook · ☆ 0 · MIT · Forks 4 · Issues 0 · Pull requests 0 · Updated on May 28, 2021

IM-Fish Public
Fisher Matrix codes for IM and cross-correlations
Jupyter Notebook · ☆ 1 · GPL-3.0 · Forks 2 · Issues 0 · Pull requests 0 · Updated on Feb 25, 2019

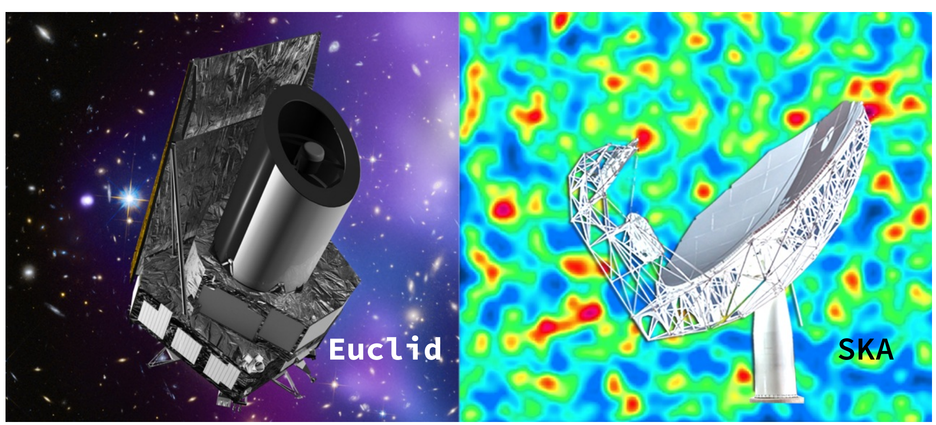
IM-Inflation Public
Fisher Matrix codes for cosmological and inflationary parameters.
Jupyter Notebook · ☆ 0 · GPL-3.0 · Forks 1 · Issues 0 · Pull requests 0 · Updated on Mar 13, 2017

Contributors: Steven Cunnington, Paula Soares, Catherine Watkinson, AP

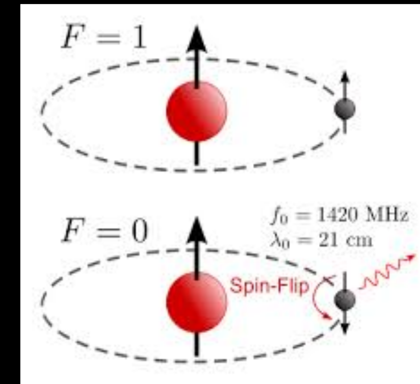
New Frontiers in Observational Cosmology



- ✦ 95% of our Universe is very strange - new physics!
- ✦ Use **large scale structure surveys**, multiple wavelengths, and multiple probes
- ✦ Invest in pathfinders
- ✦ Exploit synergies



A NEW OBSERVATIONAL WINDOW: 21CM LINE



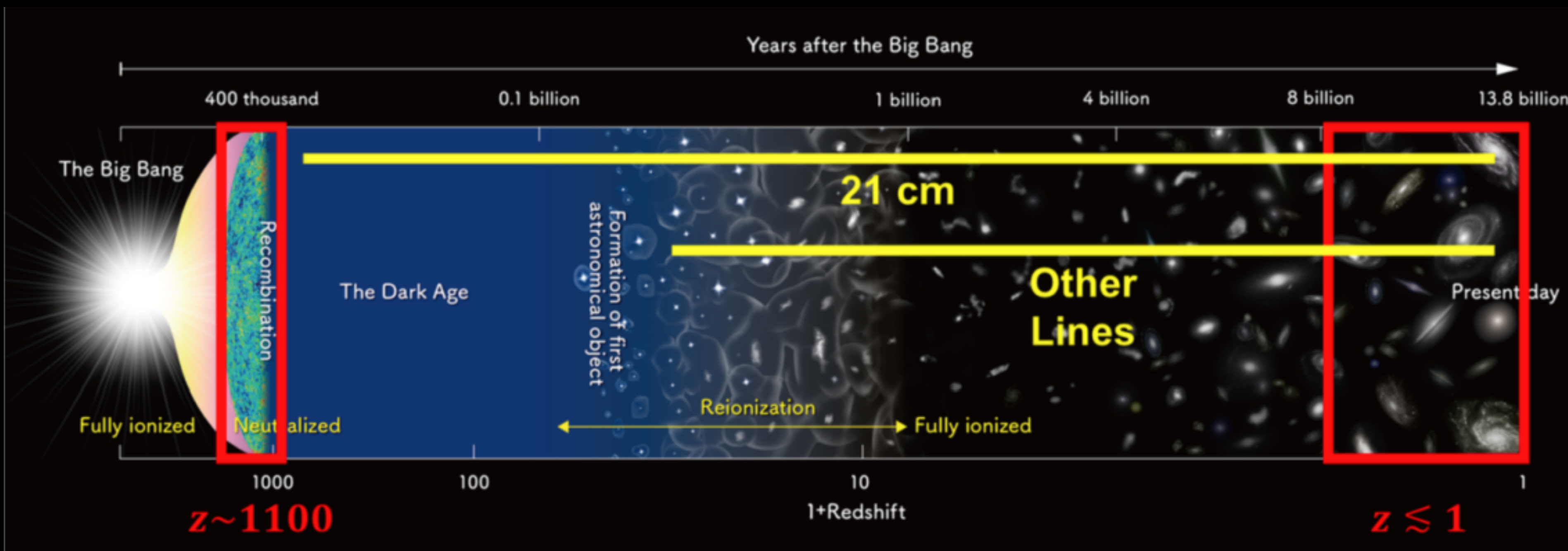
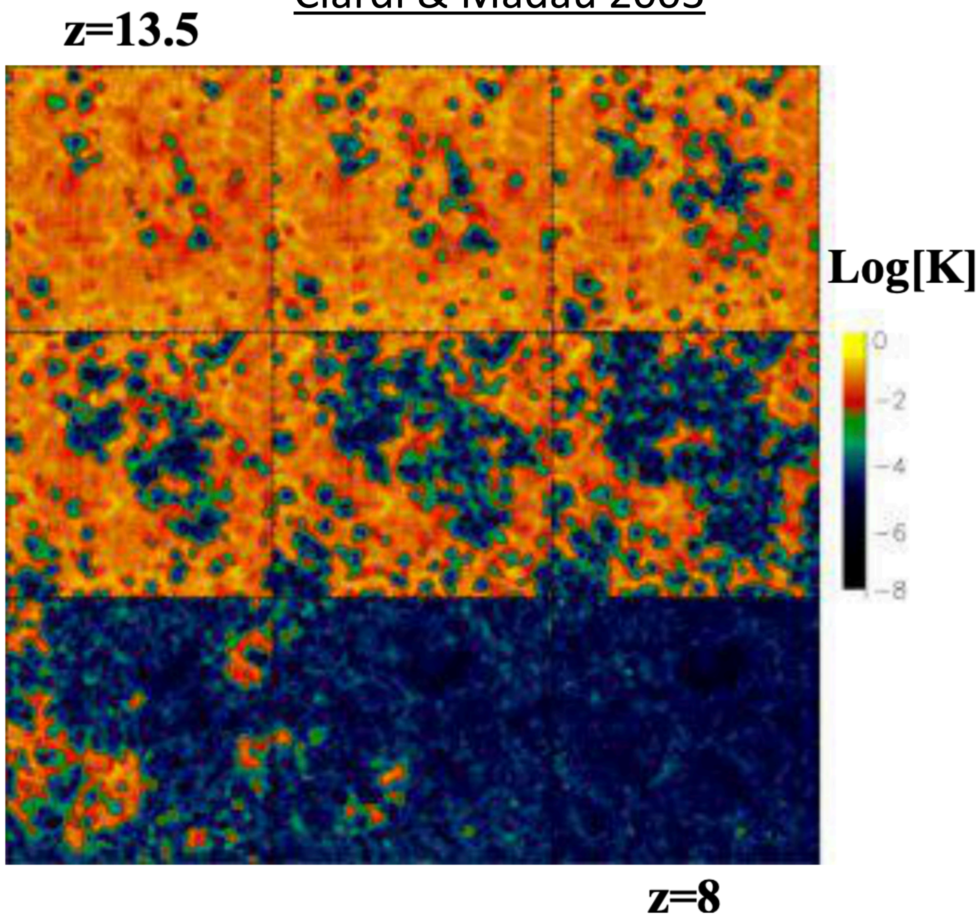


Image Credit: NAOJ [Kovetz et al. 2017]

Ciardi & Madau 2003



- Brightness temperature field
- T(θ , ϕ ,z) → 3D mapping of structure
- Like CMB but extended in 3D
- Many statistically independent frequency (redshift) slices
- Ideal for tomography
- Redshift directly given by observing frequency:

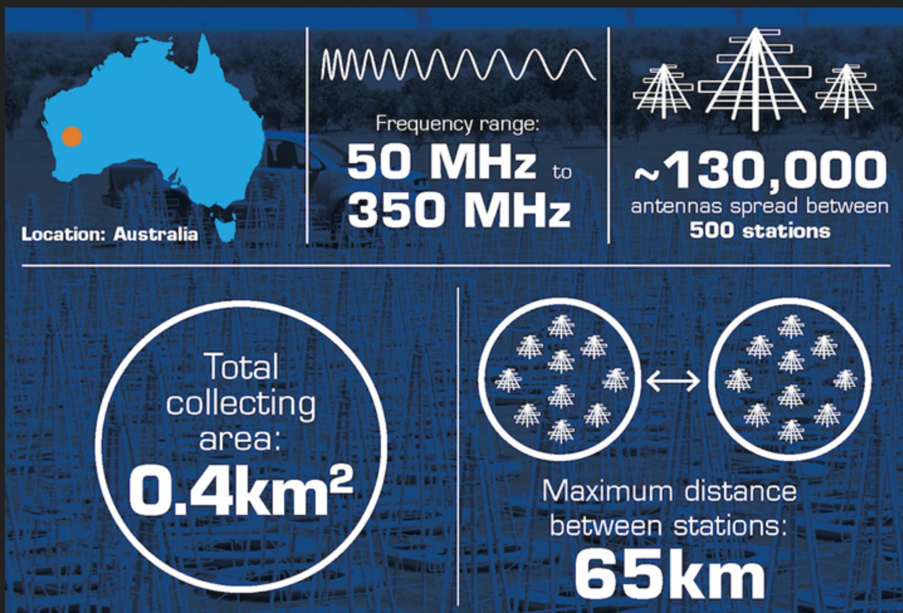
f = 157 MHz → z = 8

f = 473 MHz → z = 2

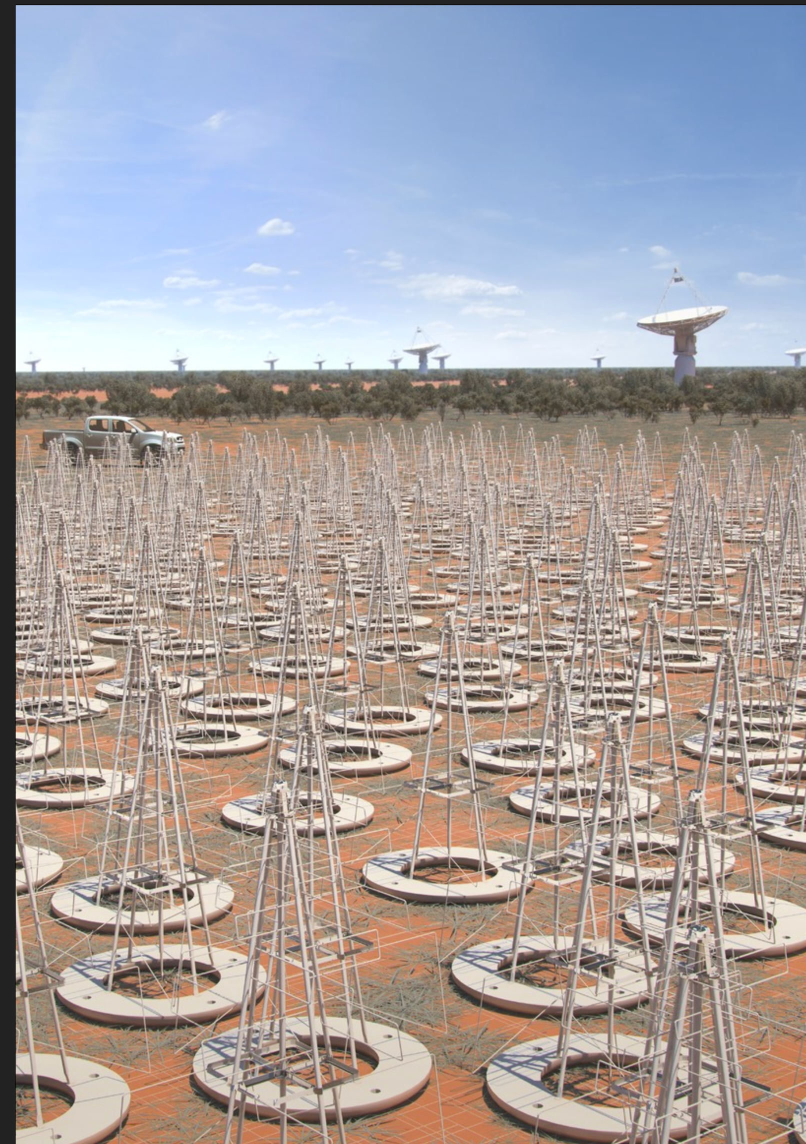
$$f_{\rm obs} = \frac{1420}{1+z}\,{\rm MHz}$$

SQUARE KILOMETRE ARRAY (SKA) - FIRST LIGHT: 2028

SKA - LOW (Australia)

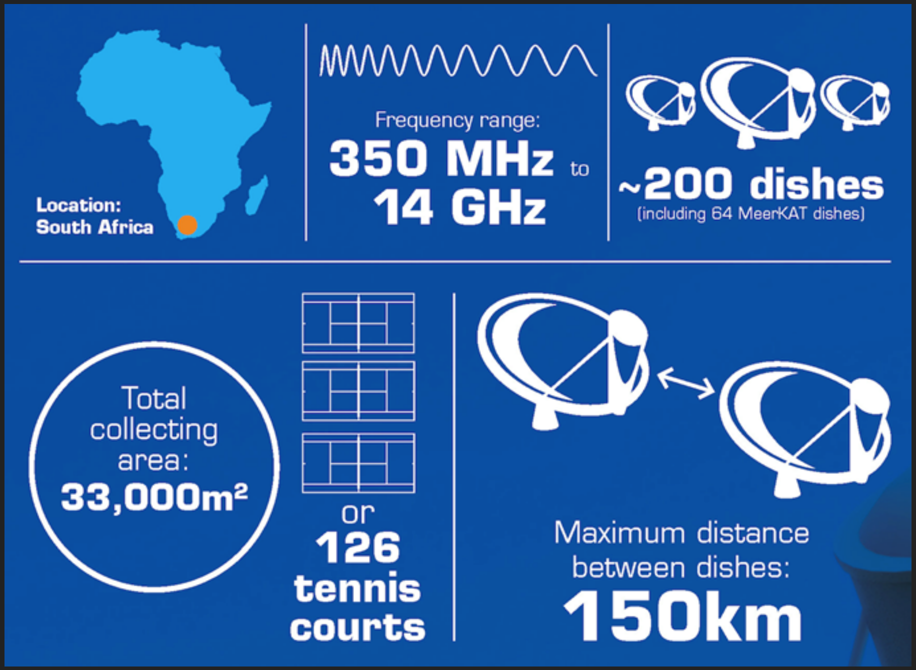


- Redshift range: $3 < z < 25$
- Epoch of Reionization and Cosmic Dawn



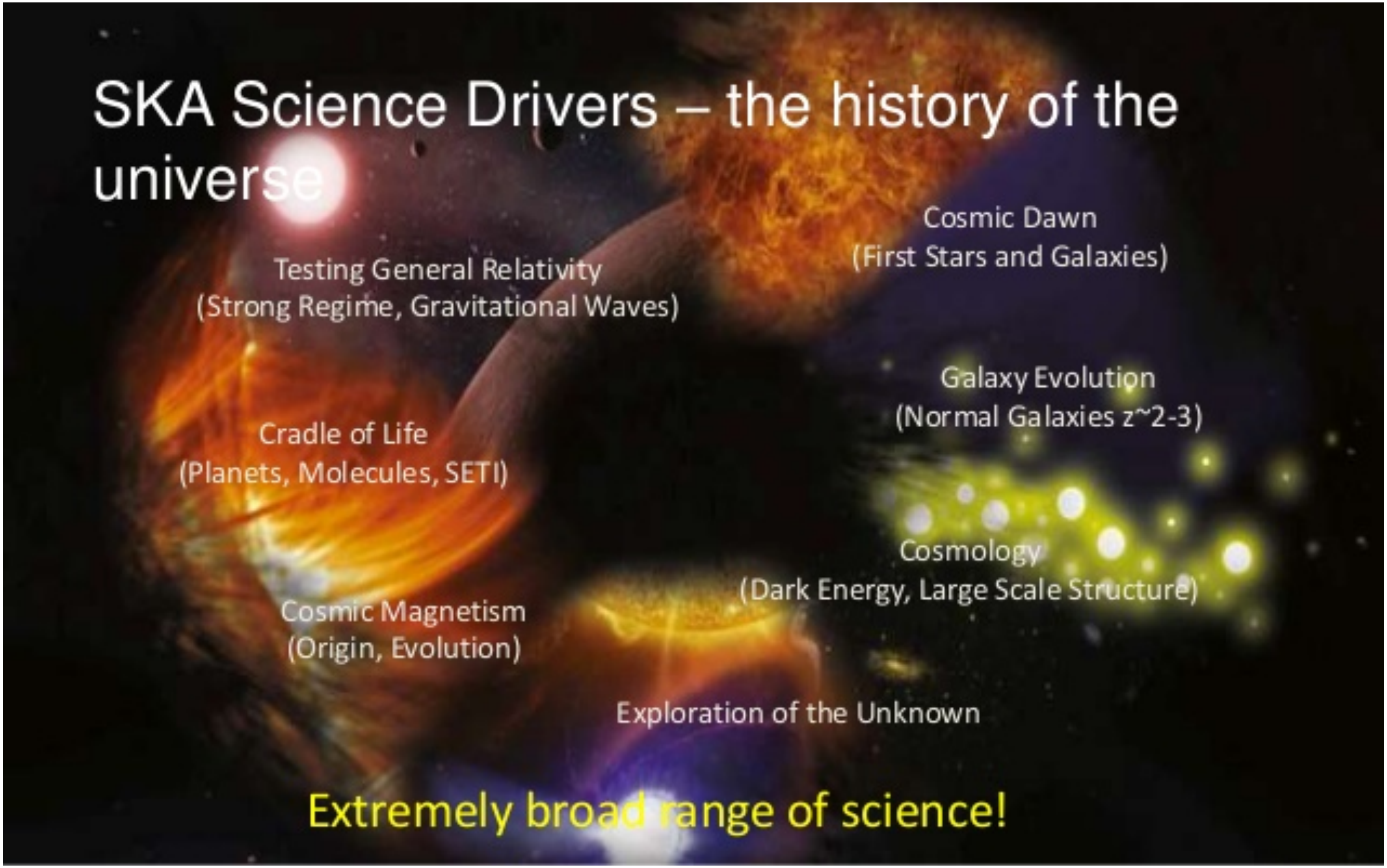
SQUARE KILOMETRE ARRAY (SKA) - FIRST LIGHT: 2028

SKA - MID (South Africa)



- Redshift range: $0 < z < 3$
- Late Universe, can complement optical surveys

SKA SCIENCE



[SKA Science Book 2015]

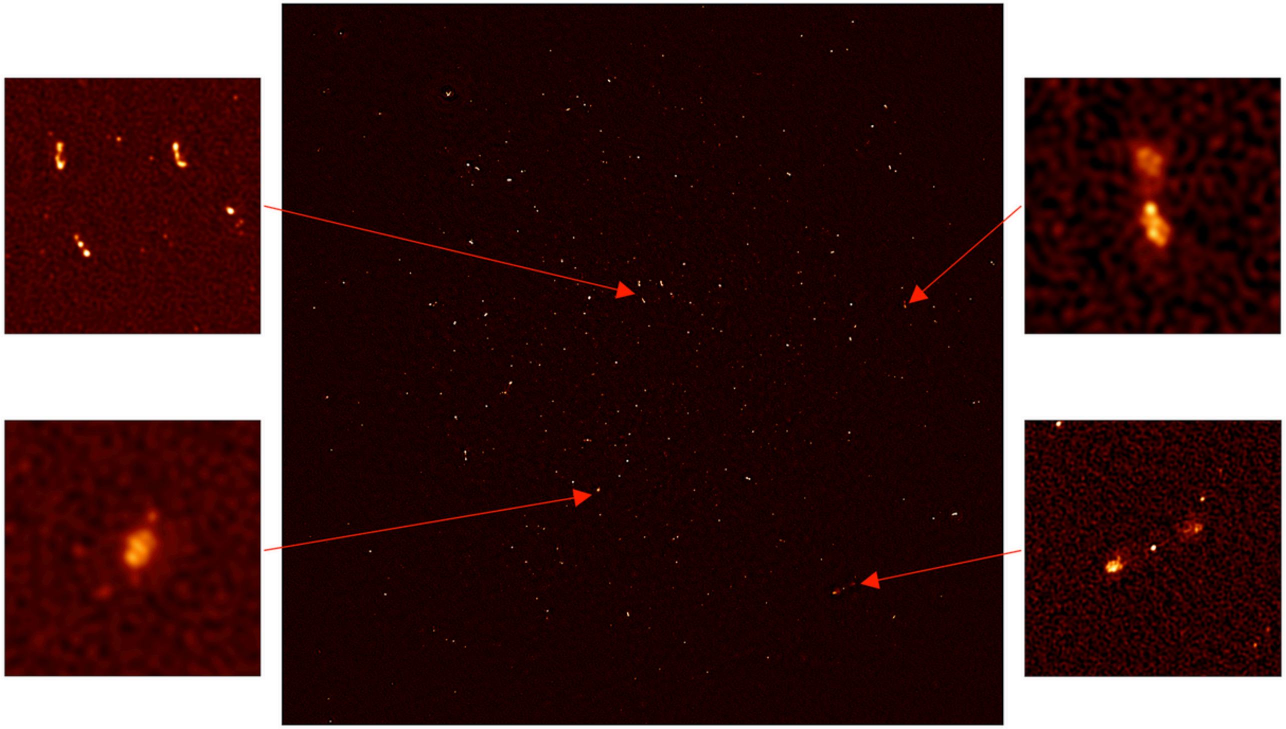
SKA Office / A. Bonaldi

MEERKAT (SKA'S PATHFINDER) - OPERATIONAL !

- 64 dishes, will become part of SKA-MID
- $0.2 < z < 0.58$ (L-band)
- $0.4 < z < 1.45$ (UHF-band)

MEERKAT'S FIRST LIGHT

At only a quarter of its eventual capacity, the MeerKat radio telescope captures 1,300 galaxies in tiny corner of universe where only 70 were known before



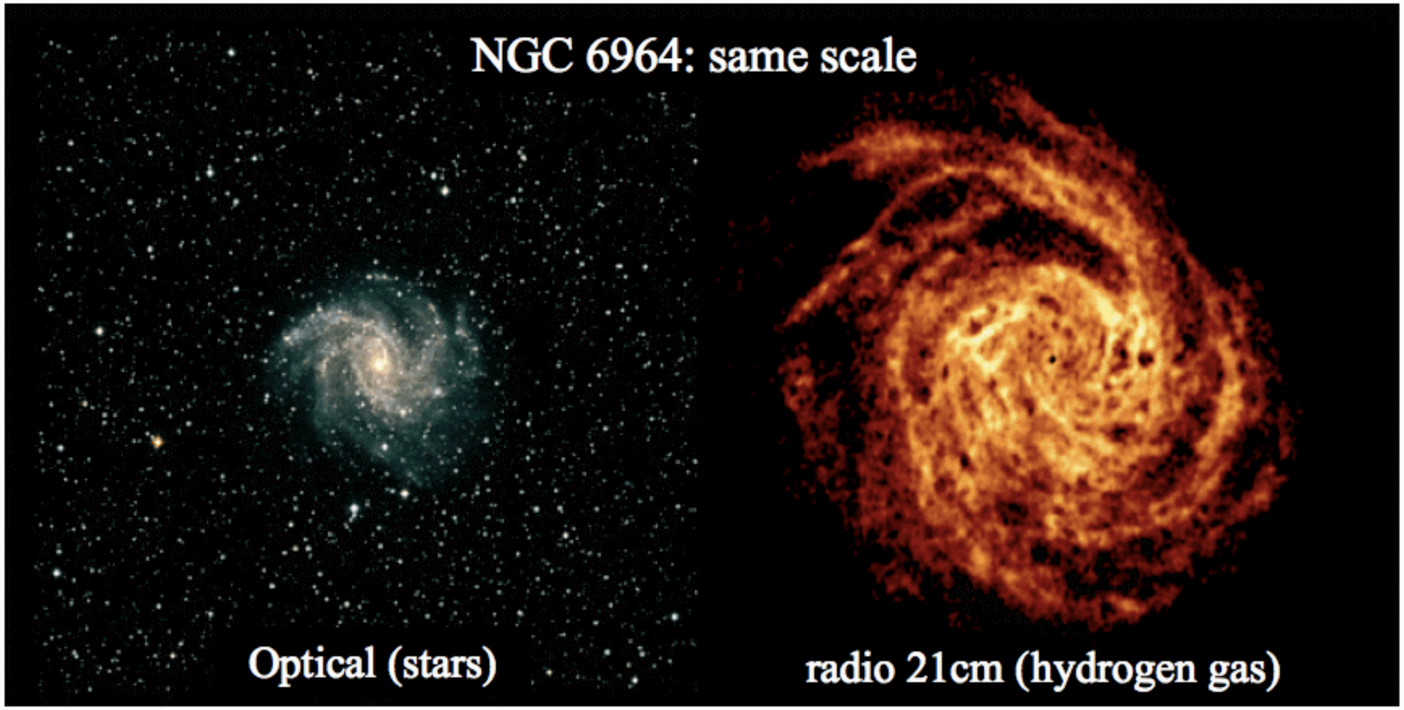
▲ A montage of the MeerKat radio telescope's First Light image with four zoomed-in insets - the two panels to the right show distant galaxies with massive black holes at their centres; at lower left is a galaxy approximately 200m light years away where hydrogen gas is being used up to form stars in large numbers. Photograph: MeerKat/SKA South Africa

The Guardian, 17 July 2016

Big data era is here: MeerKAT's digitisers generate 5 GB/sec

RADIO VS OPTICAL: GALAXIES

- HI in galaxies more extended than the stellar light distribution
- HI disk much larger than the stellar disk

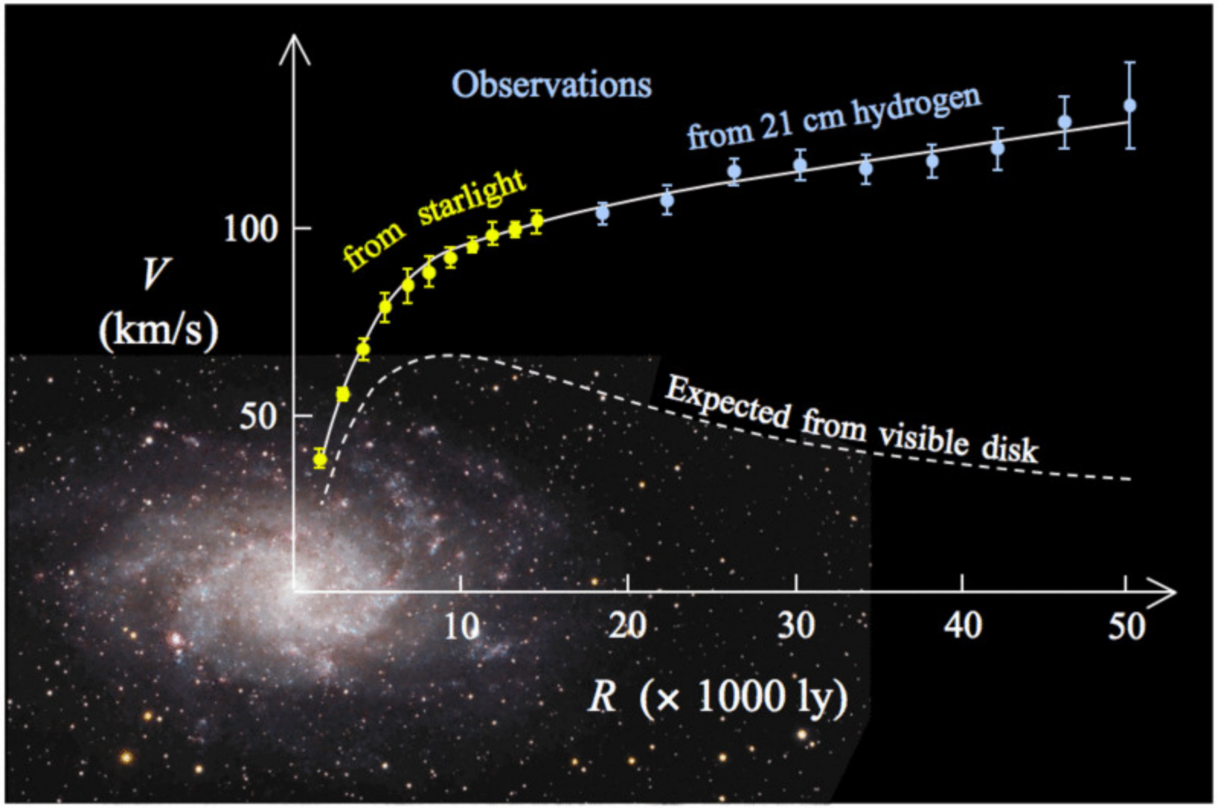


Boomsma et al. 2007

https://www.skao.int/en/explore/science-goals/131/exploring-galaxy-evolution

RADIO VS OPTICAL: GALAXIES

- Velocities (stars or gas) are used to calculate rotation curves and trace the total mass distribution to very large radii



see e.g. Corbelli and Salucci 2000

INTERFEROMETRY IN A NUTSHELL

- In the early days of radio astronomy, single dishes were the norm …
- Resolution $\theta_B = \lambda / D_{\rm dish}$
- For precision astronomy we need **sub-arcsecond resolution**

- But with a single dish, at about $D_{\rm dish}$= 100 m, we're done - and that's nowhere near enough for precision astronomy …

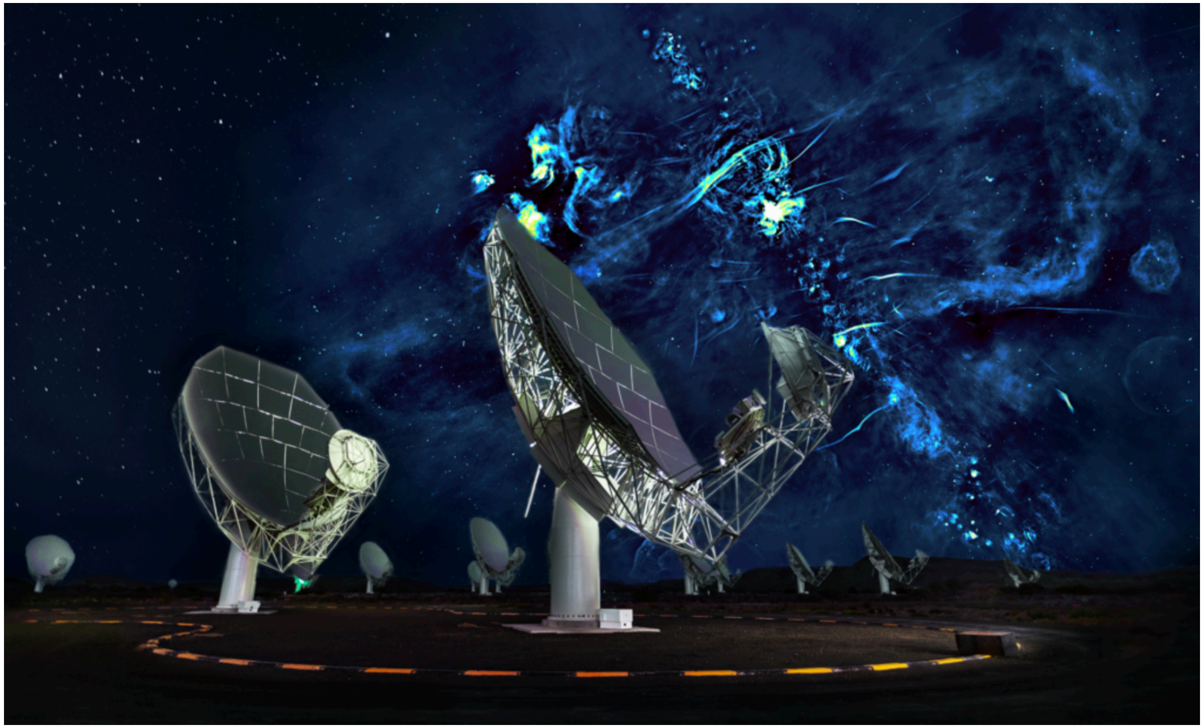
https://public.nrao.edu/telescopes/radio-telescopes/

Interferometry in a nutshell

- We cannot build or operate a single radio dish of 1 square kilometre collecting area

- **Idea:** combine the views of a group of dishes/ antennae spread over a large area

- Operate them together as a single, gigantic telescope!



https://www.sarao.ac.za/gallery/meerkat/

RADIO ARRAYS: TWO MODES OF OPERATION

Single-dish mode

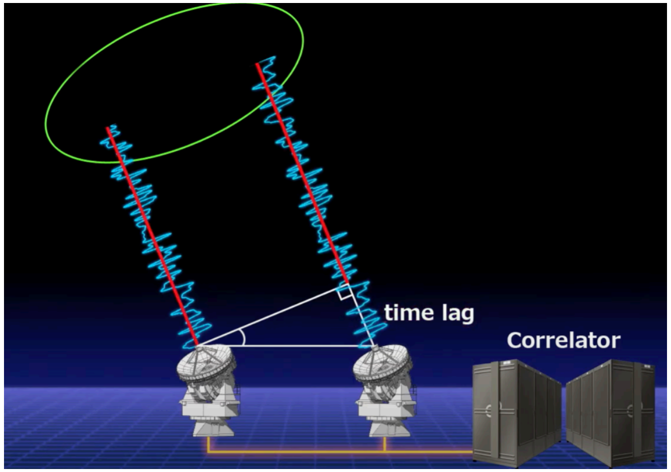
- The auto-correlation signal from one or more dishes
  - observe targets “point by point” , no detail
- Smallest scale the array can probe is set by the dish resolution (beam)
- **Single dish mode can probe large volumes — ultra-large scales on the sky**

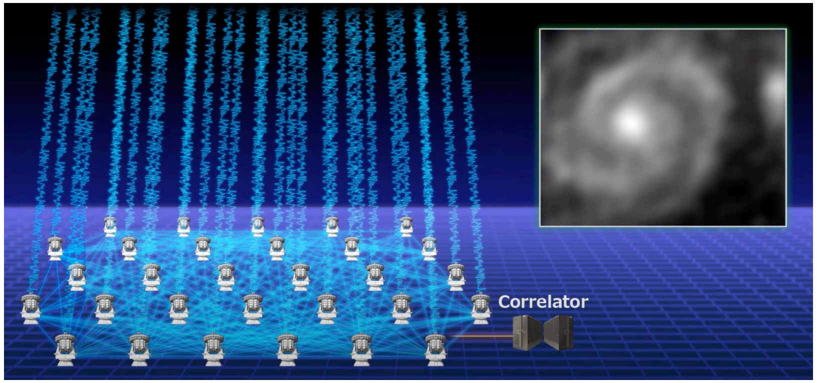
Interferometric mode

- The cross-correlation signal from two or more dishes
- Smallest scale the array can probe is set by the maximum baseline
  - **can achieve very high angular resolution**
- Can probe large volumes if (a) extremely compact array of very small dishes (b) “purpose-built” geometry **SKA has neither**

Interferometry in a nutshell

- Signals slightly out of sync
- **Correlating the signals we can determine the position of the source very precisely**
- Correlator finds the point of overlap
- Multiple antennae (dishes) needed for resolving astrophysical objects

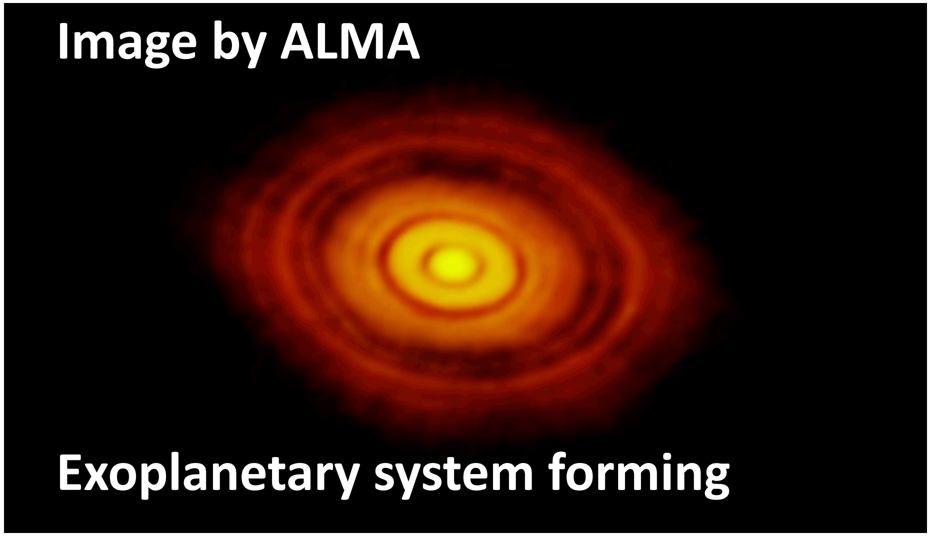


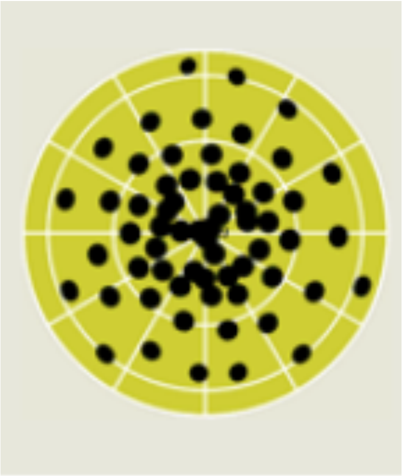


ALMA video

Aperture synthesis

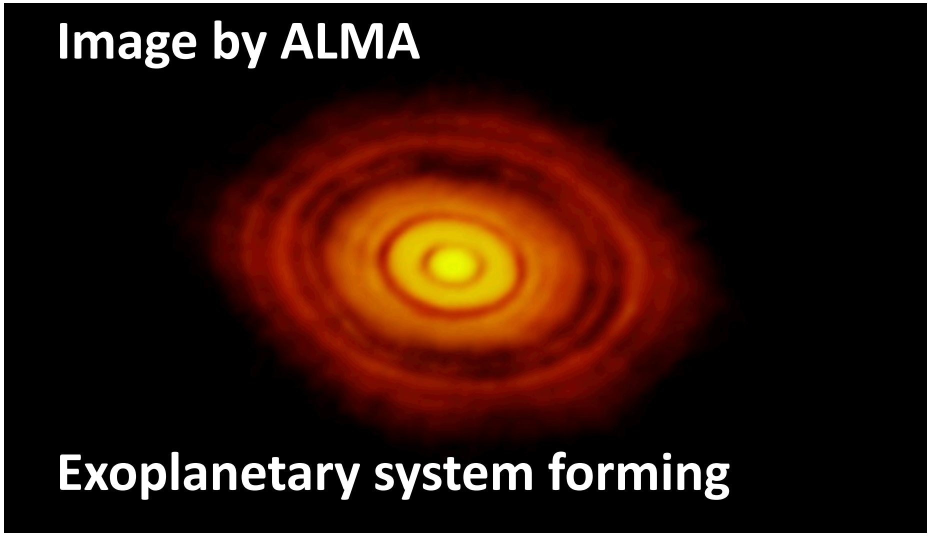
- 2 dishes/antennas will give you one point on the sky
- Dozens of antennas give lots of points, one for each pairing of antennas.

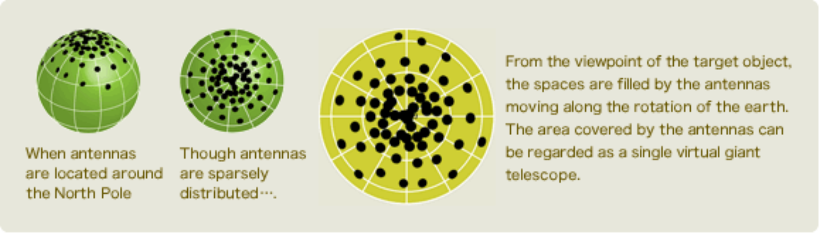




Aperture synthesis

- 2 dishes/antennas will give you one point in the sky
- Dozens of antennas give lots of points, one for each pairing of antennas.
- Earth's rotation helps fill in the gaps (Earth Aperture Synthesis)
- The results are spectacular!





*The actual ALMA antenna location differs from the figure above. The figure is a conceptual illustration to explain the principle of the "aperture synthesis" technique (interferometric imaging method) in a very simple way.

https://briankoberlein.com/2015/10/14/how-does-interferometry-work/

Even More spectacular results!

Credit: Event Horizon Telescope collaboration et al.

WHAT ABOUT COSMOLOGY?

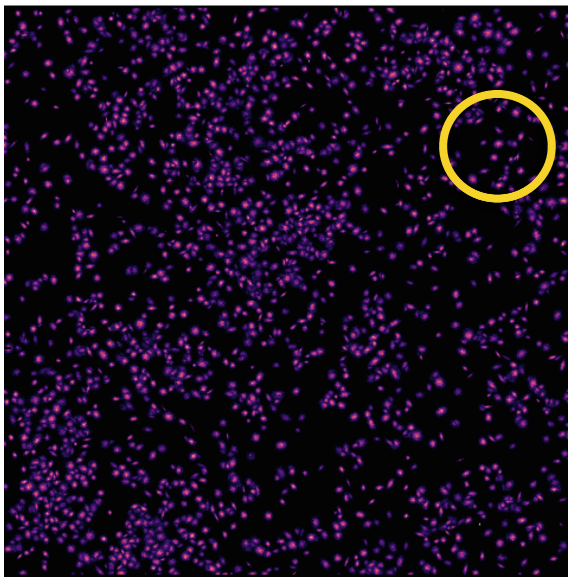
Waiting for SKA Phase 2 …

- What about cosmology with a multi-dish array?
- Detecting millions of galaxies in the radio is very difficult
- We would need the **full SKA Phase 2, performing a billion galaxy survey in the radio**, to be competitive with optical
- Can we do something sooner? **Yes! With HI intensity mapping**.

RADIO PRECISION COSMOLOGY: THE INTENSITY MAPPING METHOD

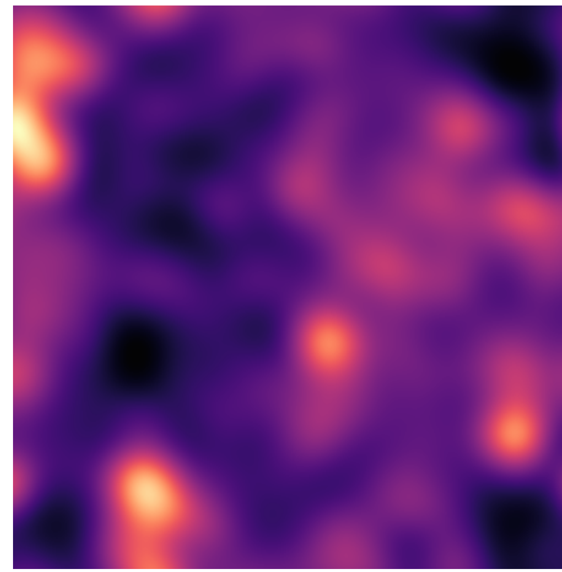
[Chang et al 2008, Peterson et al 2009, Seo et al 2010, …]

Galaxies

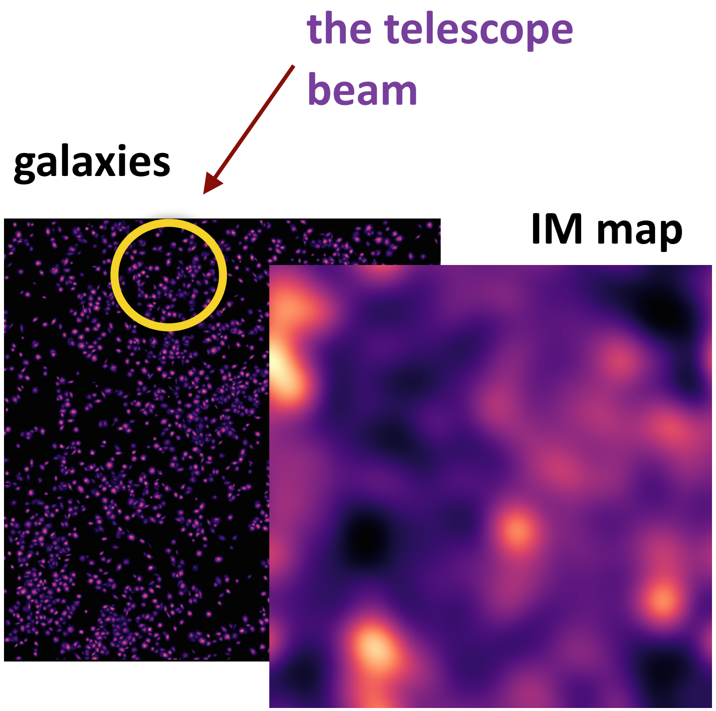


the telescope beam

Intensity map



RADIO PRECISION COSMOLOGY: THE INTENSITY MAPPING METHOD



[Simulations by S. Cunnington]

- Detecting HI (neutral hydrogen) galaxies via their 21cm emission line is very expensive
- But cosmological information is on large scales
- Get intensity map of the HI 21cm emission line - like CMB but 3D!
- **Excellent redshift resolution**
- **Signal of the order 0.1 mK – foregrounds larger by 3-4 orders of magnitude**

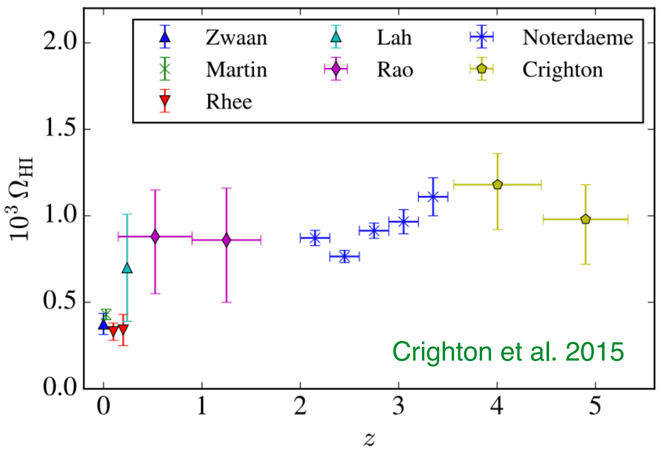
21cm IM surveys: GBT, CHIME, HIRAX, MeerKAT, SKA!

GOALS: Probe HI evolution, dark energy, gravity, inflation, …

CHARACTERISING THE POST-REIONIZATION HI SIGNAL

$$\bar{T}_{\rm obs}(z) = 44\mu{\rm K}\left(\frac{\Omega_{\rm HI}(z)h}{2.45\times10^{-4}}\right)\frac{(1+z)^2}{E(z)},$$

$$T_{\rm obs} \propto \Omega_{\rm HI}$$



Battye, AP et al. 2013

CHARACTERISING THE INSTRUMENTAL NOISE

The pixel thermal noise is given by

$$\sigma_{\rm pix} = \frac{T_{\rm sys}}{\sqrt{\Delta f \, t_{\rm total} (\Omega_{\rm pix}/\Omega_{\rm tot}) N_{\rm dishes} N_{\rm beams}}}$$

receiver temperature ($T_{\rm sys}$)

channel width (Δf)

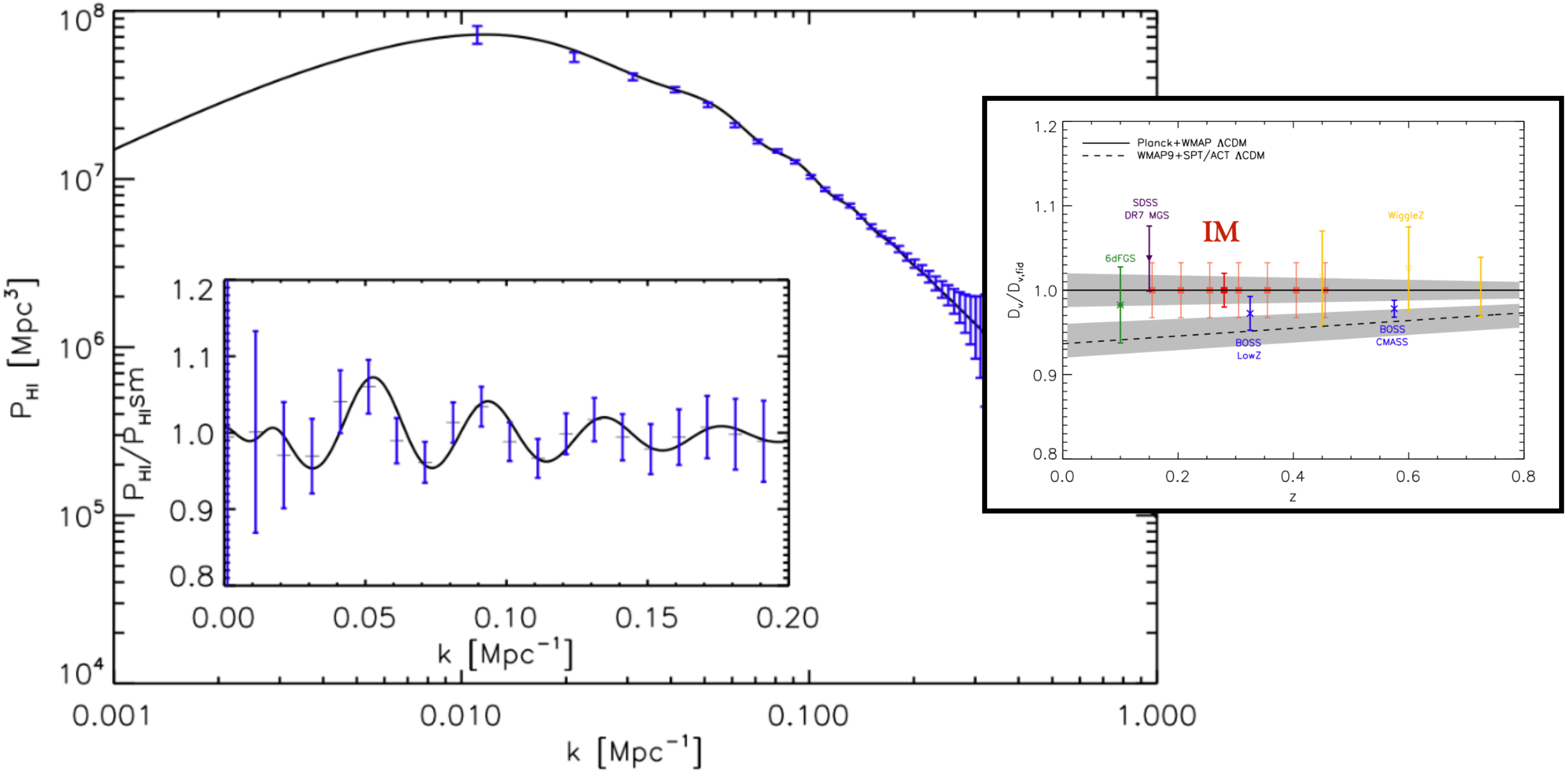
observing time ($t_{\rm total}$)

pixel/survey (total) area ($\Omega_{\rm pix}/\Omega_{\rm tot}$)

- MeerKAT has 64 dishes (no multi-beam system)
- It has a receiver temperature of about 30 K
- A channel width of 50 kHz
- The area and observing time are determined from the survey strategy (can be optimised for different science goals)

NEUTRAL HYDROGEN INTENSITY MAPPING POWER SPECTRUM

- Measuring BAOs with a single-dish telescope
- z=0.3, 40 arcmin resolution, 5000 sq. deg, 1 year observations



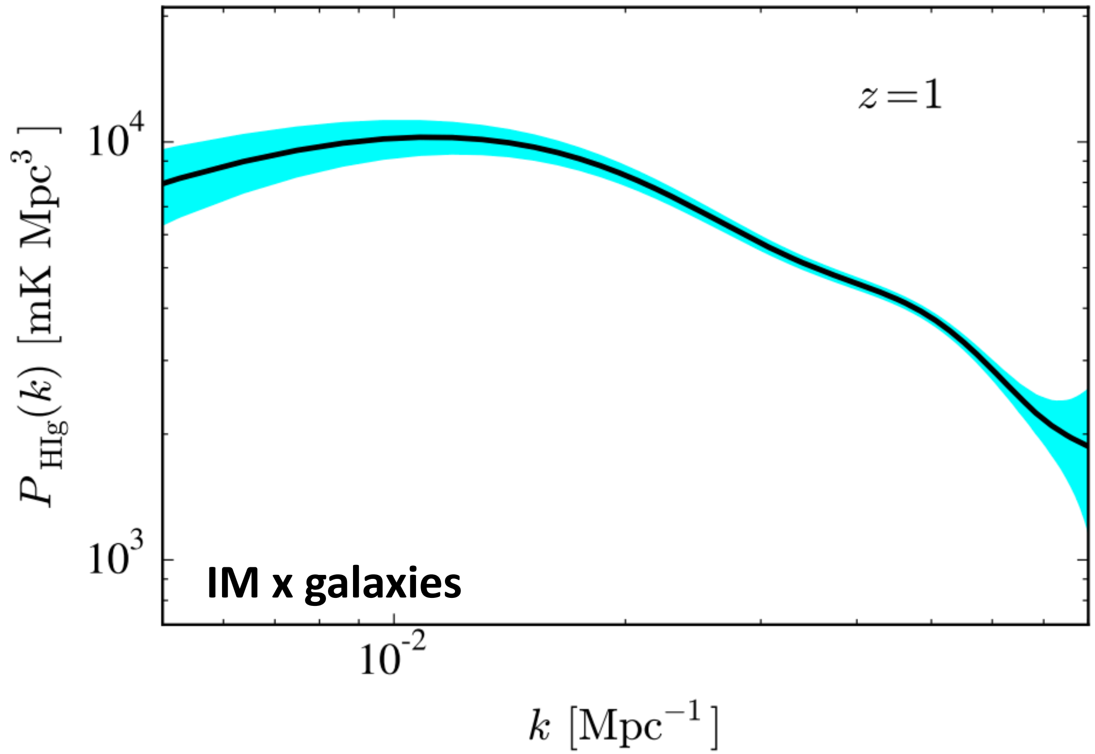
Battye, AP et al. 2013

NEUTRAL HYDROGEN INTENSITY MAPPING POWER SPECTRUM

- With intensity mapping we can constrain HI and cosmological parameters

$$P_{\mathrm{HI}} \propto \Omega_{\mathrm{HI}}^2 b_{\mathrm{HI}}^2 P_{\mathrm{m}} \qquad P_{\mathrm{HI,g}} \propto \Omega_{\mathrm{HI}} b_{\mathrm{HI}} b_g r P_{\mathrm{m}}$$

- The r coefficient tells us about the HI content of different galaxy samples, for example the different HI content of ELGs vs LRGs.

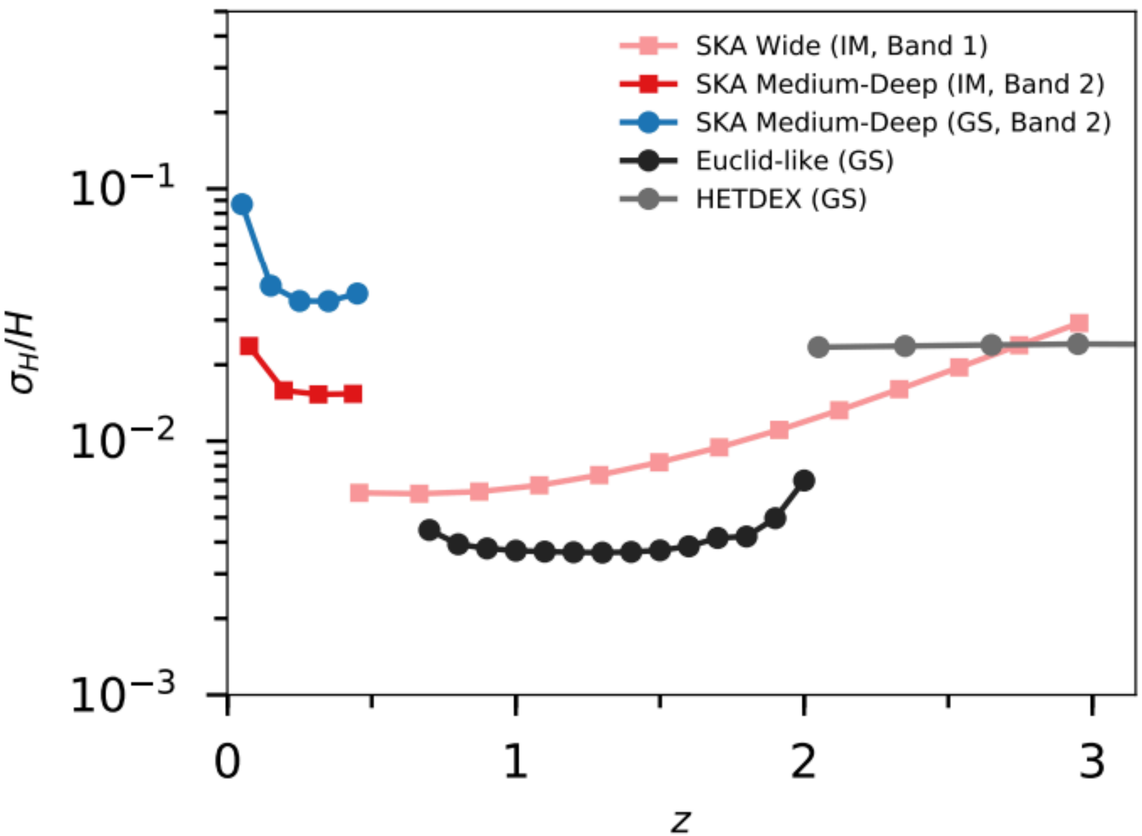


https://github.com/IntensityTools/IM-Fish

SKA INTENSITY MAPPING FORECASTS

- Competitive with Stage-IV optical (Euclid, DESI)
- Can get to much higher redshifts

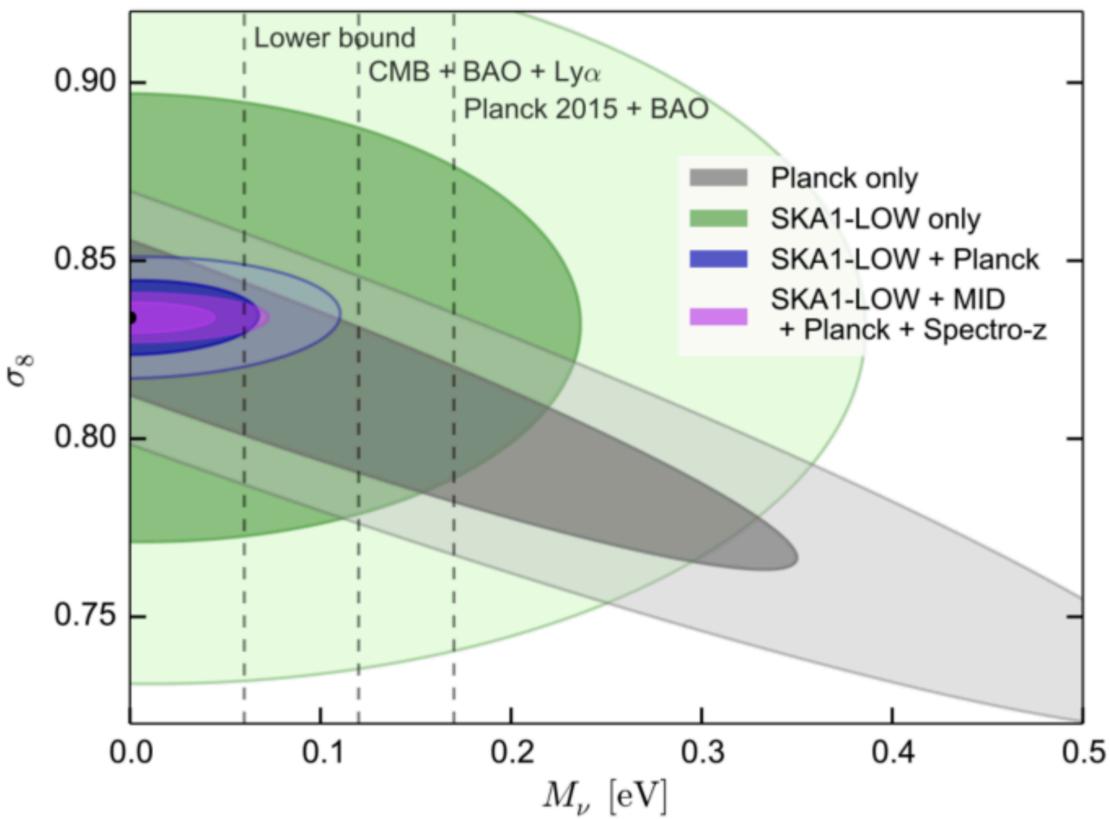
SKA Cosmology Red Book



Bull et al. 2015

SKA INTENSITY MAPPING FORECASTS

- Competitive with Stage-IV optical (Euclid, DESI)
- Can get to much higher redshifts



SKA Cosmology Red Book

Phased Array Feeds (PAFs):

In "single-dish" mode they greatly increase the signal-to-noise ratio.

They allow extremely rapid imaging!

Applications outside physics (e.g. medical imaging)

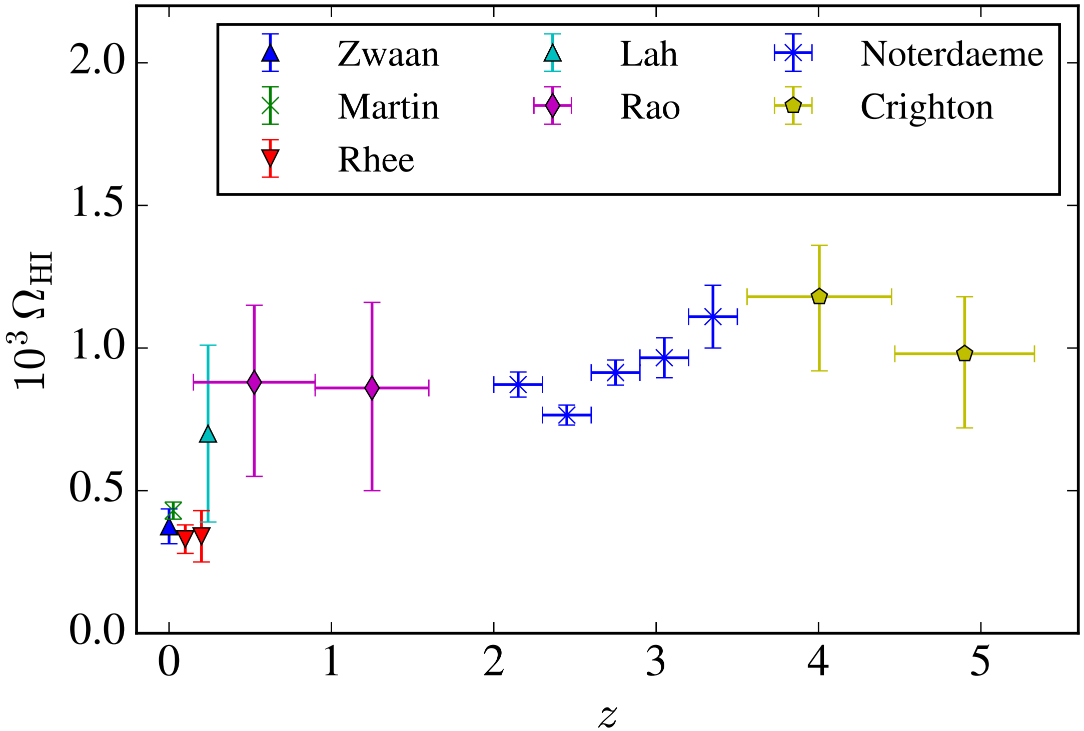
$$P_{\rm N} \propto \frac{1}{N_{\rm d} N_{\rm b} t_{\rm tot}}$$

https://www.skatelescope.org/news/askap-paf-system-award/

Already installed and operational in ASKAP, the SKA's Australian precursor [see Wolz, Blake and Wyithe 2017 for intensity mapping applications]

Optical and radio synergies

- Neutral hydrogen (HI) evolution is currently quite poorly constrained…
- Important for astrophysics and cosmology alike!



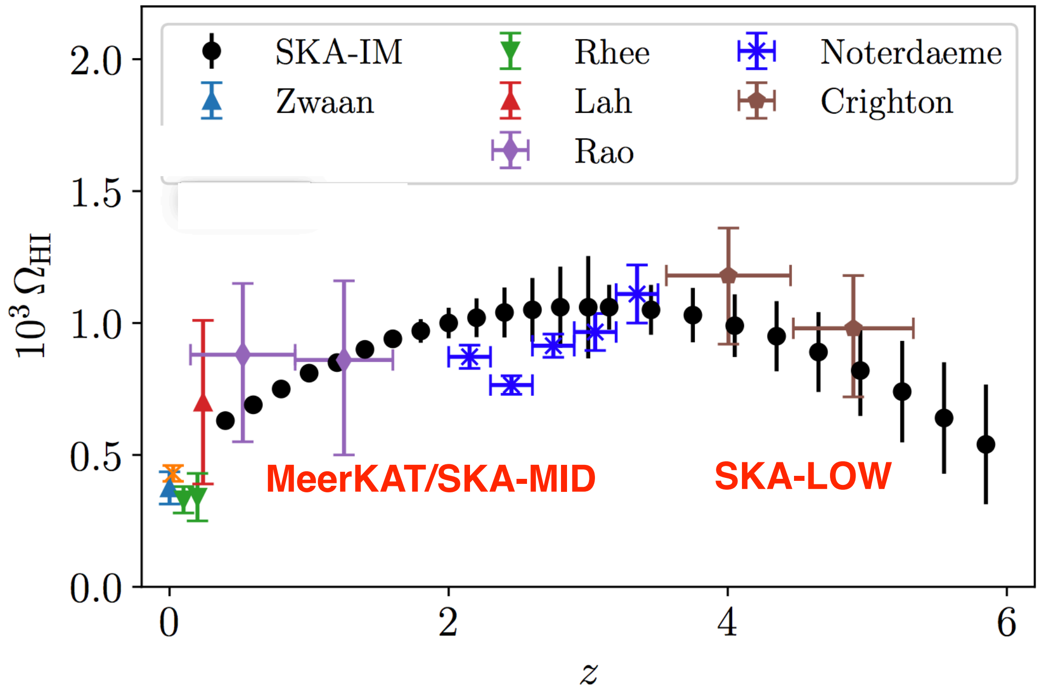
Crighton et al. 2015

GALAXY EVOLUTION

- Can greatly improve HI constraints with intensity mapping
- Cross-correlation with optical surveys helps with systematics and allows for studying the HI content of different galaxy samples

$$P_{\rm HI} \propto \Omega_{\rm HI}^2 b_{\rm HI}^2 P_{\rm m}$$

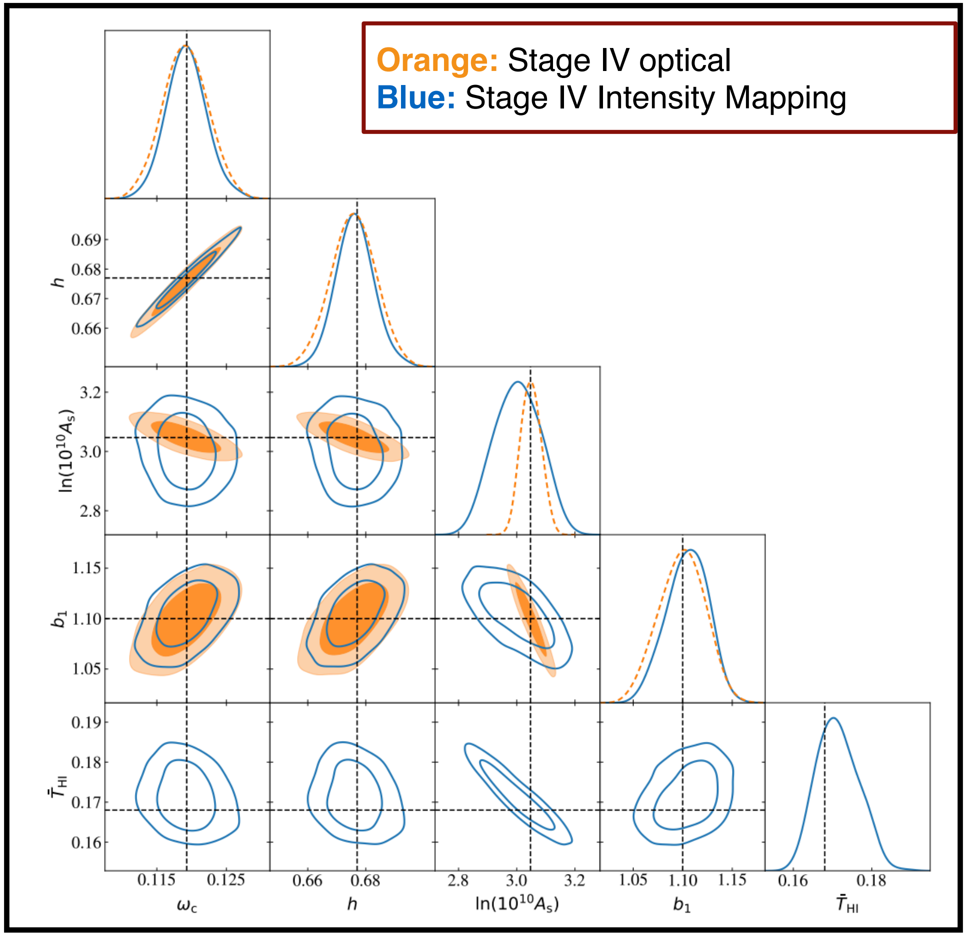
$$P_{\rm HI,g} \propto \Omega_{\rm HI} b_{\rm HI} b_g r P_{\rm m}$$



[Pourtsidou et al. 2017, SKA cosmology Red Book 2020]

EFTOFLSS FOR INTENSITY MAPPING

- Can be **competitive with optical galaxy surveys**
- Can go to high-z where optical are shot-noise limited
- **Major observational challenges (calibration, foregrounds …) should be addressed**

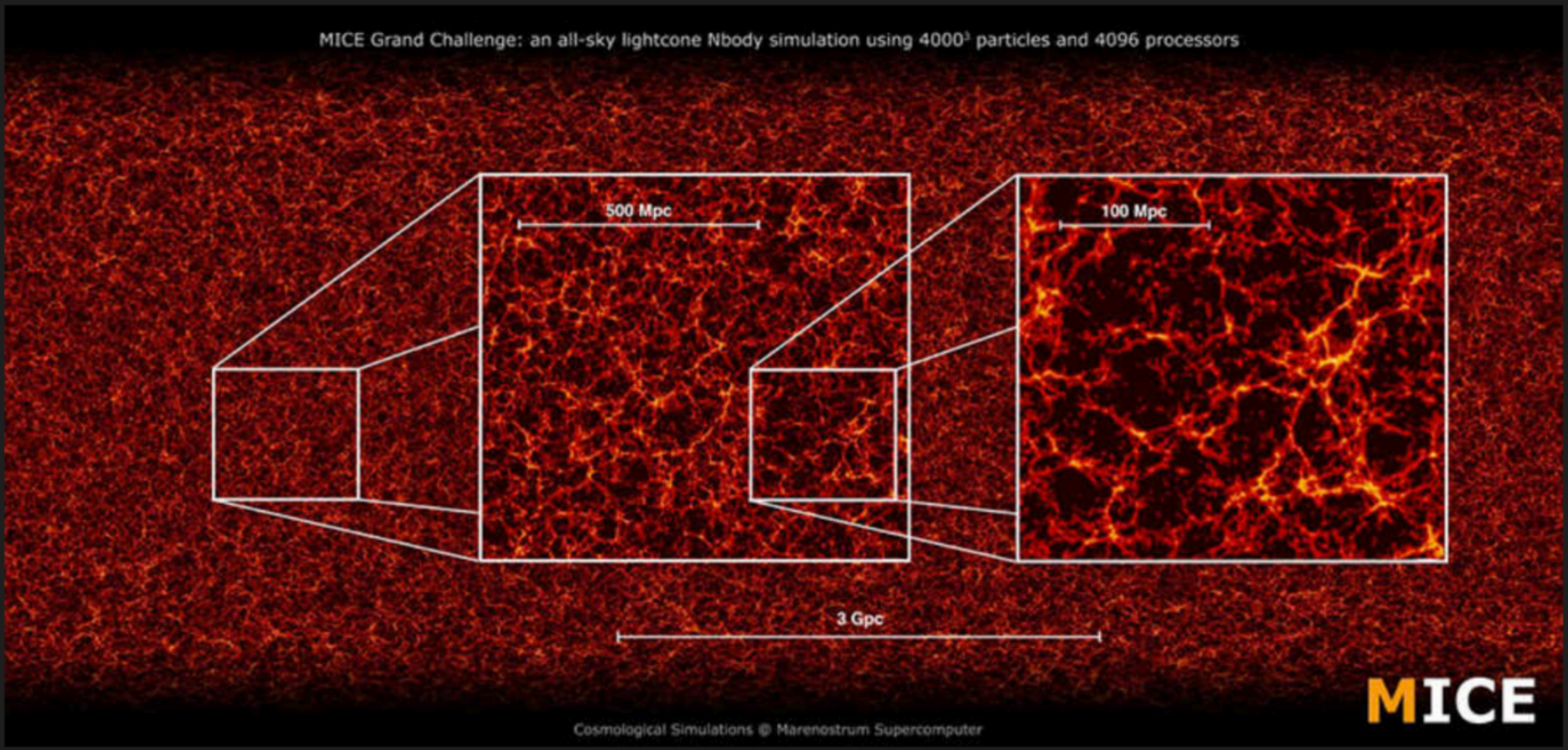


AP 2023

SIMULATING 21CM OBSERVATIONS

MICEcat v2

MICE catalogue by Castander, Carretero, Fosalba



MICE catalogue:

- 0.0 < z < 1.4
- 5000sq degrees
- 500million galaxies

BUILDING 21CM INTENSITY MAPS

- Use central galaxies and their halo mass to derive a HI mass:

$$M_{\rm HI} = 2N_1 M\left[\left(\frac{M}{M_1}\right)^{-b_1} + \left(\frac{M}{M_1}\right)^{y_1}\right]^{-1}$$

Padmanabhan & Kulkarni (2017)

- Convert HI mass field into HI intensity and then a brightness temperature T_HI for each voxel.

Difficulties

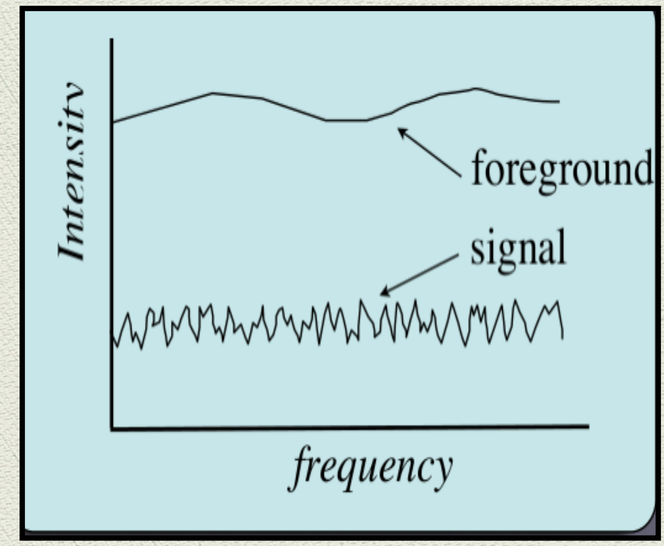
- 21cm signal is very weak
- Foregrounds are a big problem!

(i) Galactic synchrotron - relativistic cosmic ray electrons accelerated by the galactic magnetic field

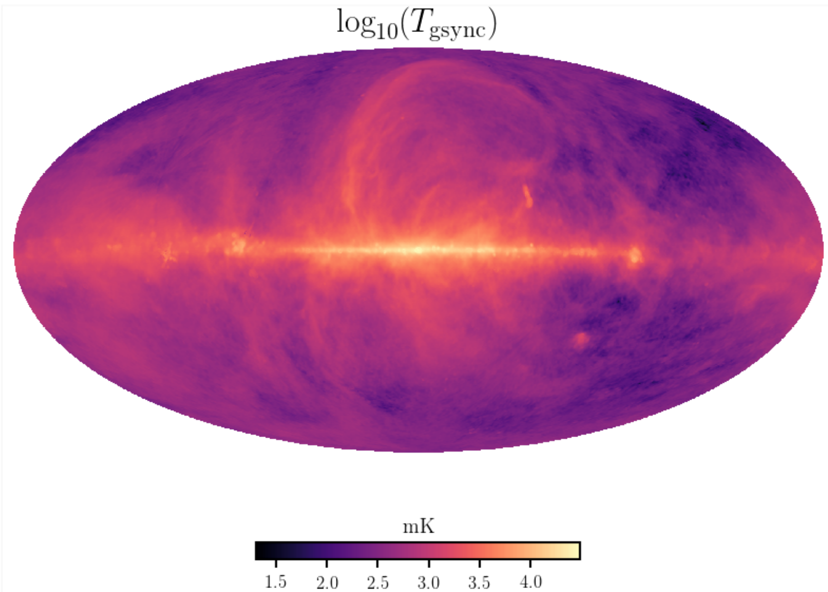
(ii) Extra-galactic point sources - objects beyond our own galaxy emitting signals close to 21cm signal

(iii) Extra-galactic free-free emission - free electrons scattering off ions without being captured and remaining free after the interaction

(iv) Galactic free-free emission - as above but within our own galaxy



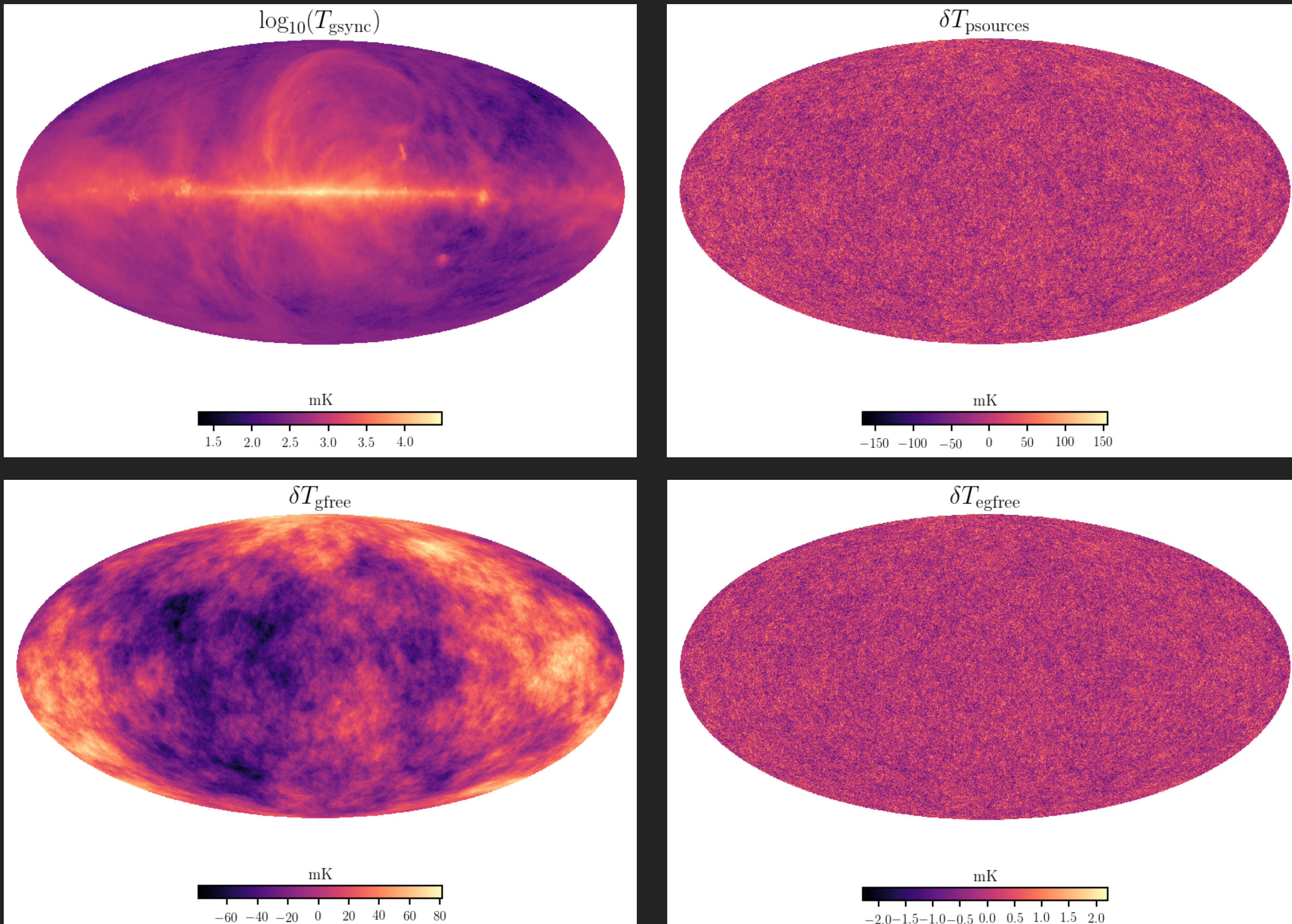
SIMULATING 21CM FOREGROUNDS



$$C_\ell(\nu) = A\left(\frac{\ell_{\rm ref}}{\ell}\right)^\beta \left(\frac{\nu_{\rm ref}}{\nu}\right)^{2\alpha}$$

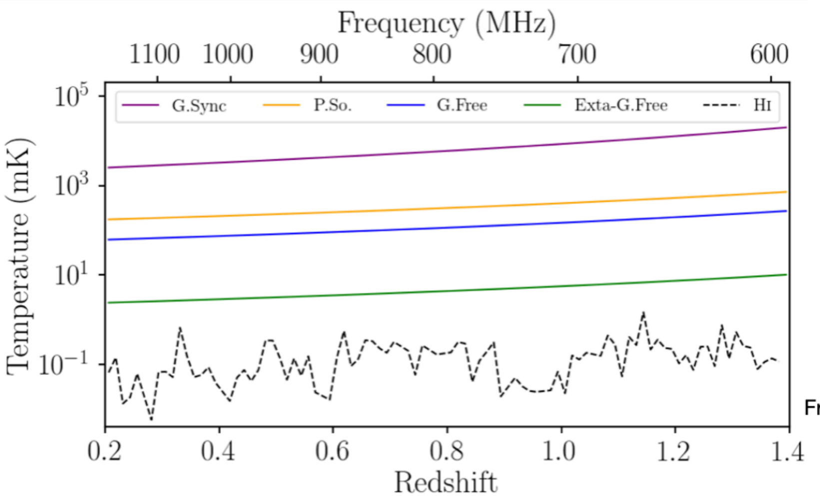
Foreground	A	β	α
Galactic synchrotron	700	2.4	2.80
Point sources	57	1.1	2.07
Galactic free-free	0.088	3.0	2.15
Extra-galactic free-free	0.014	1.0	2.10

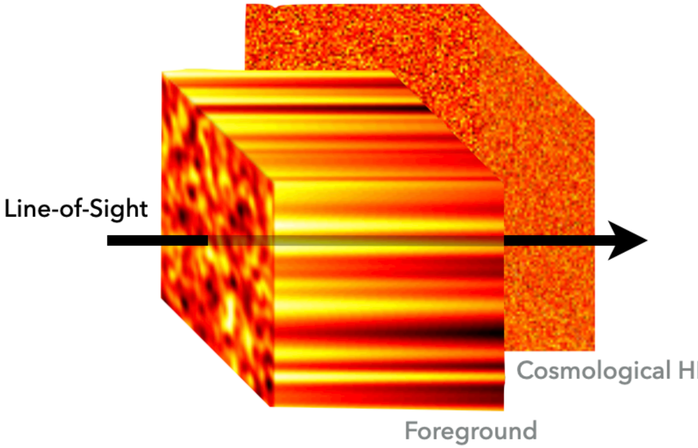
21CM FOREGROUNDS



Foregrounds are spectrally smooth

Idealised simulation demo:



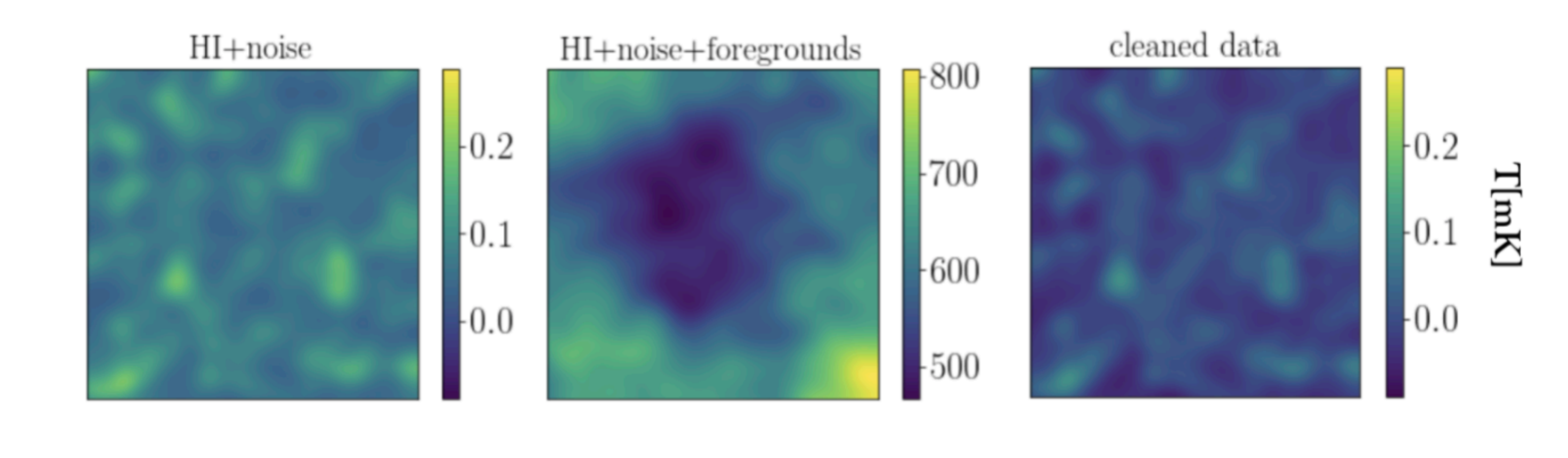


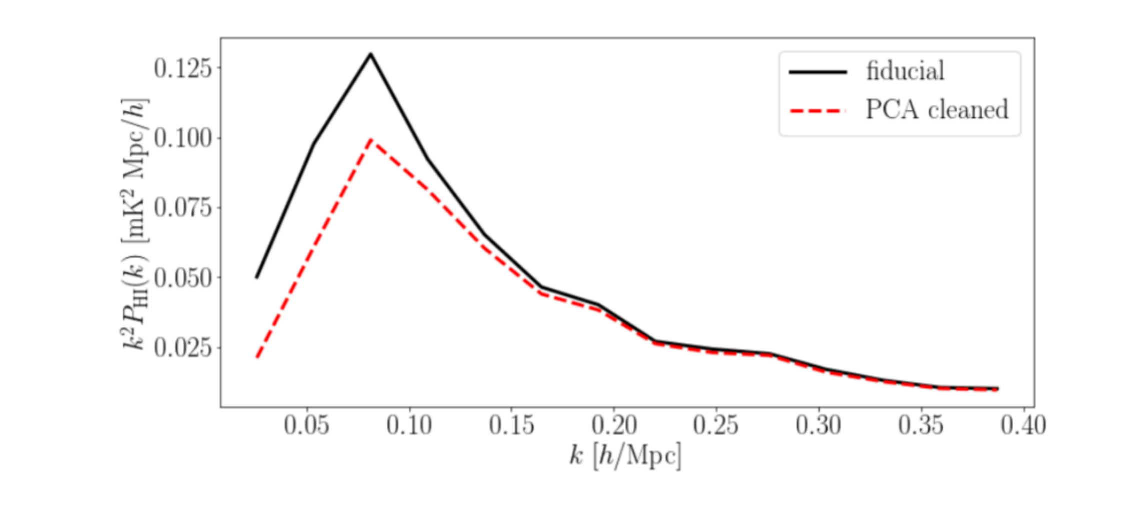
From S.Cunnington+19 [arXiv:1904.01479]

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

https://github.com/IntensityTools/gpr4im [Soares et al. 2020]

21CM FOREGROUNDS CLEANING: SIGNAL LOSS EFFECT



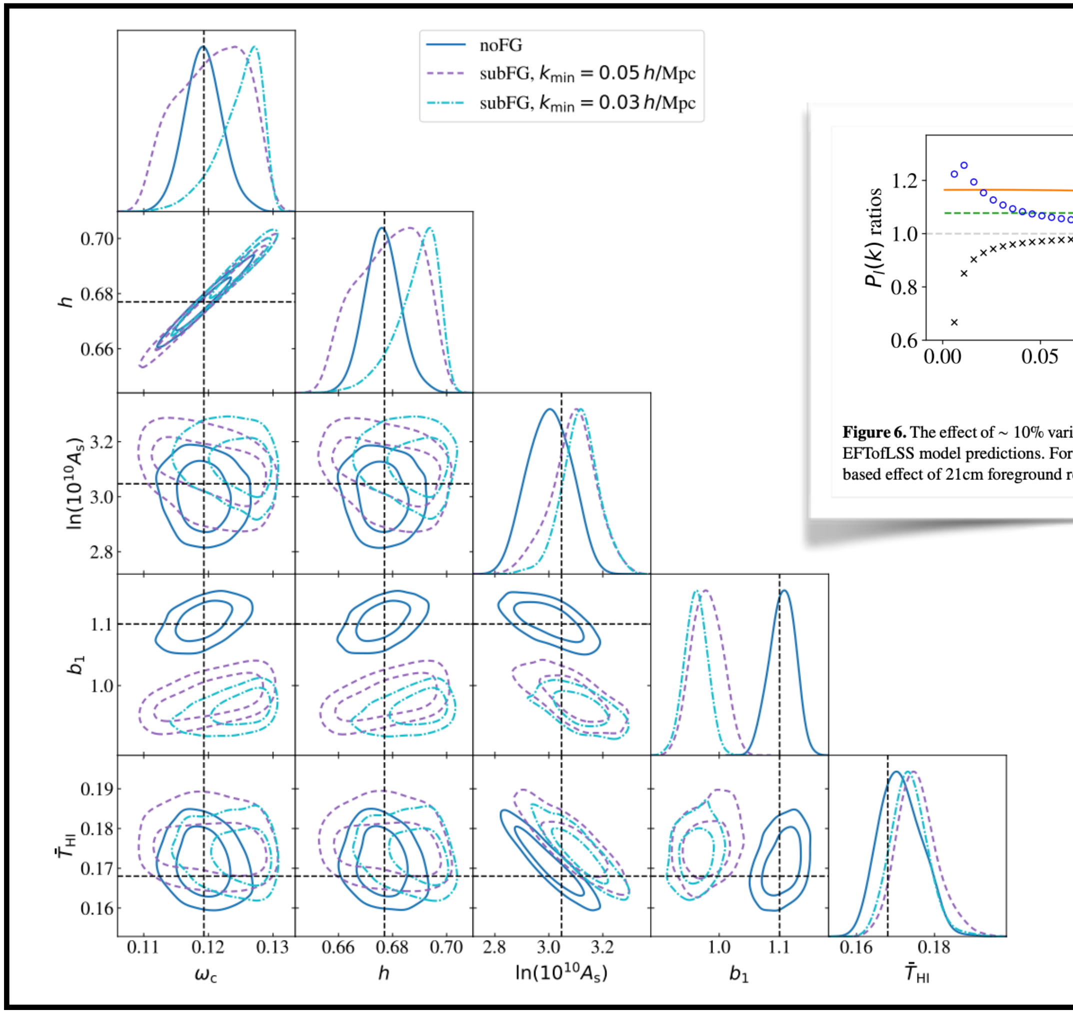


Soares, Cunnington, AP, Blake 2020

Also see work by Alonso et al., Chapman et al., Shaw et al., Wolz et al.

EFTofLSS for Intensity Mapping continued …

- Including foreground removal effects



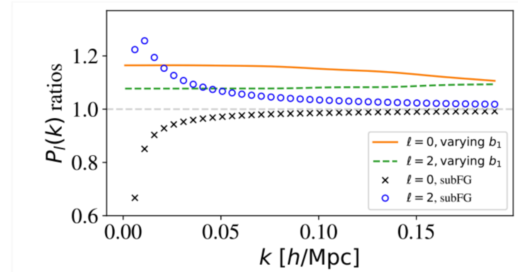


Figure 6. The effect of ~ 10% variations of the 4 parameters of interest on the EFTofLSS model predictions. For comparison, we also plot the simulations-based effect of 21cm foreground removal.

AP 2023

WHAT WE REALLY NEED: END-TO-END SIMULATIONS

SKAO HI Intensity Mapping: Blind Foreground Subtraction Challenge

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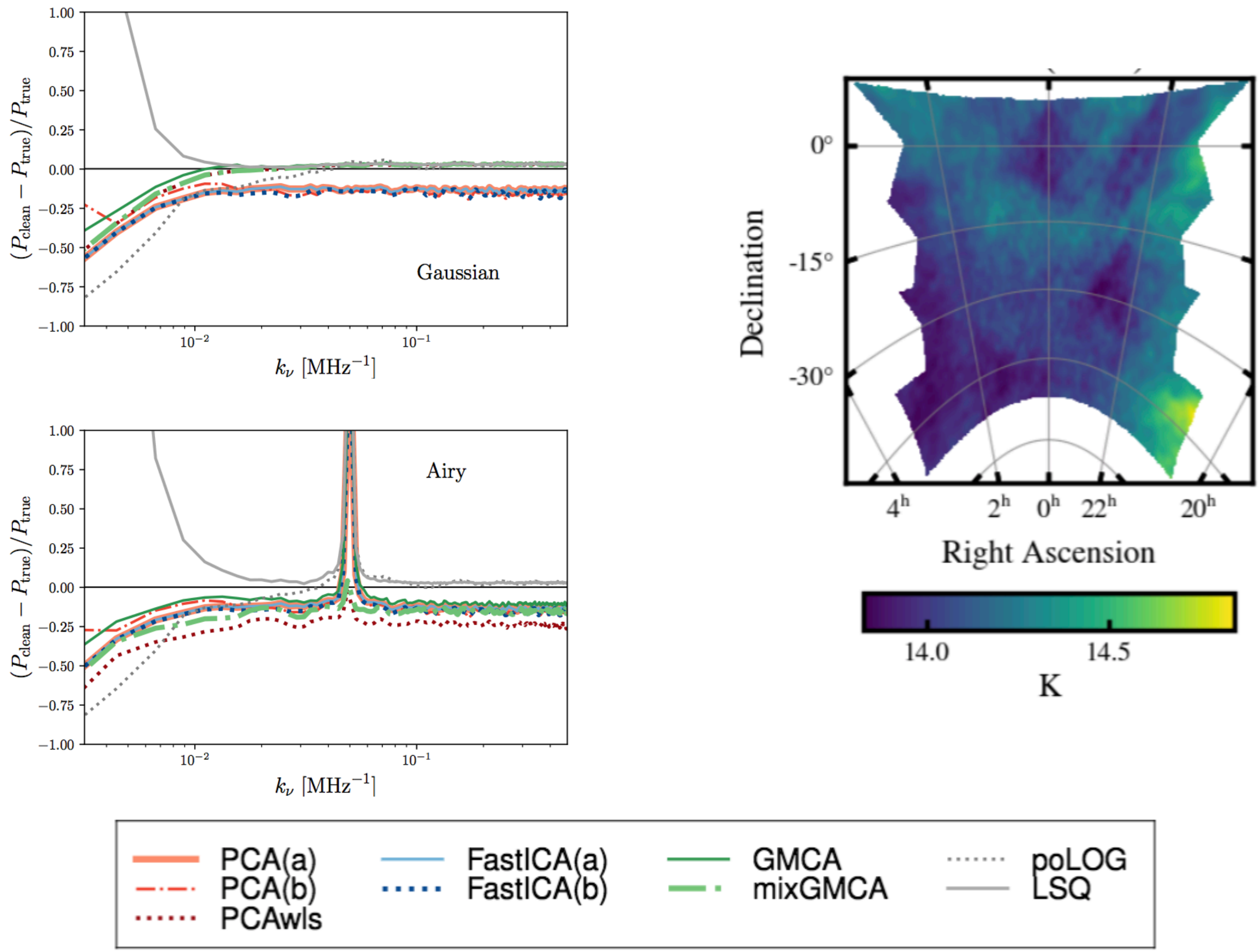


INTENSITY MAPPING: CURRENTLY OPERATING TELESCOPES

First detection in x-cross with optical

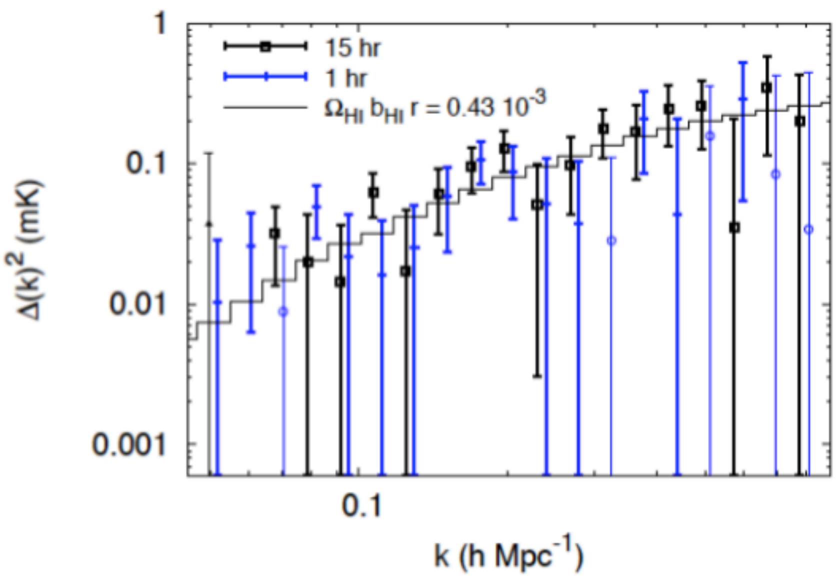
North, whole sky, 0.8<z<2.5

Survey at 0<z<1.4

THE IMPORTANCE OF CROSS-CORRELATIONS

- Systematic effects are a big challenge for 21cm intensity mapping
- GBT x WiggleZ 2013 showed that cross-correlating with optical can mitigate this! **Systematics drop out in cross-correlation.**
- 2dF x Parkes 2018 detection, GBT x eBOSS detections last year
- MeerKAT x WiggleZ this year!

$$\langle \delta T_{\mathrm{HI}} \delta_{\mathrm{g}} \rangle$$



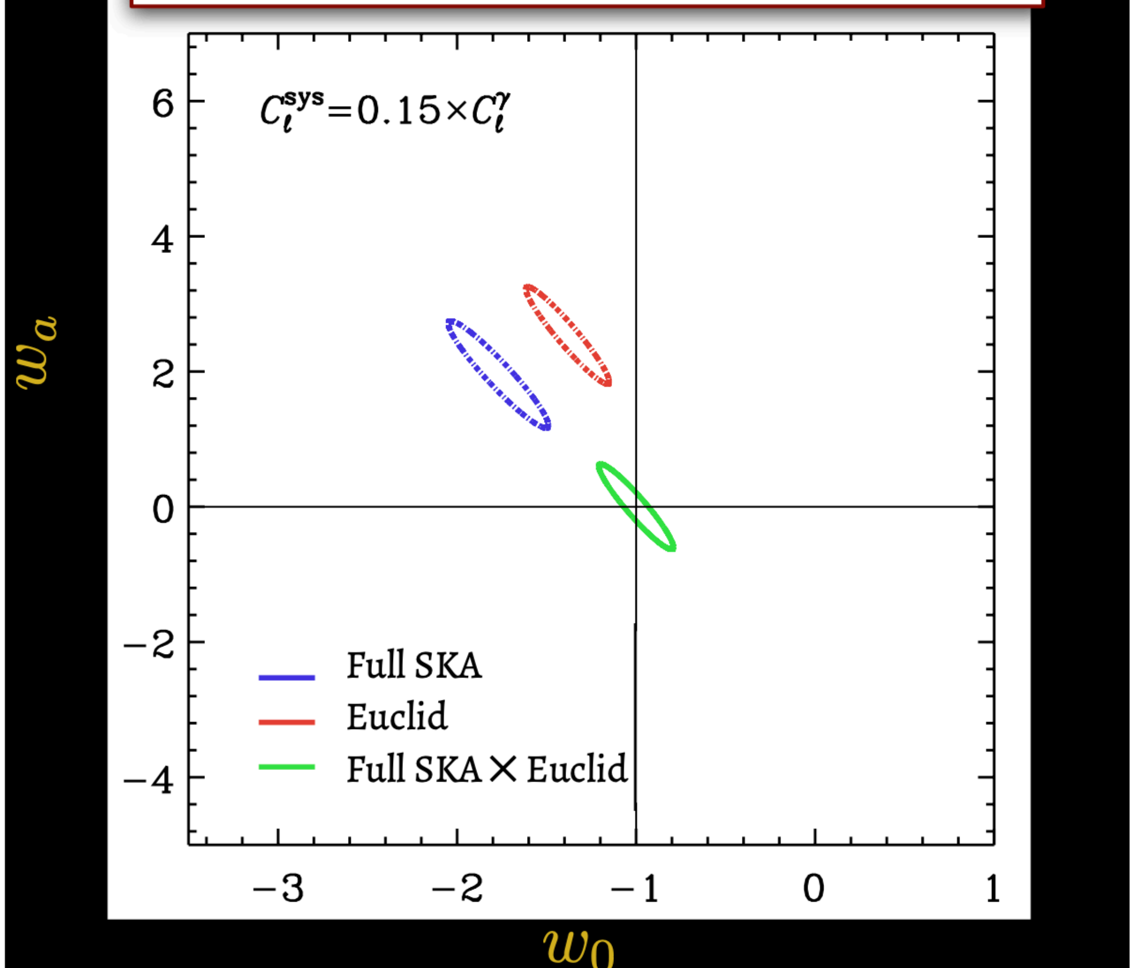
Masui, et al., ApJ 2012,
Chang et al., Nature 2010

$$\Omega_{\mathrm{HI}} b_{\mathrm{HI}} r = [0.43 \pm 0.07(stat.) \pm 0.04(sys.)] \times 10^{-3}$$

Less is more

Less systematics to worry about: **the cosmic shear case**

[Camera, Harrison, Bonaldi & Brown 2016]



CROSS-CORRELATION DATA ANALYSIS

HI constraints from the cross-correlation of eBOSS galaxies and Green Bank Telescope intensity maps

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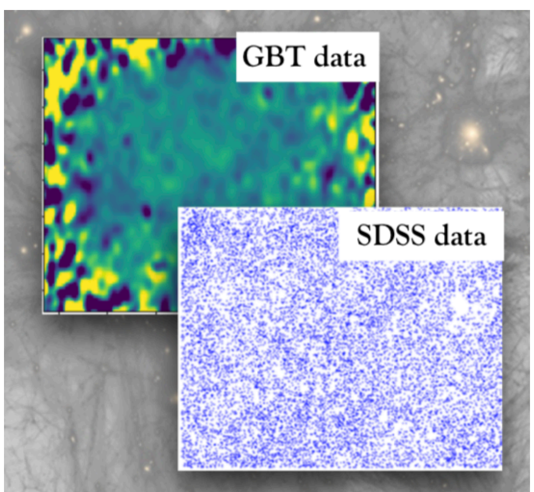
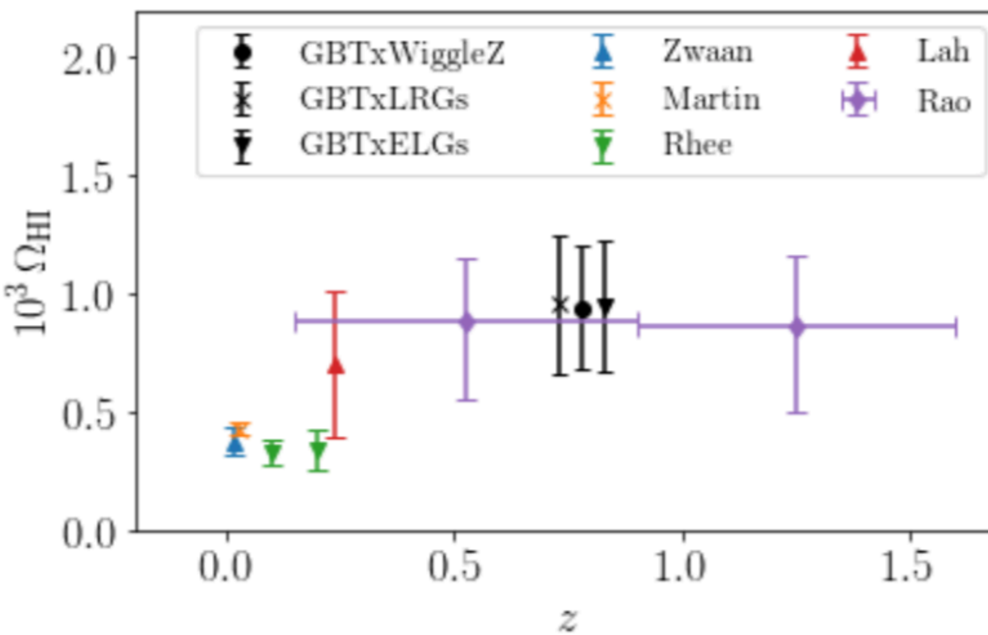
- **Green Bank Telescope intensity mapping data at $0.6<z<1$**
- **eBOSS ELGs and LRGs samples (and reanalysed the WiggleZ sample)**
- Area overlap: **100 square degrees**

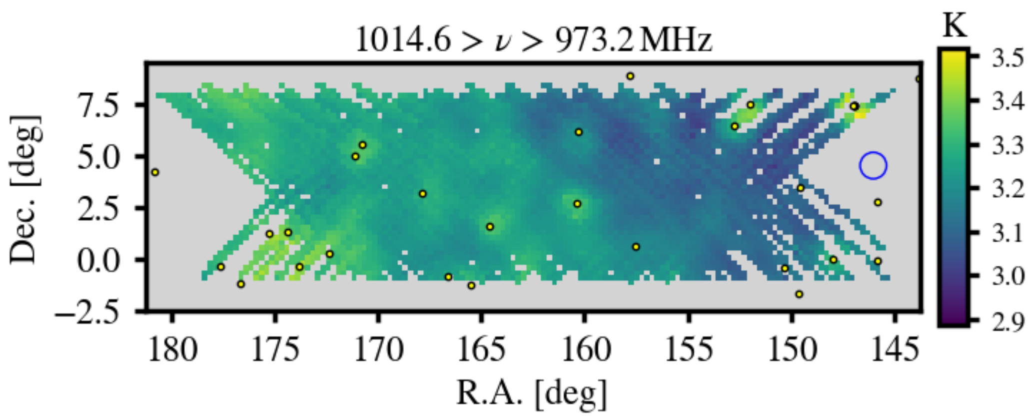


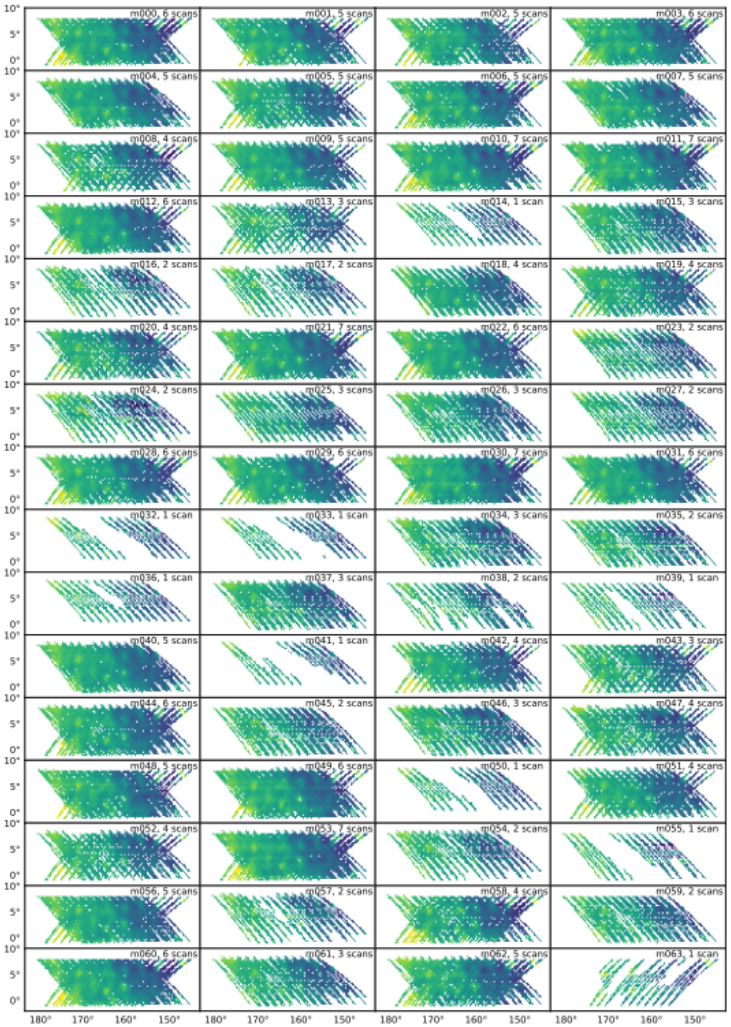


MEERKAT DATA ANALYSIS

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)



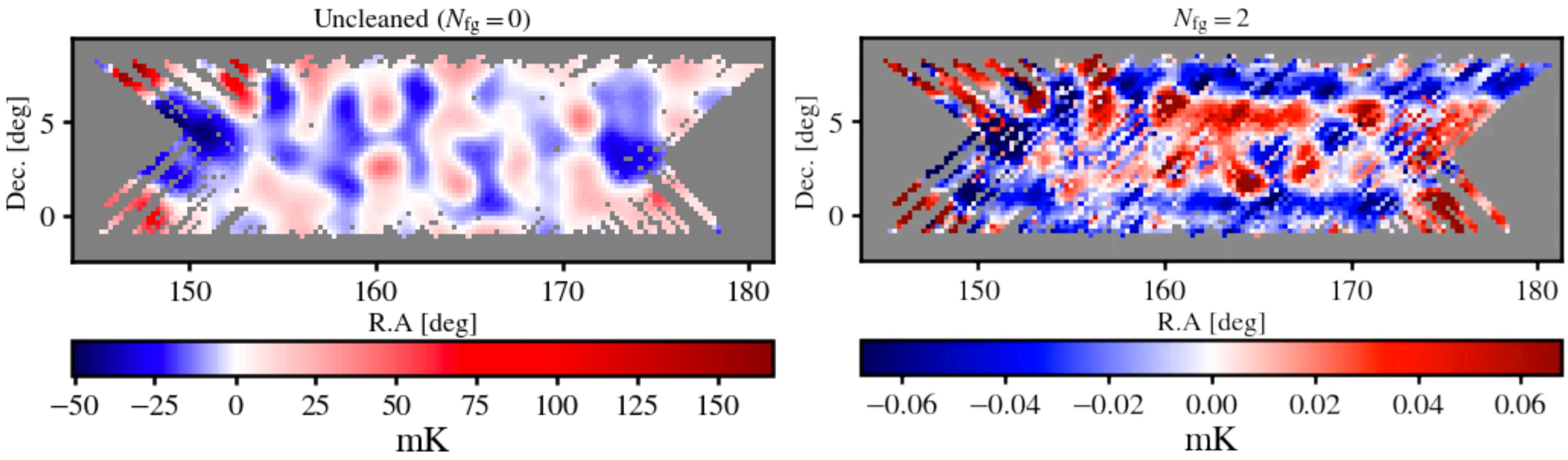


J.Wang et al. 2021

Huge problem: we lose a lot of data due to RFI

MeerKAT data analysis

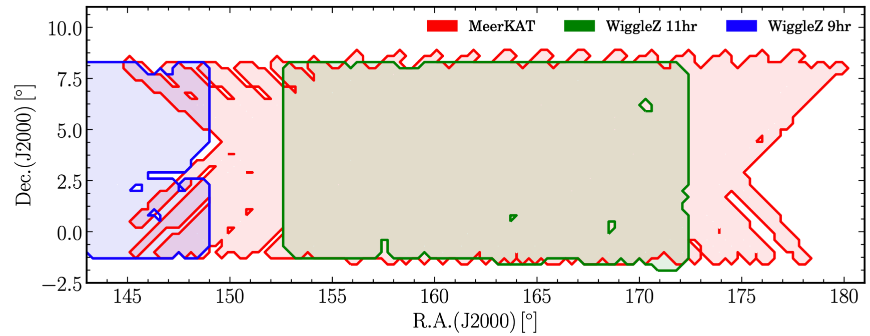
Principal Component Analysis foreground cleaning



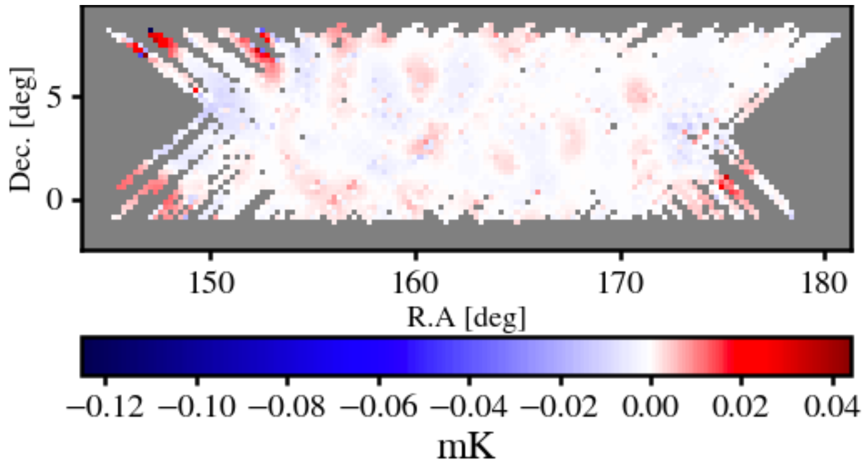
Slide from Steven Cunnington

MEERKAT X WIGGLEZ DATA ANALYSIS

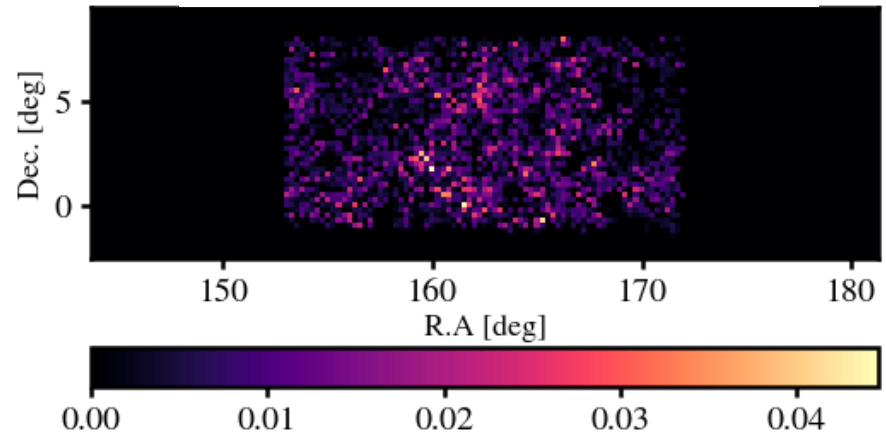
MeerKAT pilot observations on WiggleZ 11hr field



Final foreground cleaned MeerKAT HI intensity map

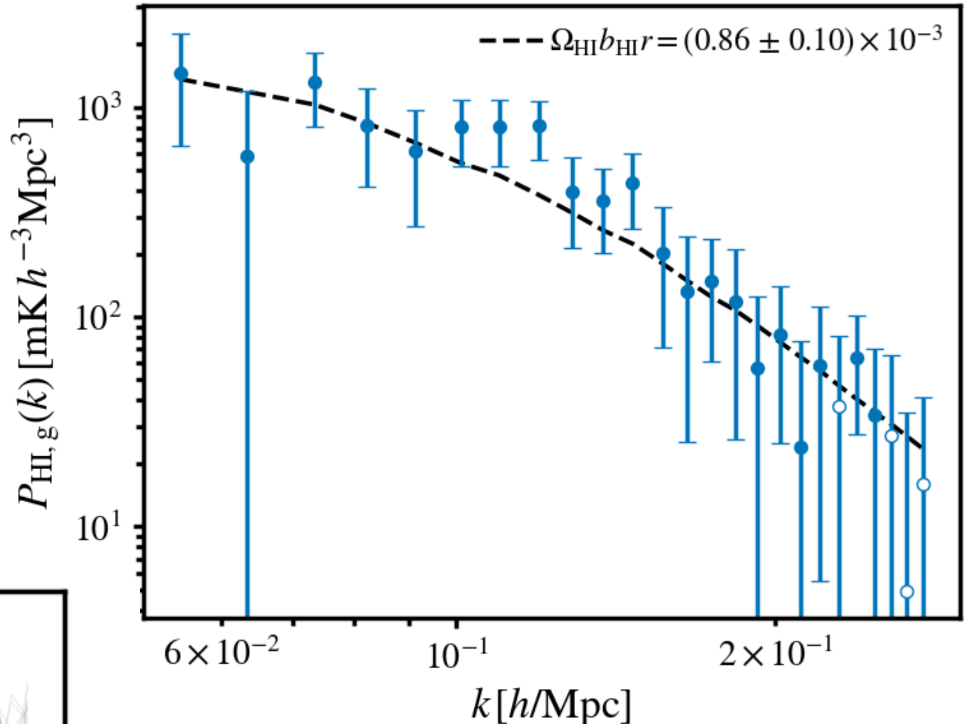


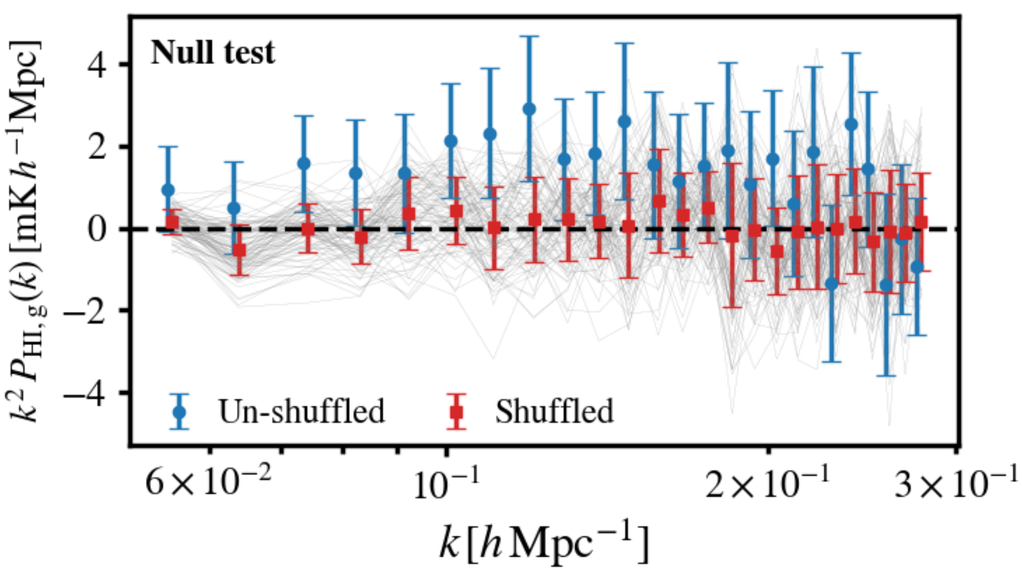
WiggleZ Dark Energy Survey galaxies



MEERKAT X WIGGLEZ DATA ANALYSIS

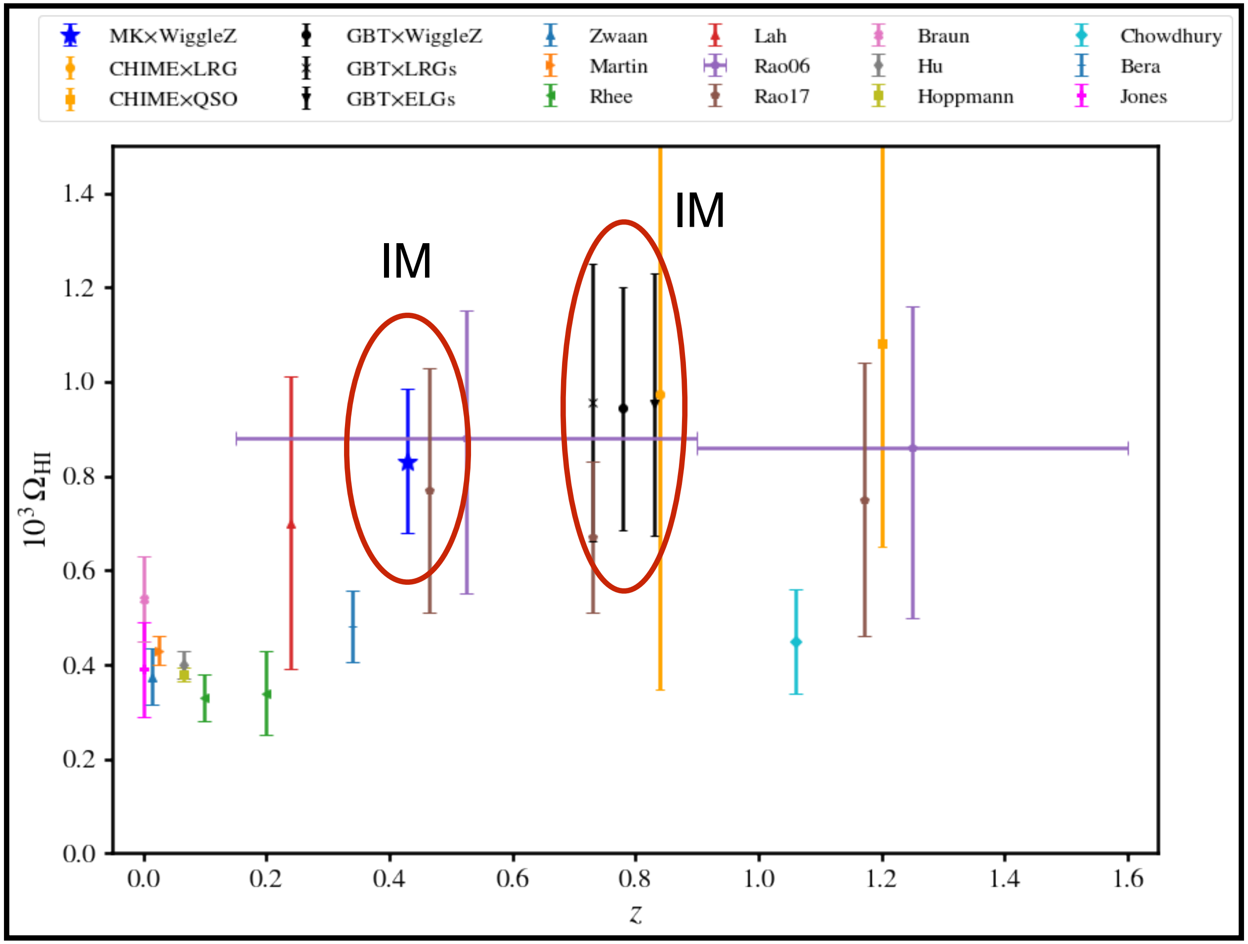
- Positive correlation (7.7σ) between galaxy survey and array of dishes in single-dish mode
- The first detection of its kind
- Important milestone for Cosmology with SKA intensity mapping





Cunnington,Li+22

MEERKAT X WIGGLEZ DATA ANALYSIS



Cunnington,Li+22

Thank you!