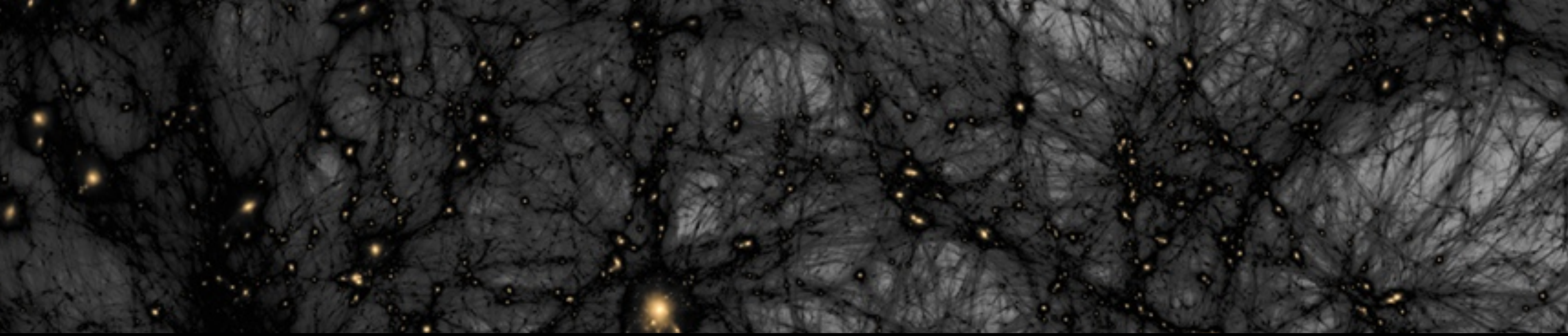


INSIGHTS FROM 21CM COSMOLOGY

Alkistis Pourtsidou

Queen Mary University of London

Science & Technology Facilities Council | UK Research and Innovation

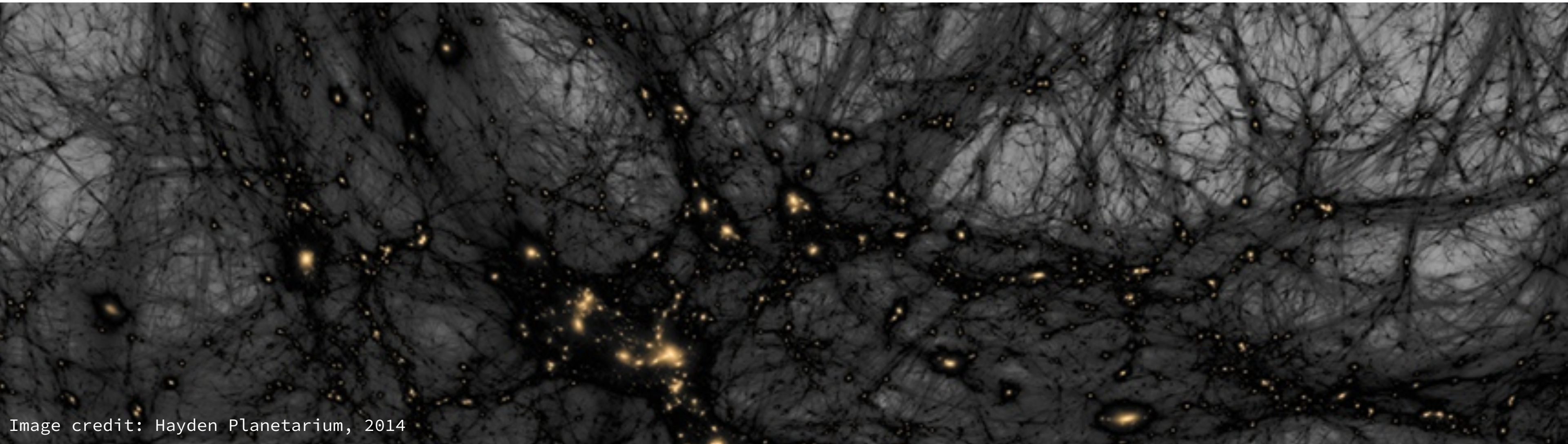


Image credit: Hayden Planetarium, 2014

GAPS IN THE COSMIC HISTORY

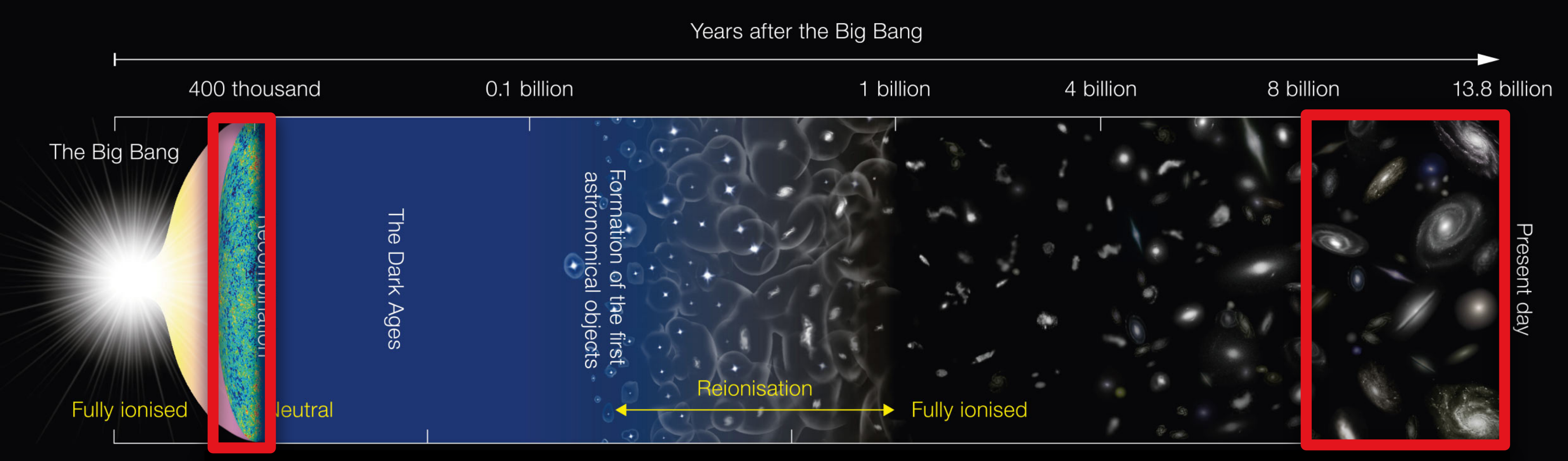
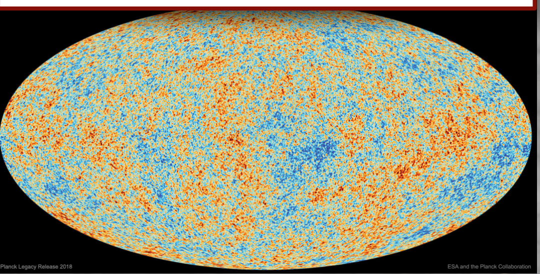


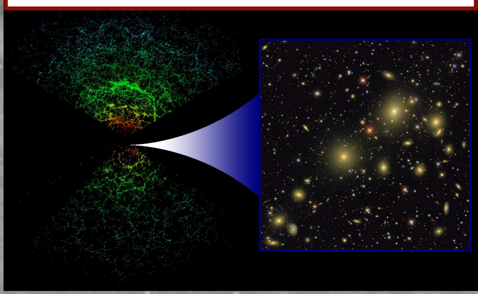
Image Credit: NAOJ

Planck satellite



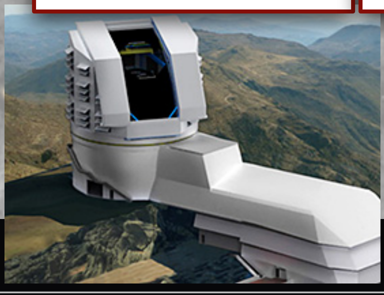
SDSS galaxy survey

SDSS: Sloan Digital Sky Survey

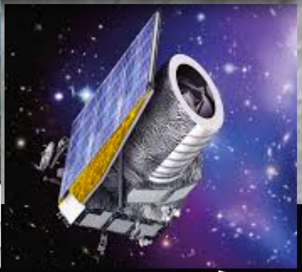


THE FUTURE

LSST



Euclid satellite



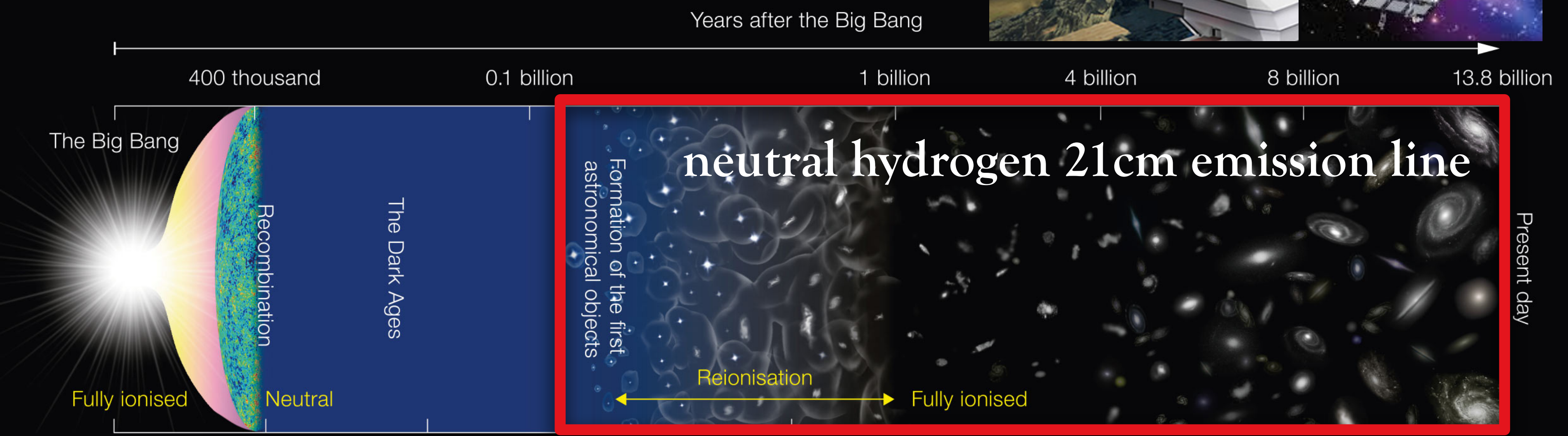
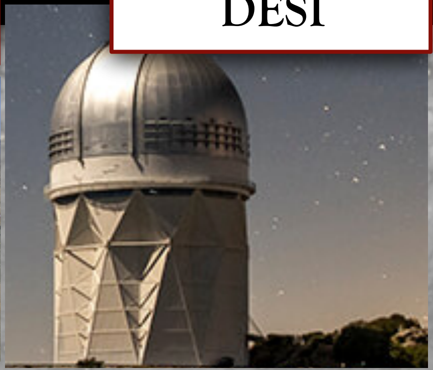


Image Credit: NAOJ

MeerKAT and the SKA

DESI



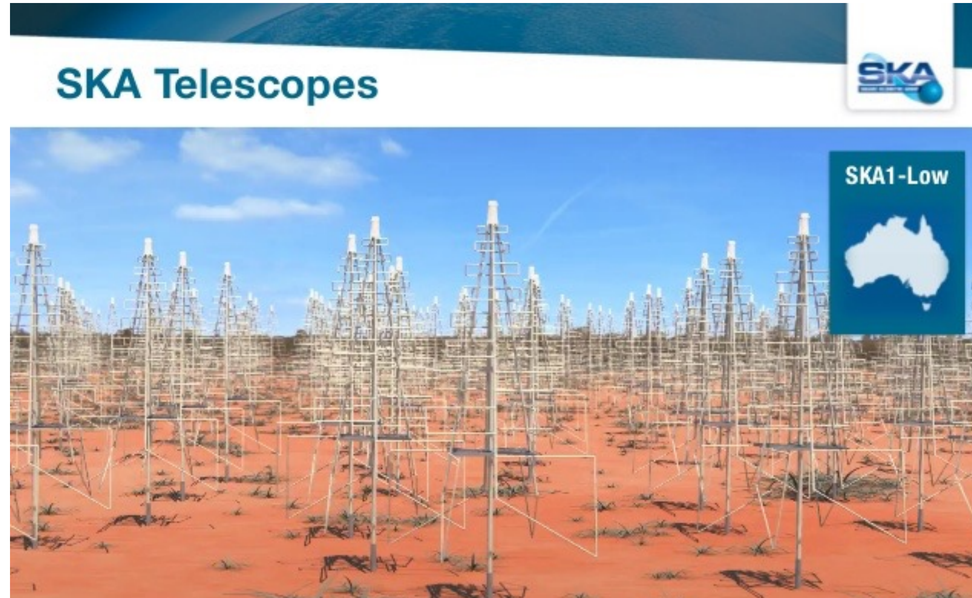
THE SQUARE KILOMETRE ARRAY (SKA)

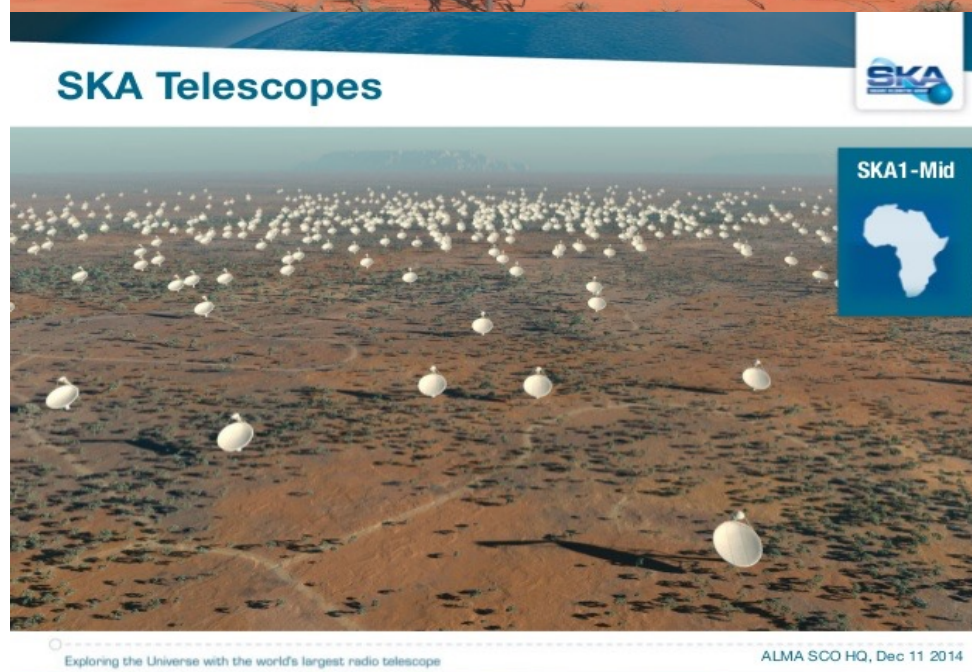
- Series of radio telescopes, very sensitive to a wide range of frequencies (redshifts)
- **SKA Phase 1**: 2028+
- **MeerKAT** live now!

MeerKAT

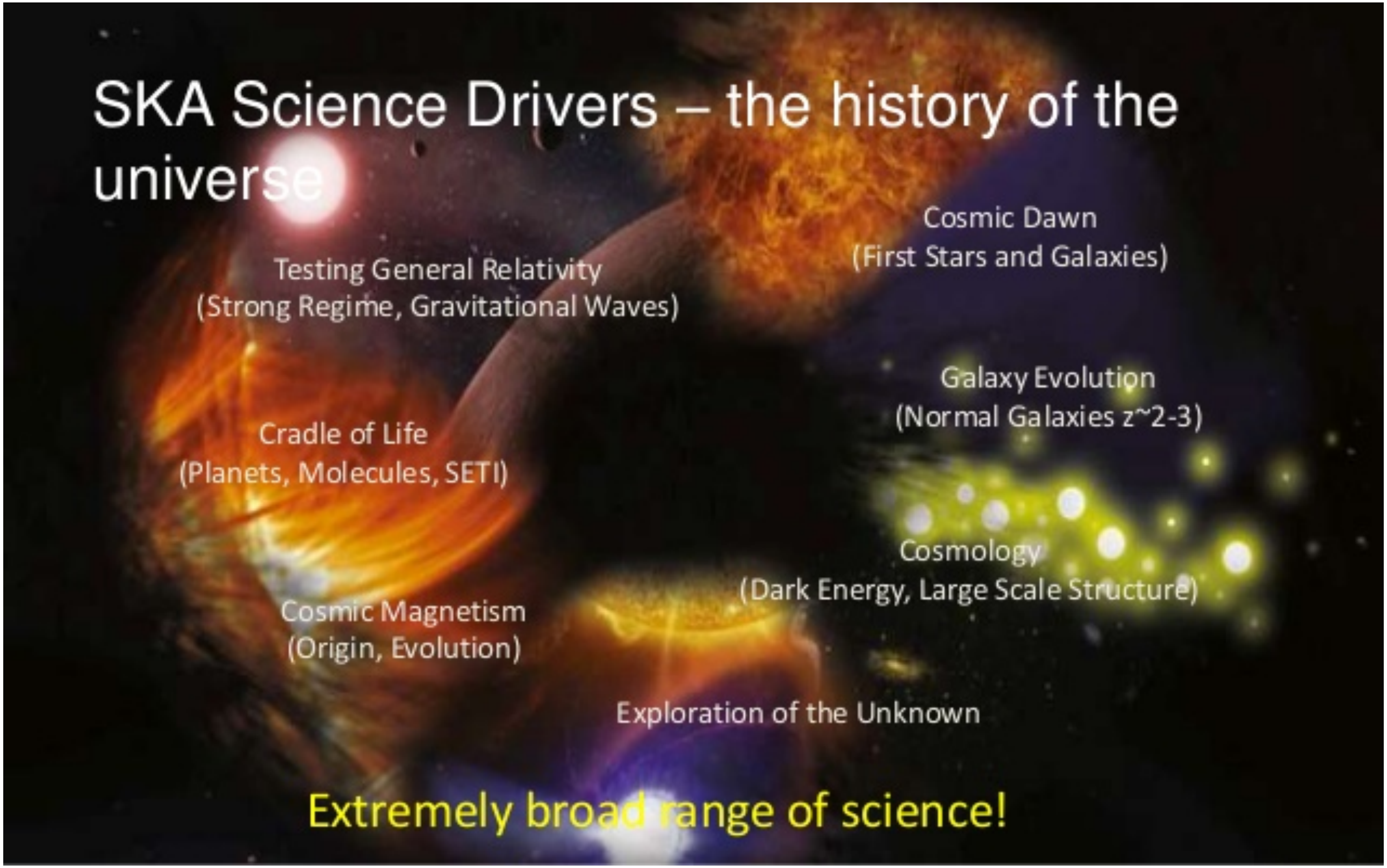
MeerKAT/SKA-Mid will complement and compete with optical galaxy surveys (0<z<3)

SKA-Low will explore the unknown (3<z<25) based on lessons from LOFAR, MWA, HERA...

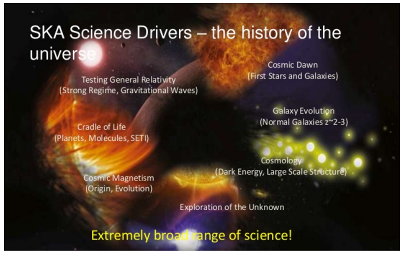




SKA SCIENCE



SKA Office / A. Bonaldi



Publications of the Astronomical Society of Australia (PASA)
doi: 10.1017/pas.2018.xxx.

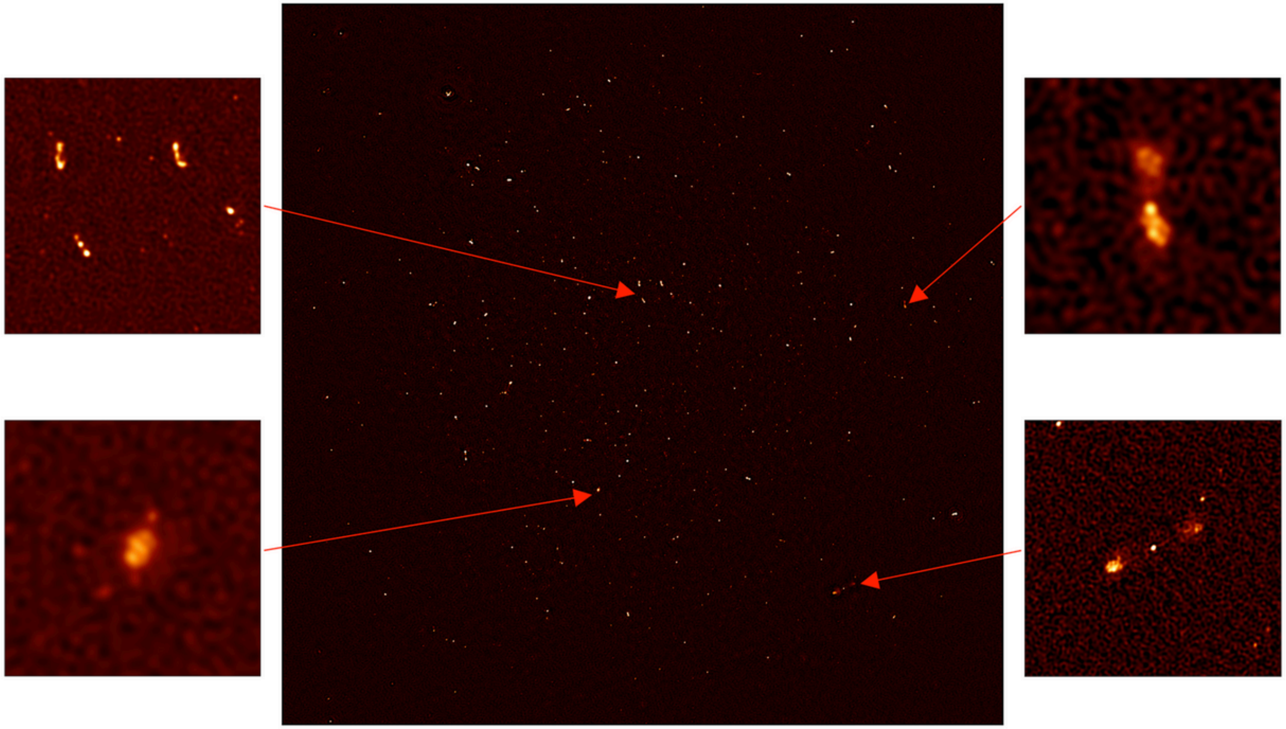
Cosmology with Phase 1 of the Square Kilometre Array

Red Book 2018: Technical specifications and performance forecasts

Square Kilometre Array Cosmology Science Working Group: David J. Bacon[1], Richard A. Battye[2,*], Philip Bull[3], Stefano Camera[4,5,6,2], Pedro G. Ferreira[7], Ian Harrison[2,7], David Parkinson[8], Alkistis Pourtsidou[3], Mário G. Santos[9,10,11], Laura Wolz[12,*], Filipe Abdalla[13,14], Yashar Akrami[15,16], David Alonso[7], Sambatra Andrianomena[9,10,17], Mario Ballardini[9,18], José Luis Bernal[19,20], Daniele Bertacca[21,36], Carlos A.P. Bengaly[9], Anna Bonaldi[22], Camille Bonvin[23], Michael L. Brown[2], Emma Chapman[24], Song Chen[9], Xuelei Chen[25], Steven Cunnington[1], Tamara M. Davis[27], Clive Dickinson[2], José Fonseca[9,36], Keith Grainge[2], Stuart Harper[2], Matt J. Jarvis[7,9], Roy Maartens[1,9], Natasha Maddox[28], Hamsa Padmanabhan[29], Jonathan R. Pritchard[24], Alvise Raccanelli[19], Marzia Rivi[13,18], Sambit Roychowdhury[2], Martin Sahlén[30], Dominik J. Schwarz[31], Thilo M. Siewert[31], Matteo Viel[32], Francisco Villaescusa-Navarro[33], Yidong Xu[25], Daisuke Yamauchi[34], Joe Zuntz[35]
Affiliations listed after references

MEERKAT 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

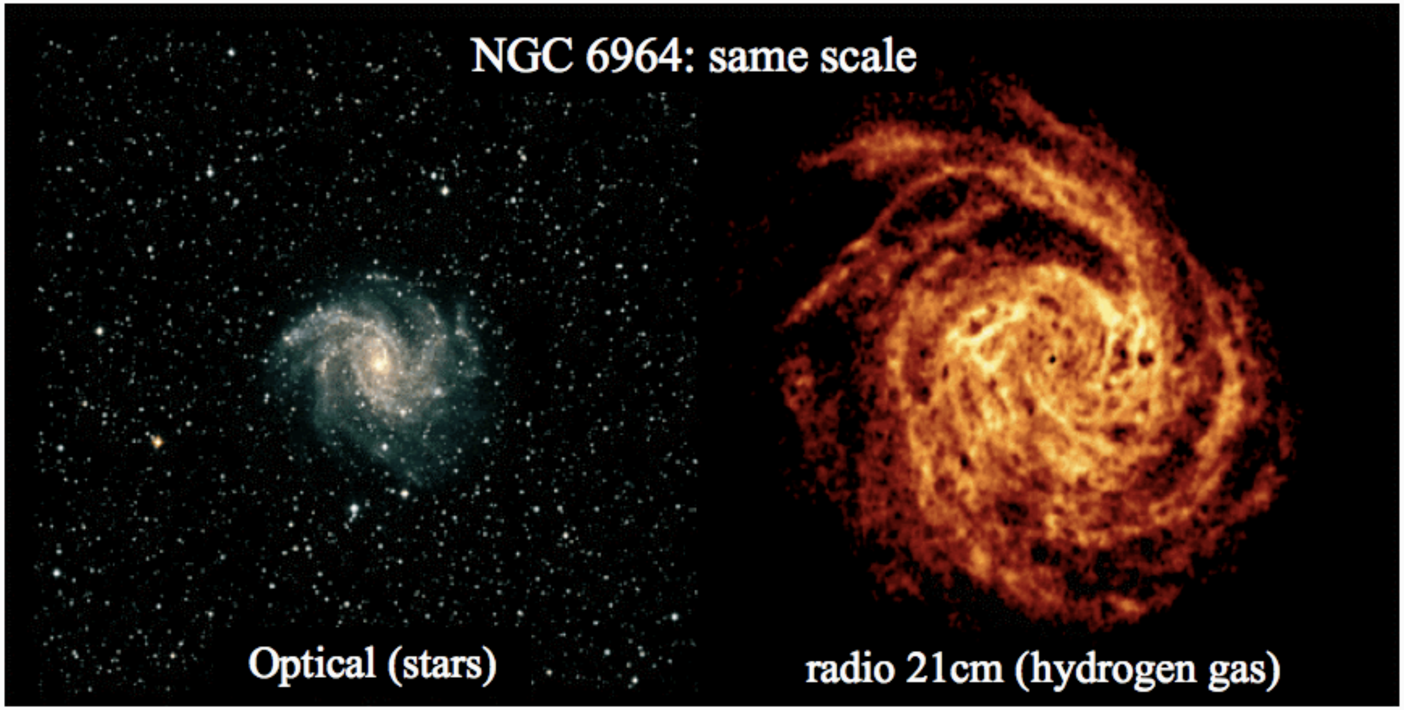


▲ A montage of the MeerKat radio telescope's First Light image with four zoomed-in insets – the two panels to the right show distant galaxies with massive black holes at their centres; at lower left is a galaxy approximately 200m light years away where hydrogen gas is being used up to form stars in large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

From The Guardian, 17 July 2016

RADIO VS OPTICAL: GALAXIES

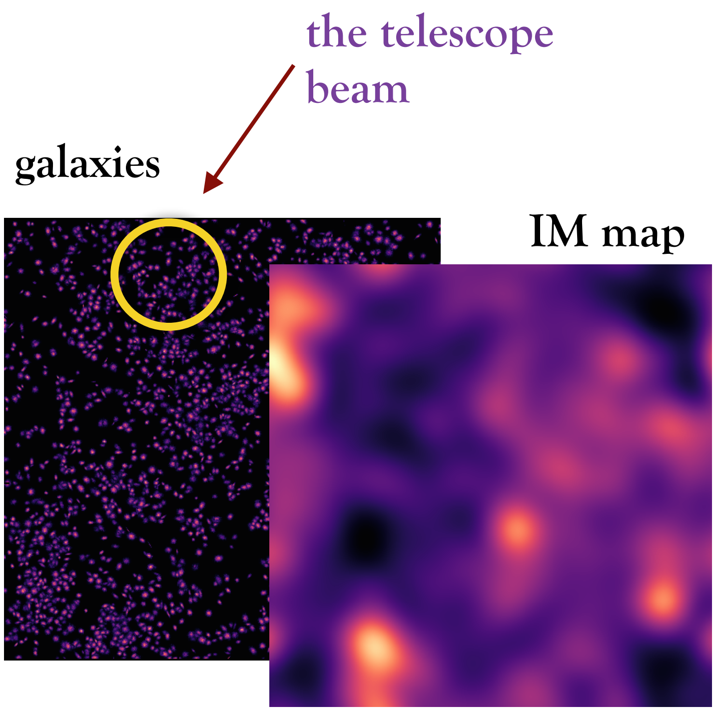
- HI in galaxies more extended than the stellar light distribution
- HI disk much larger than the stellar disk
- HI velocity fields can be used to calculate rotation curves and trace the total mass distribution to very large radii



https://www.skatelescope.org/galaxyevolution/

RADIO PRECISION COSMOLOGY: THE INTENSITY MAPPING METHOD

[Battye et al 2004, Chang et al 2008, Peterson et al 2009, Seo et al 2010, …]



[Simulations by S. Cunnington]

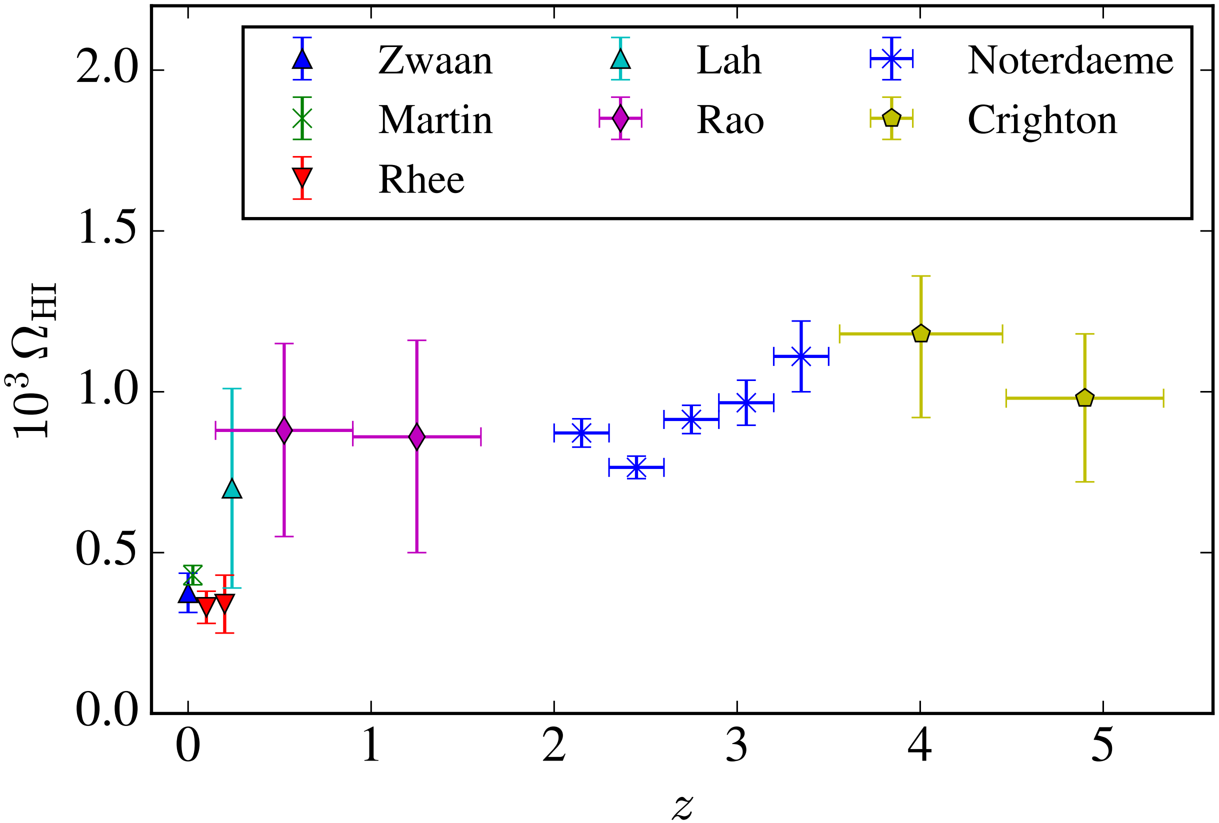
- Detecting HI (neutral hydrogen) galaxies via their 21cm emission line is very expensive
- But cosmological information is on large scales
- Get intensity map of the HI 21cm emission line - like CMB but 3D!
- Excellent redshift resolution
- Signal of the order 0.1 mK – foregrounds much bigger
- Foregrounds can be cleaned with methods similar to the ones used in CMB analysis

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

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

INTENSITY MAPPING AND GALAXY EVOLUTION

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



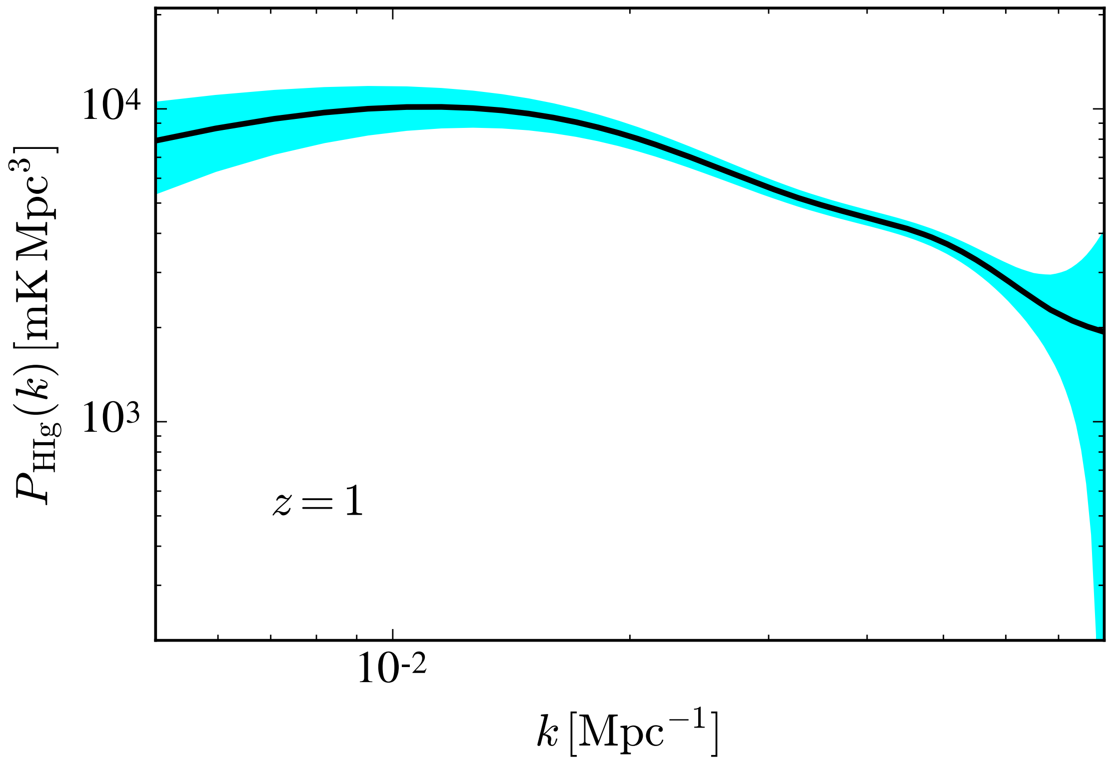
[c.f. Crighton et al 2015]

HI AUTO AND CROSS POWER SPECTRUM

- With 21cm intensity mapping we can constrain the HI abundance and bias using the power spectrum

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

[e.g. SKA1-MID x Euclid]

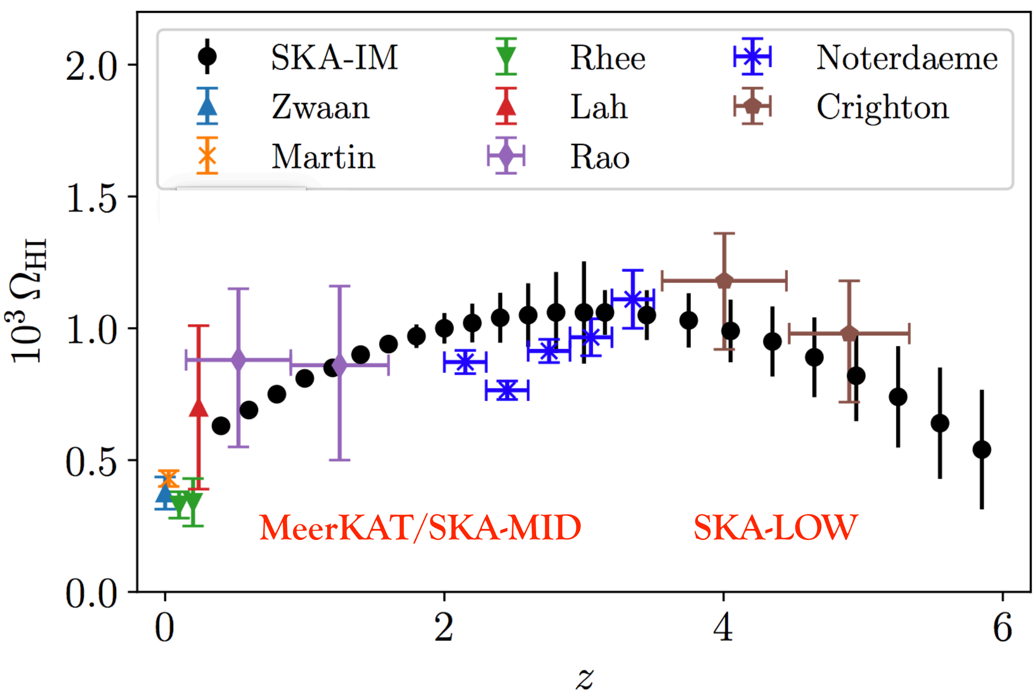


GALAXY EVOLUTION

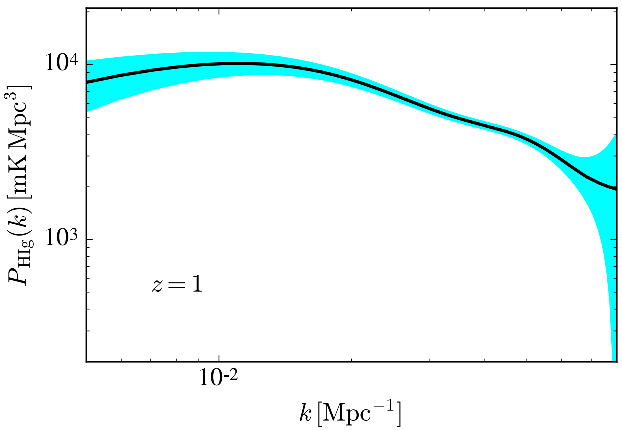
- Can greatly improve HI constraints with intensity mapping
- Cross-correlation with optical surveys helps with systematics and allows for studying the HI content of different galaxy samples

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

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



[SKA cosmology Red Book 2018]

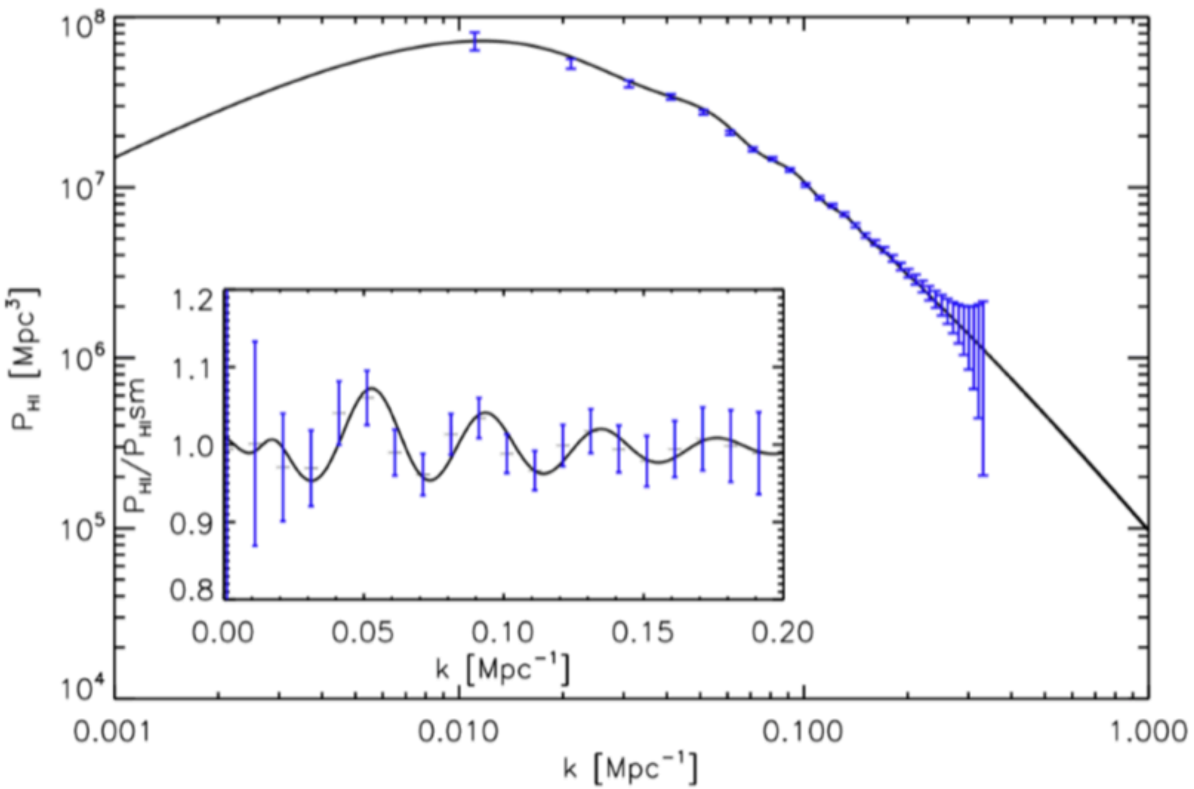


- **Also precision cosmology:** BAO, RSDs, primordial non-gaussianity, neutrino mass, multiple tracers, lensing…[see SKA Cosmology Red Book 2018 and references therein]

MEASURING THE BAO SCALE

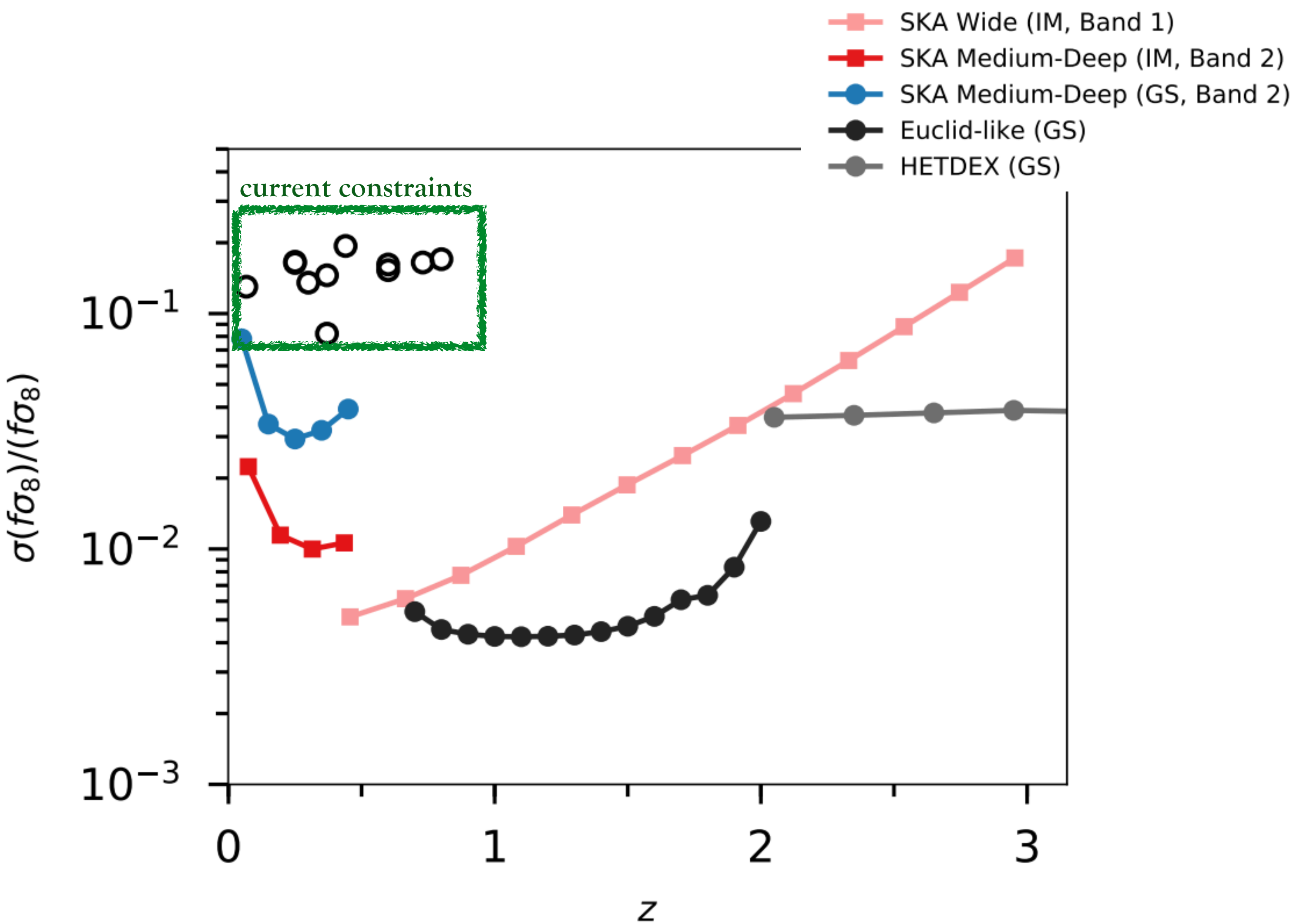
- A "single-dish" experiment can measure the BAO scale competitively to state-of-the art optical galaxy surveys
- Forecasts are great but assume foregrounds and systematics are under exquisite control - we need to work with pathfinder data and realistic simulations

[Battye, AP et al. 2013]



[also see e.g. Bull et al. 2015, Villaescusa-Navarro et al. 2016, Olivari et al. 2017]

MEASURING THE GROWTH OF STRUCTURE



[SKA cosmology Red Book 2018]

FORECASTS VS REALITY

Difficulties

Slide by Steve Cunnington

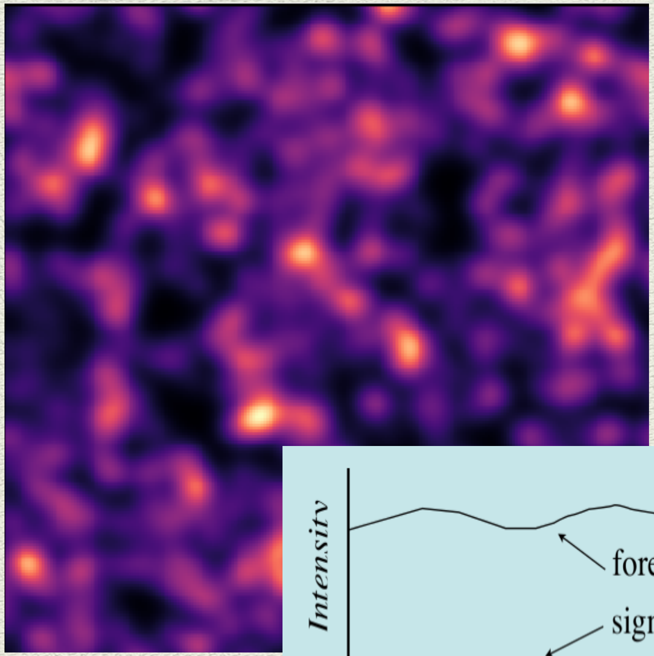
- 21cm signal is very weak
- Foregrounds are a big problem!

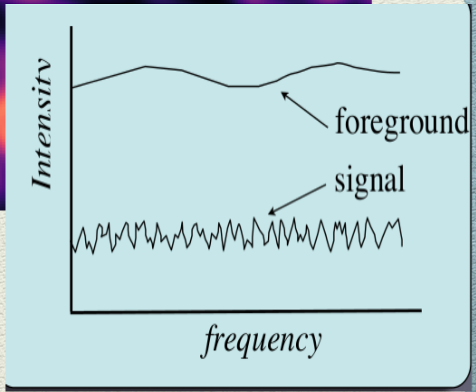
(i) Galactic synchrotron - relativistic cosmic ray electrons accelerated by the galactic magnetic field

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

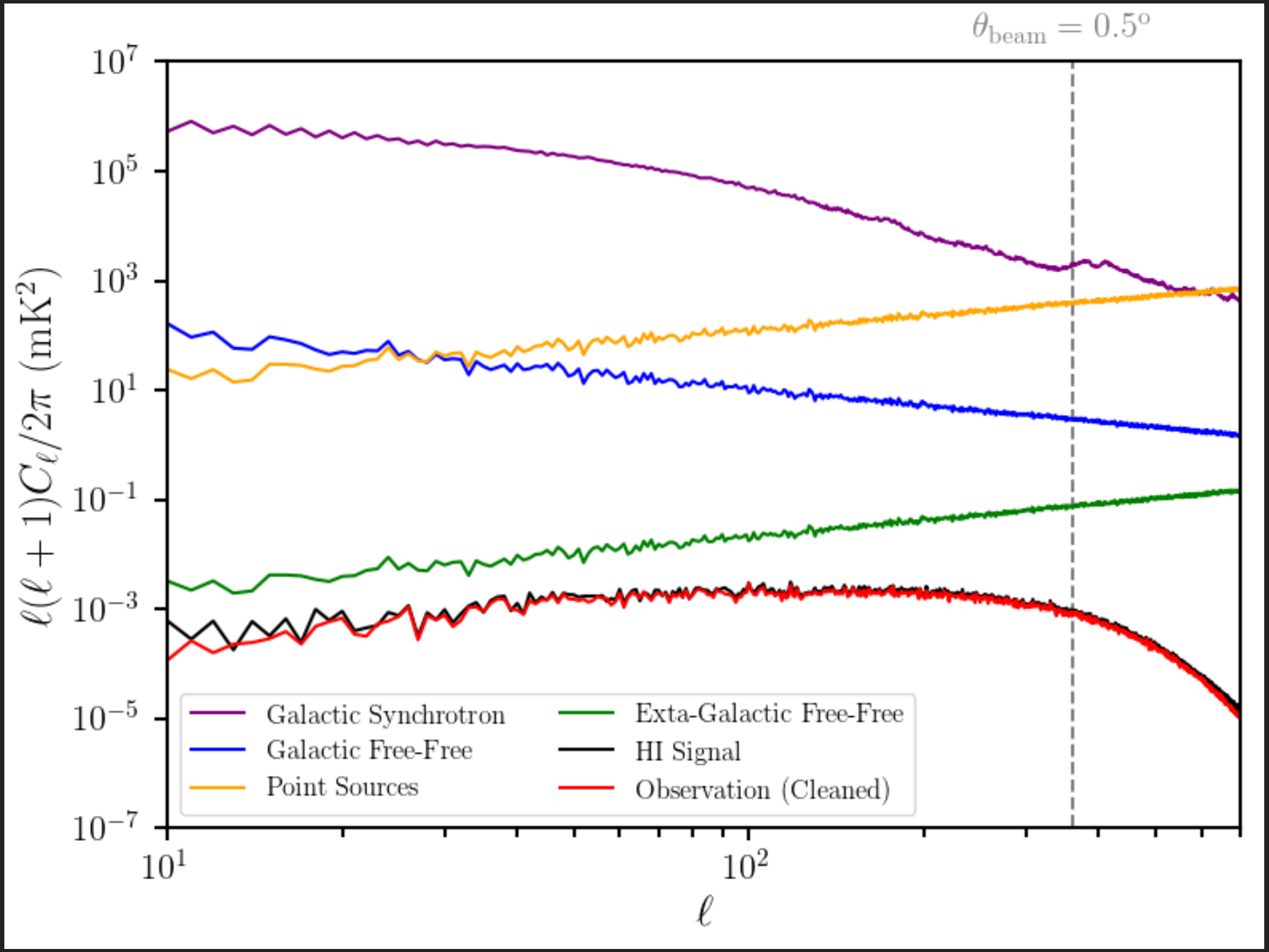
(iii) Extra-galactic free-free emission - free electrons scattering off ions without being captured and remaining free after the interaction

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





Cunnington, Wolz, AP, Bacon 2018



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

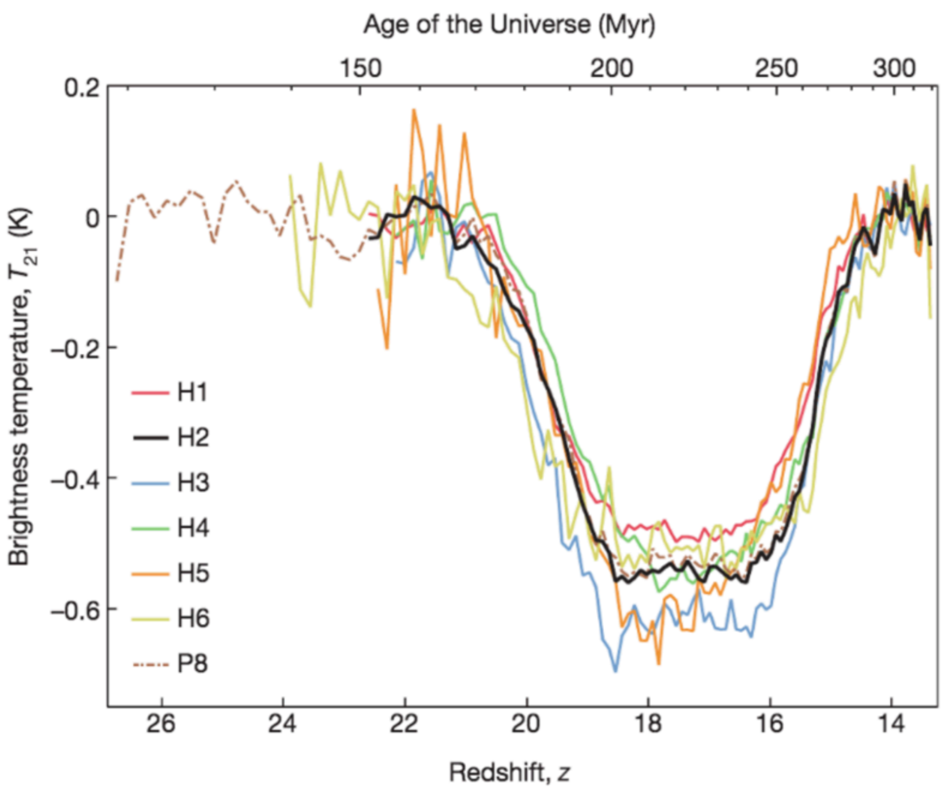
INTENSITY MAPPING: CURRENTLY OPERATING TELESCOPES

First detection in x-cross with optical

North, whole sky, 0.8<z<2.5

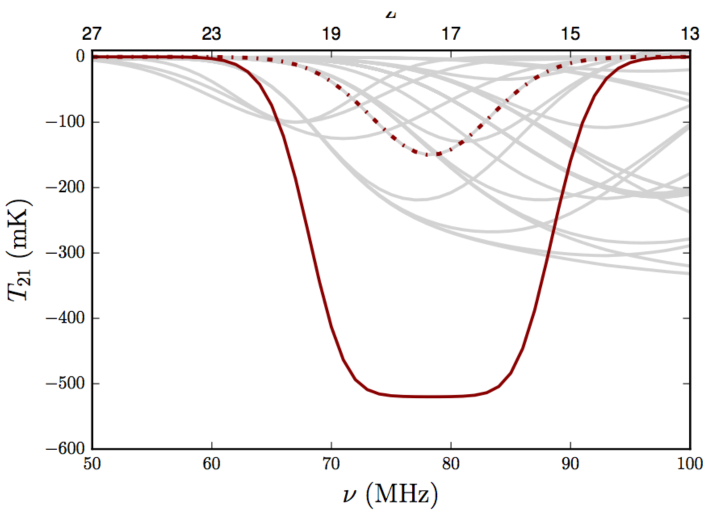
Survey at 0<z<0.6

THE EDGES DETECTION



From EDGES Nature Paper: (Bowman et al. 2018)

Differences in amplitude & shape



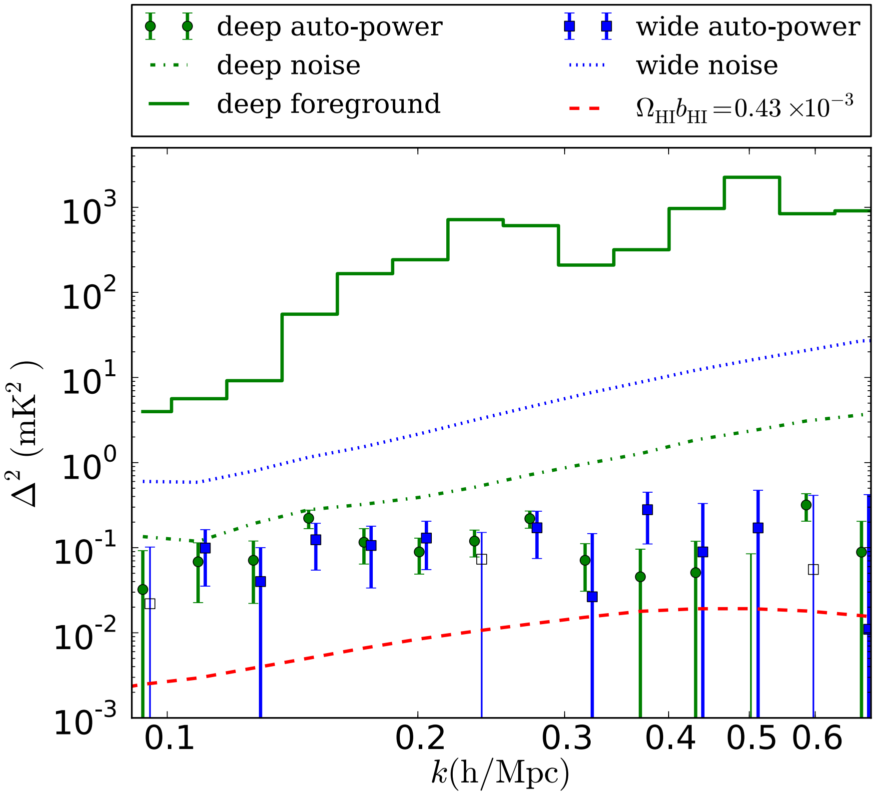
[Spinelli et al. 2019]

THE AFTERMATH...

[Adapted slide from S. Cunnington]

THE GBT AUTO POWER SPECTRUM

- 200-hr HI survey of the WiggleZ fields at 0.6 < z < 1



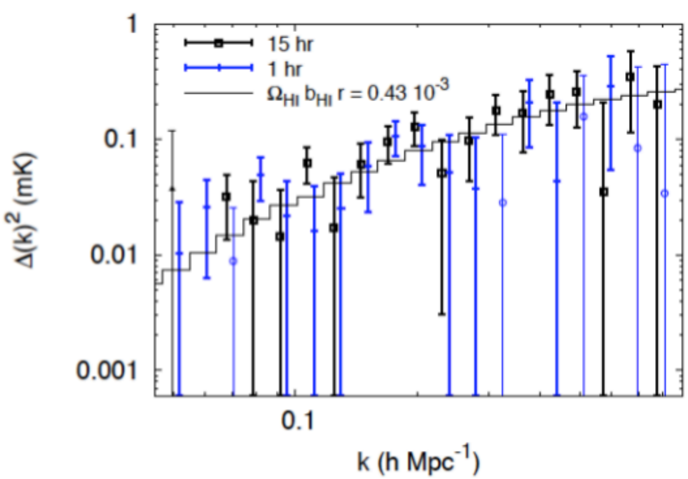
[see Switzer et al 2013, Wolz et al 2017]

GBT X EBOSS DATA ANALYSIS (SDSS-IV PROJECT)

In progress with Wolz, Bautista, Cunnington, Avila, Berger, Chang, Liao, Masui, Mueller, et al.

- GBT updated intensity mapping data at 0.6<z<1
- eBOSS ELGs and LRGs samples (and WiggleZ)
- Area overlap: **100 square degrees**

The project builds upon the first pioneering detection: **GBT x WiggleZ** [Masui et al. 2013]



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

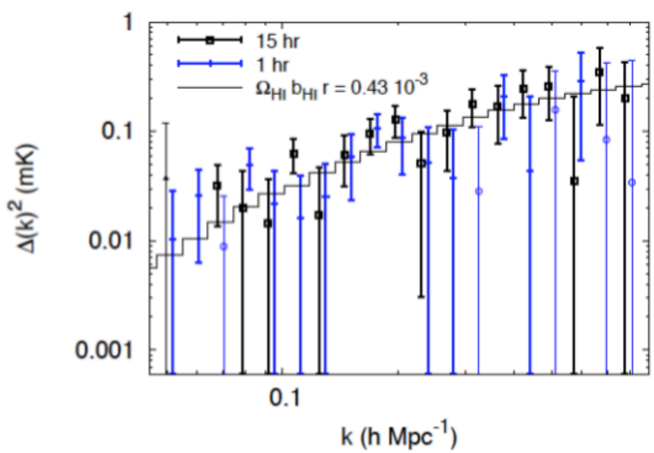
$$\Omega_{\rm HI} b_{\rm HI} r = [0.43 \pm 0.07(stat.) \pm 0.04(sys.)] \times 10^{-3}$$

GBT X EBOSS DATA ANALYSIS (SDSS-IV PROJECT)

In progress with Wolz, Bautista, Cunnington, Avila, Berger, Chang, Liao, Masui, Mueller, et al.

- GBT updated intensity mapping data at $0.6<z<1$
- **eBOSS ELGs and LRGs samples (and WiggleZ)**
- Area overlap: **100 square degrees**

- **Goal:** estimate the HI content of eBOSS ELGs and LRGs via cross-correlation with GBT HI intensity maps
- **Goal:** constrain HI density and HI bias at z=0.8
- **Goal:** compare different foreground removal methods
- **Goal:** understand systematics better



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

STAY TUNED…

- We will present results for 3 different galaxy samples cross-correlated with GBT: **WiggleZ, eBOSS LRGs, and eBOSS ELGs**
- We are working hard on cross-correlation simulations
- We have **200 square degrees MeerKAT data overlapping with WiggleZ**. At the moment busy with calibration **[led by Mario Santos and the South African UWC MeerKAT team]**
- **Future:** a large sky survey with MeerKAT