Early Universe Physics from 21cm surveys

Jonathan Pritchard

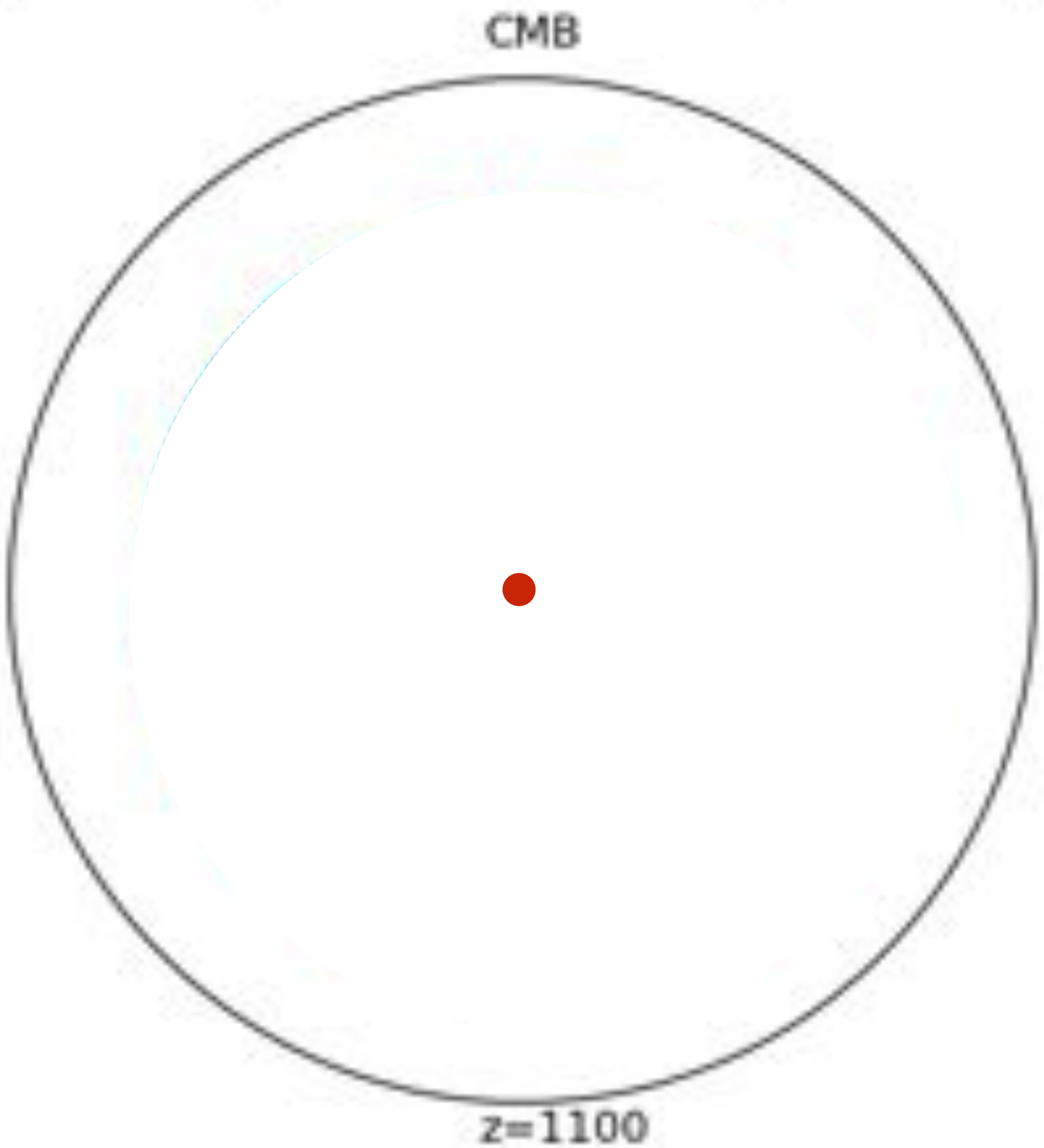
Imperial College London

SEVENTH FRAMEWORK PROGRAMME

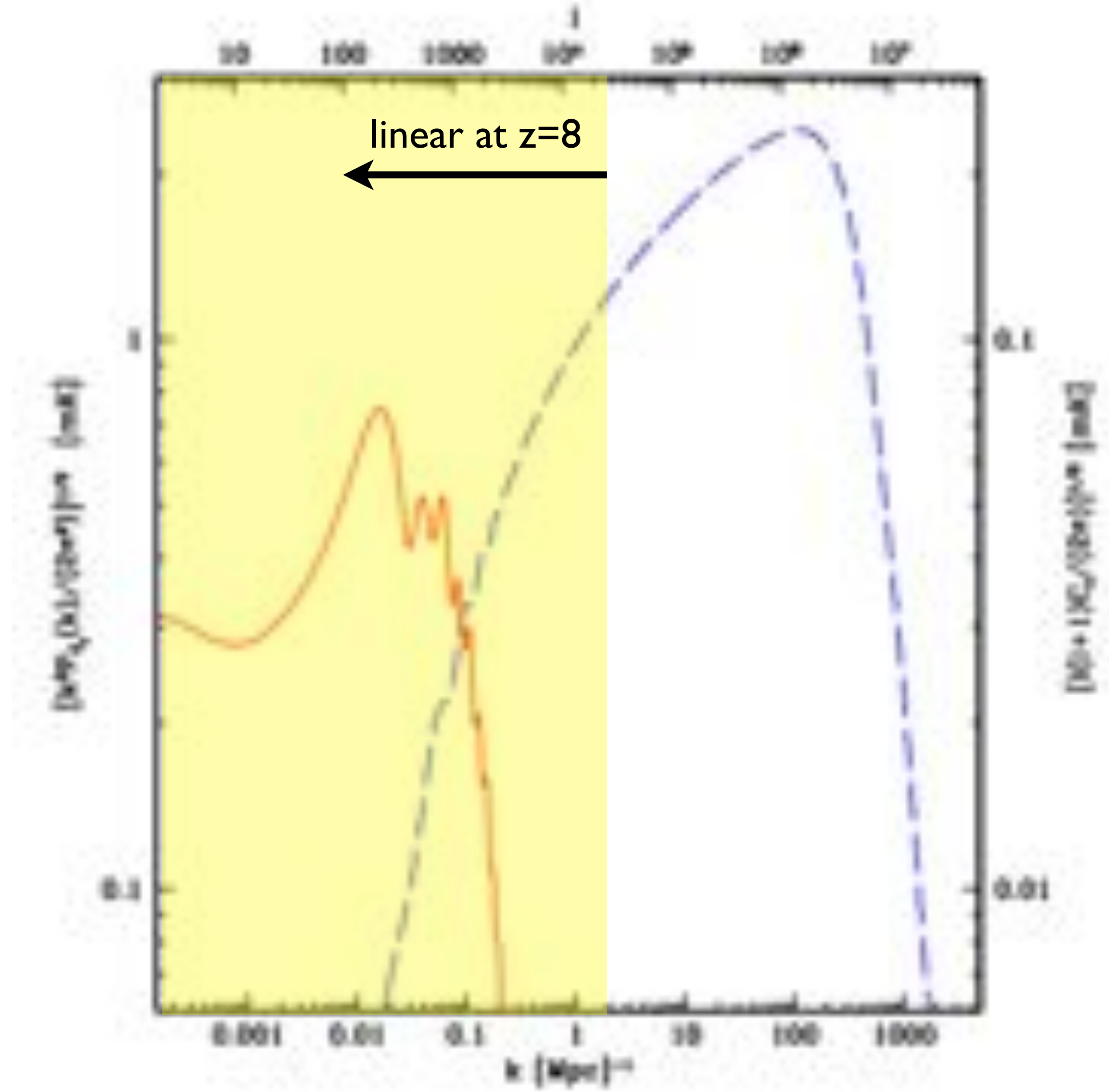
Science & Technology Facilities Council

Advantages of 21cm for cosmology

Map out more of the Universe



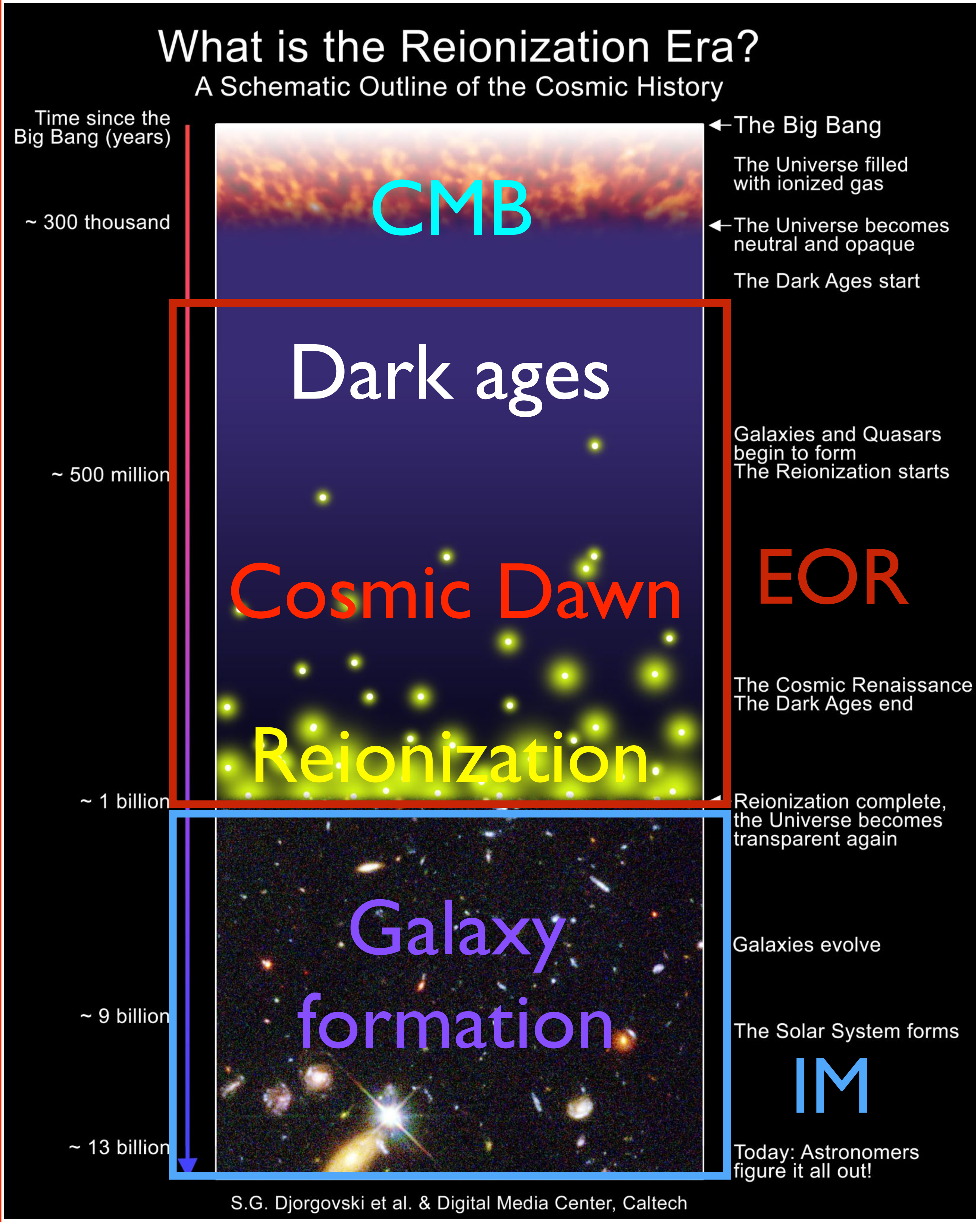
New volume



New scales

Kleban+ 2007

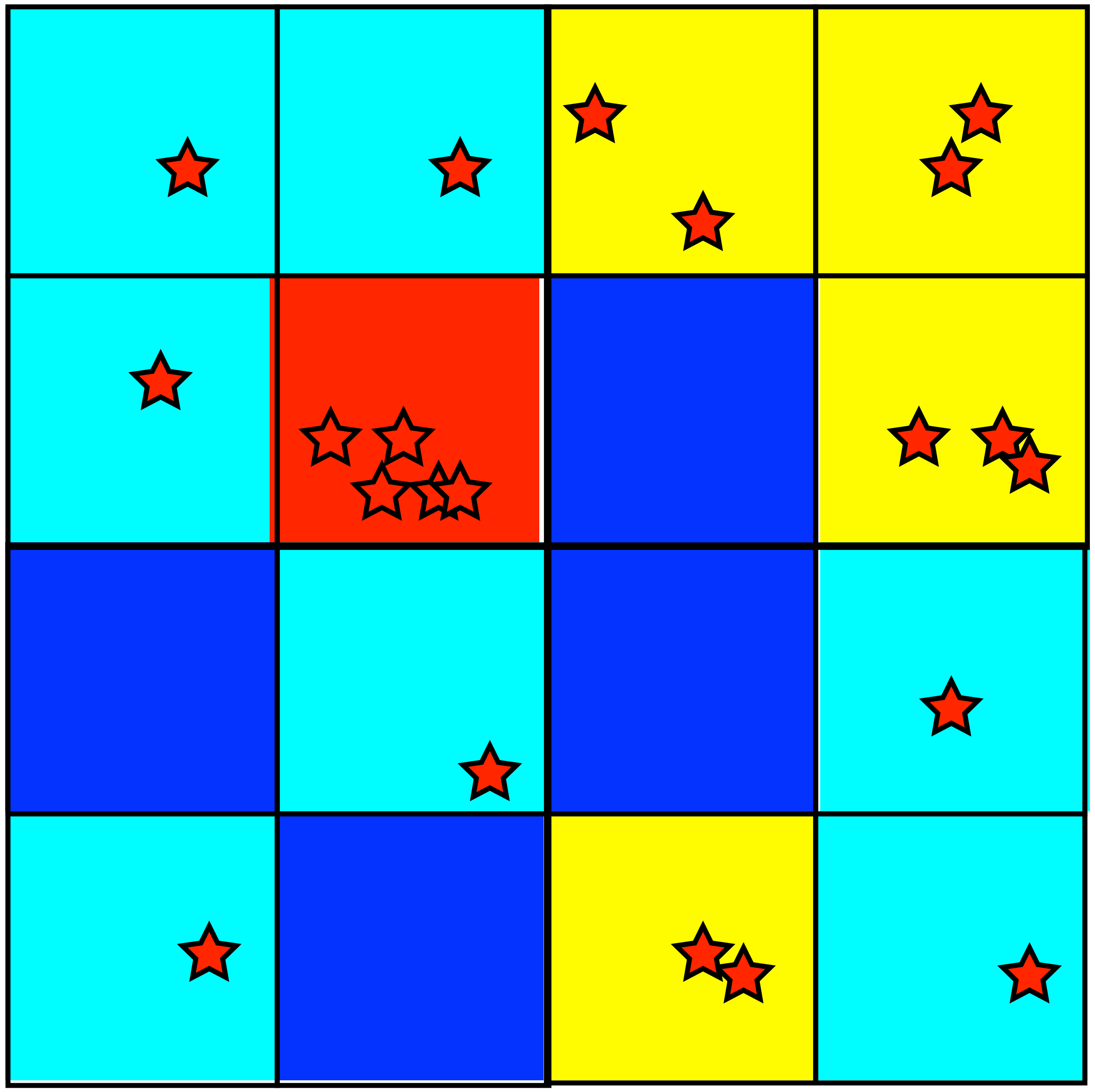
Overview



- 21 cm intensity mapping (z<6)
- 21 cm EoR (6<z<30)
- Status of experiments

ν_{21cm}=1420 MHz

Intensity mapping in outline



Traditional galaxy survey identifies individual galaxies

Bin galaxies to estimate density field

Intensity mapping integrates flux from all galaxies

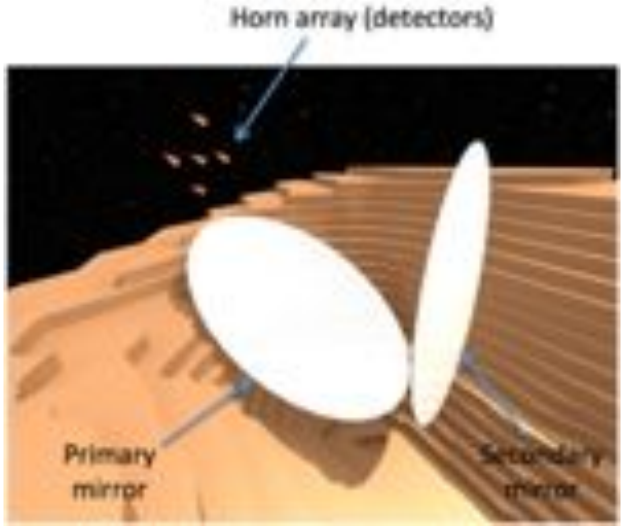
3D picture from different frequencies

Goal is efficent probe of large scale structure

21cm intensity mapping

GBT

BINGO

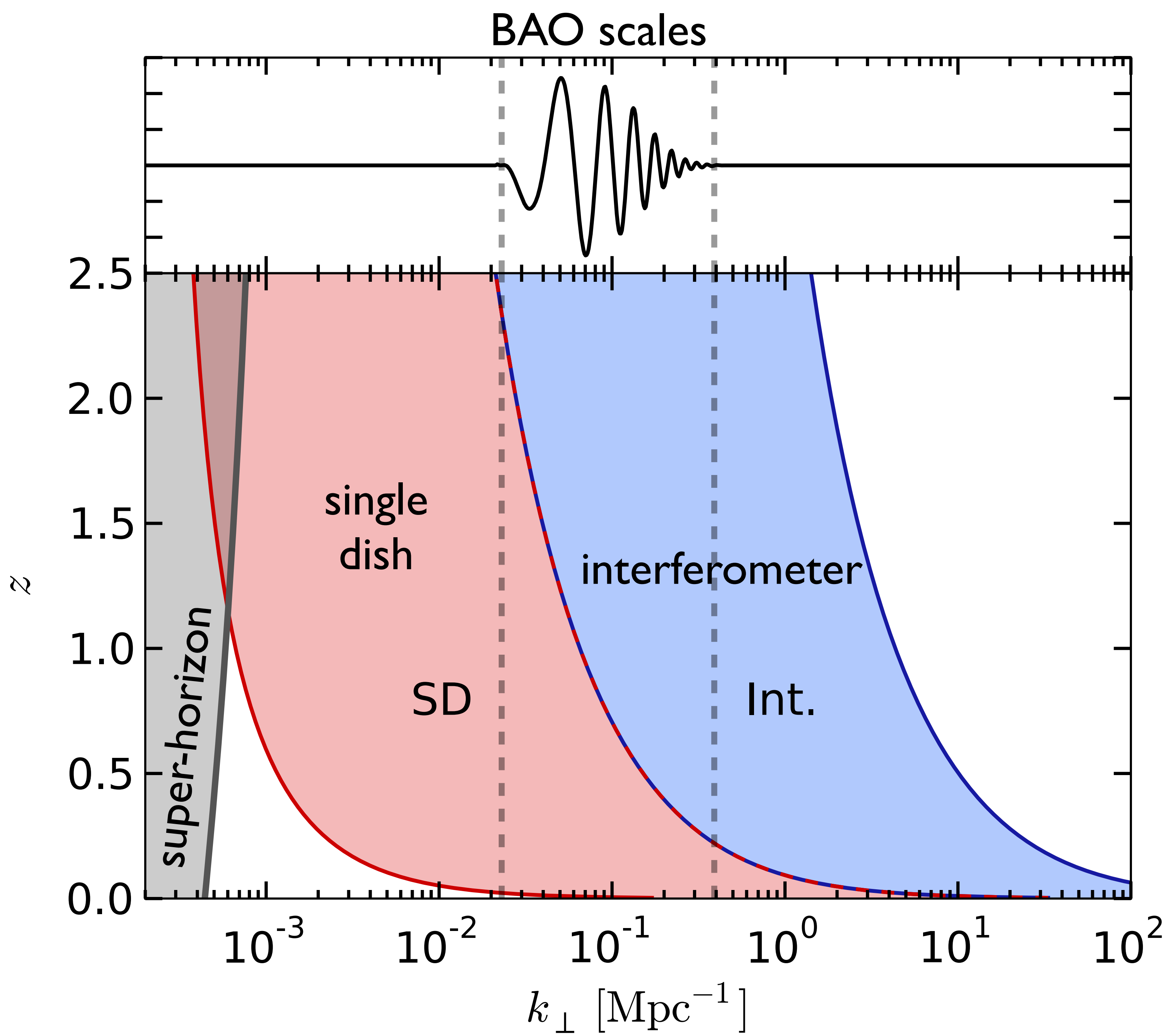


(see poster E. Ferreira)

Also BAOBAB, KZN array

Dish vs Interferometer

Bull+ 2014



Interferometer lacks small baselines

Compensate by using in single dish mode

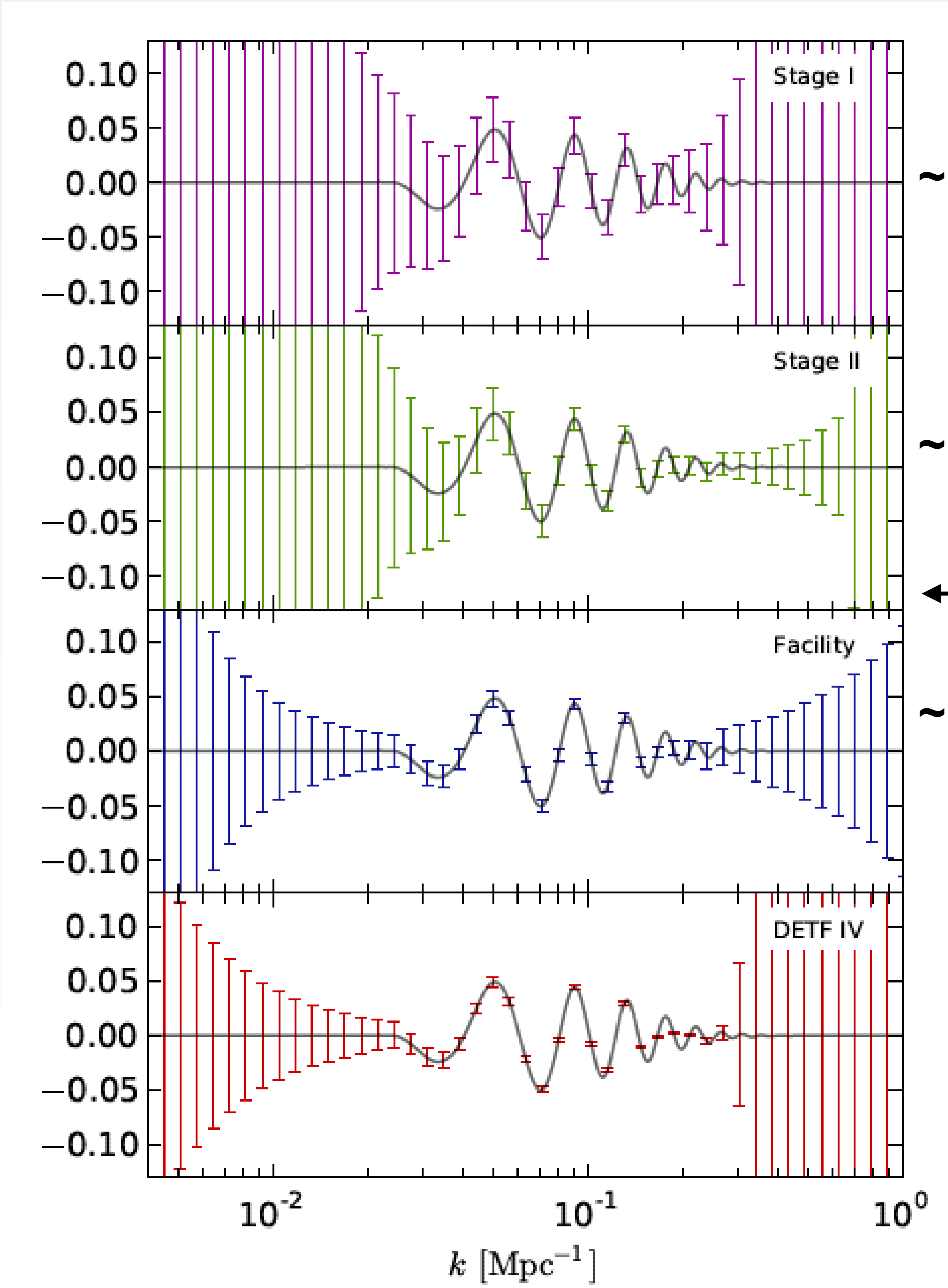
Like many copies of GBT

Interferometric mode complements with small scale information

e.g. SKA1-MID with15m dishes

BAO

Bull+ 2014



~ **BINGO**

~ **MeerKAT**

CHIME

~ **SKA1-Mid base (up to z ~ 2.0)**

~ **Euclid**

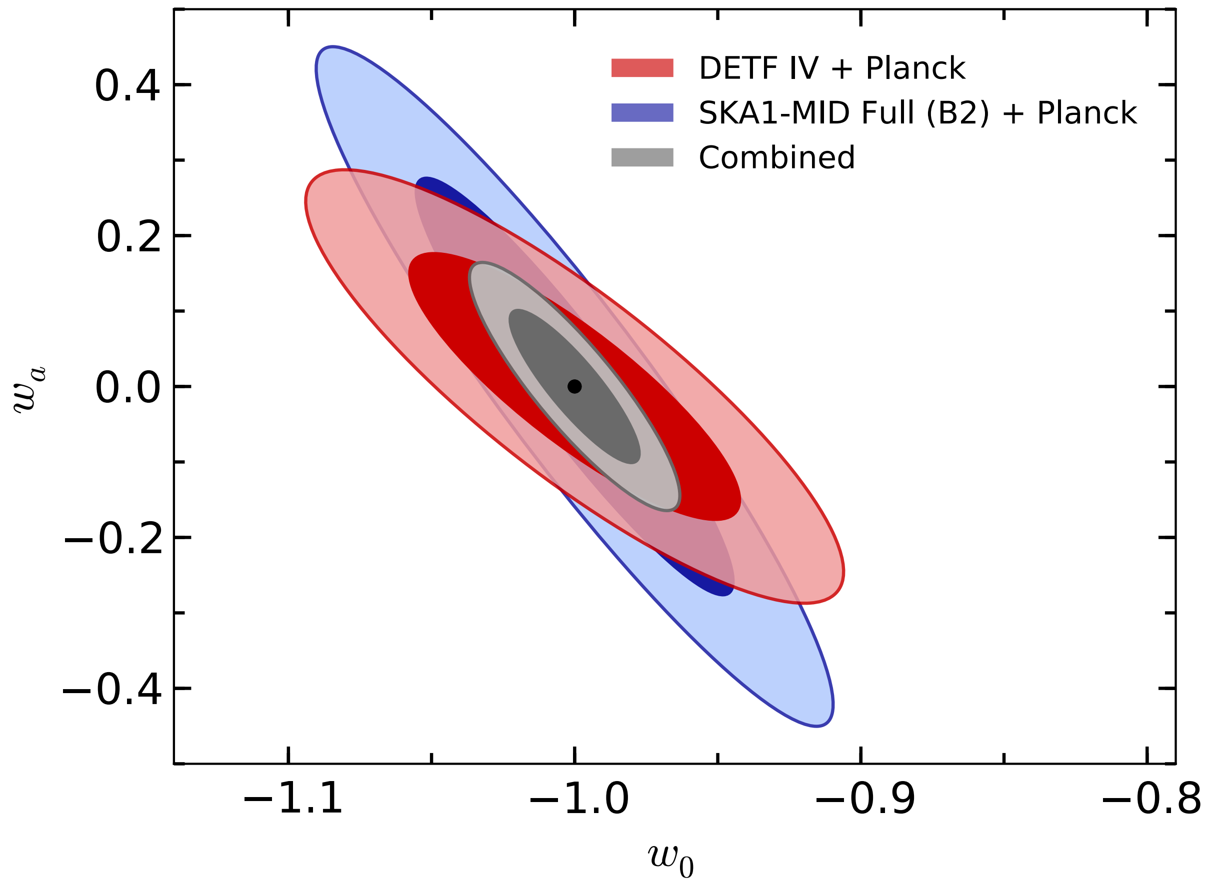
First instruments measure D_A at z<1

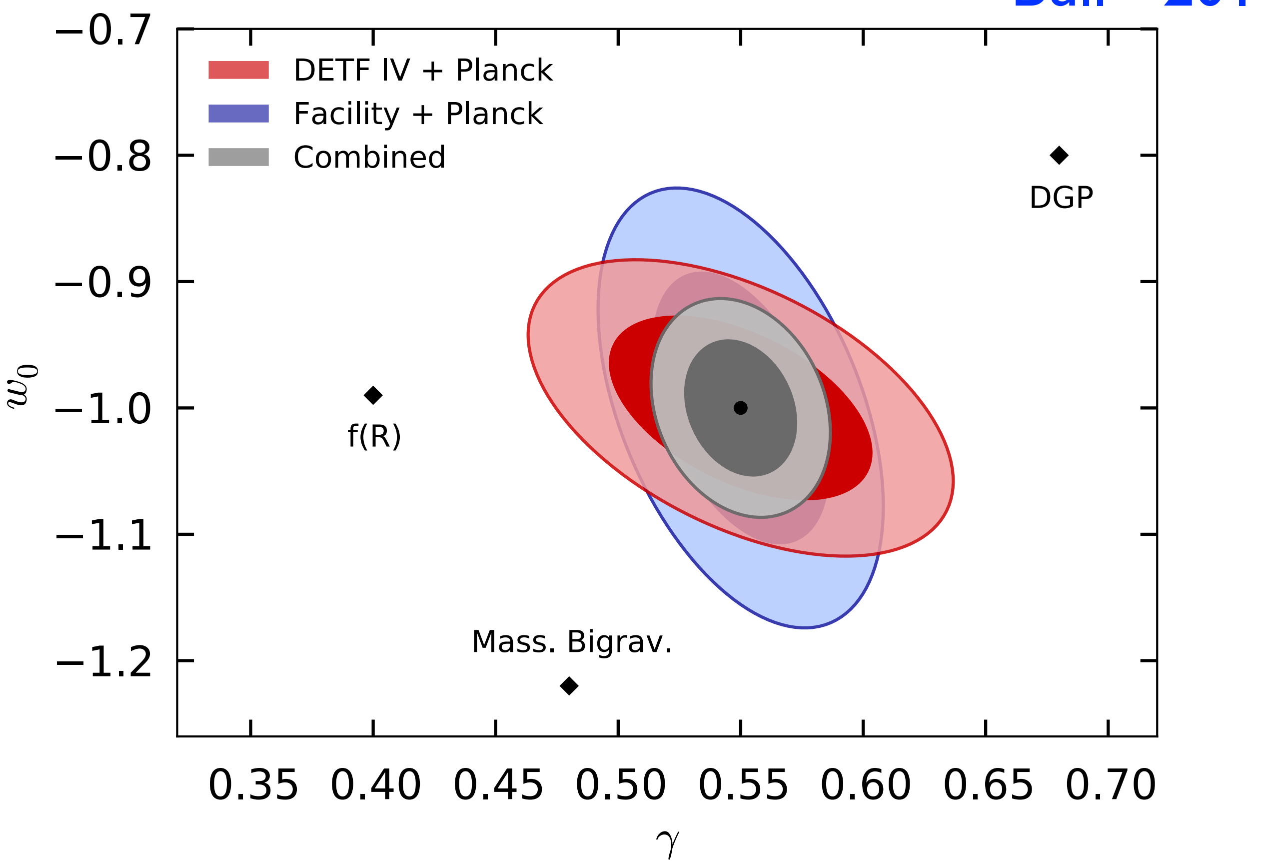
SKA1-MID comparable to DETF IV probe

Dark energy & modified gravity

BAO+RSD => dark energy constraints

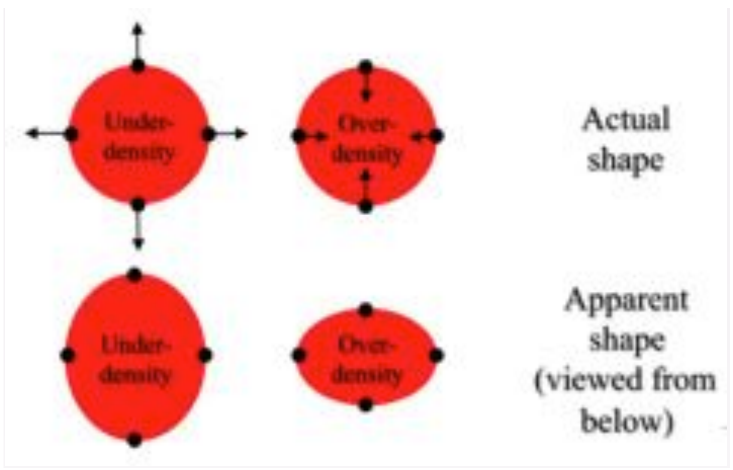
Bull+ 2014





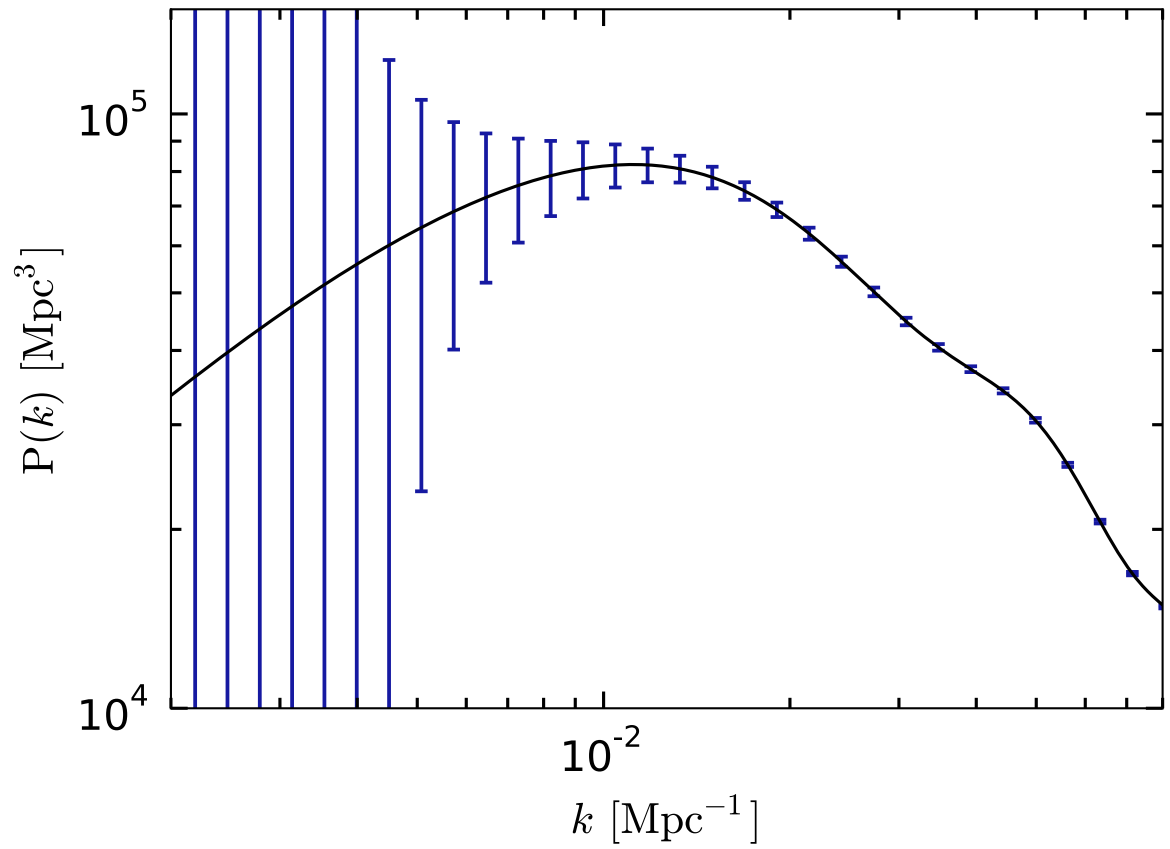
IM probes higher z than optical so complementary

RSD=>growth of structure



Ultra-large scales

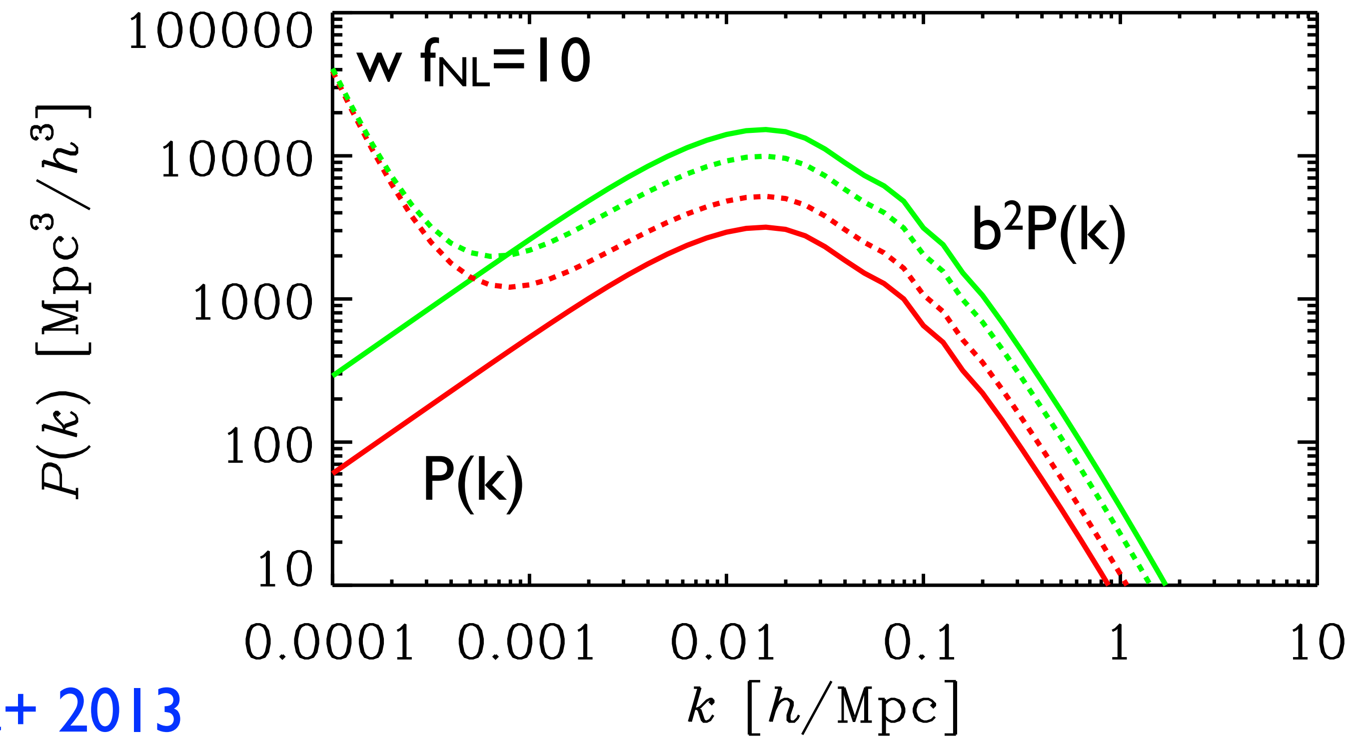
Bull+ 2014



SKA1-SUR
25,000 deg^2
z=0.5-2.5

Full SKA would push to z<5

Able to detect turnover in power spectrum



Camera+ 2013

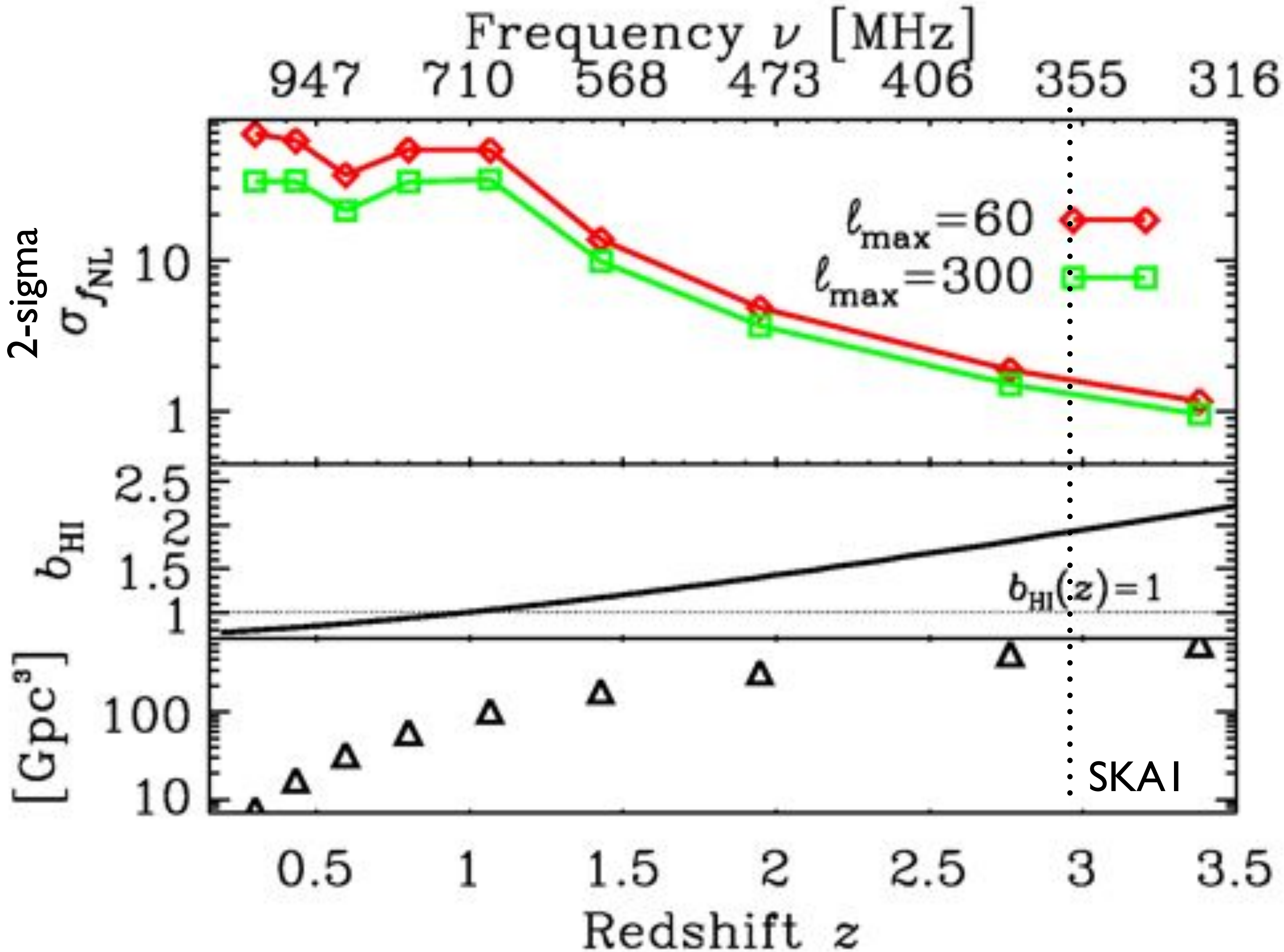
Scale dependant bias

Relativistic effects

(see poster by Deutsch)

Cosmology from ultra-large scales

Camera+ 2013

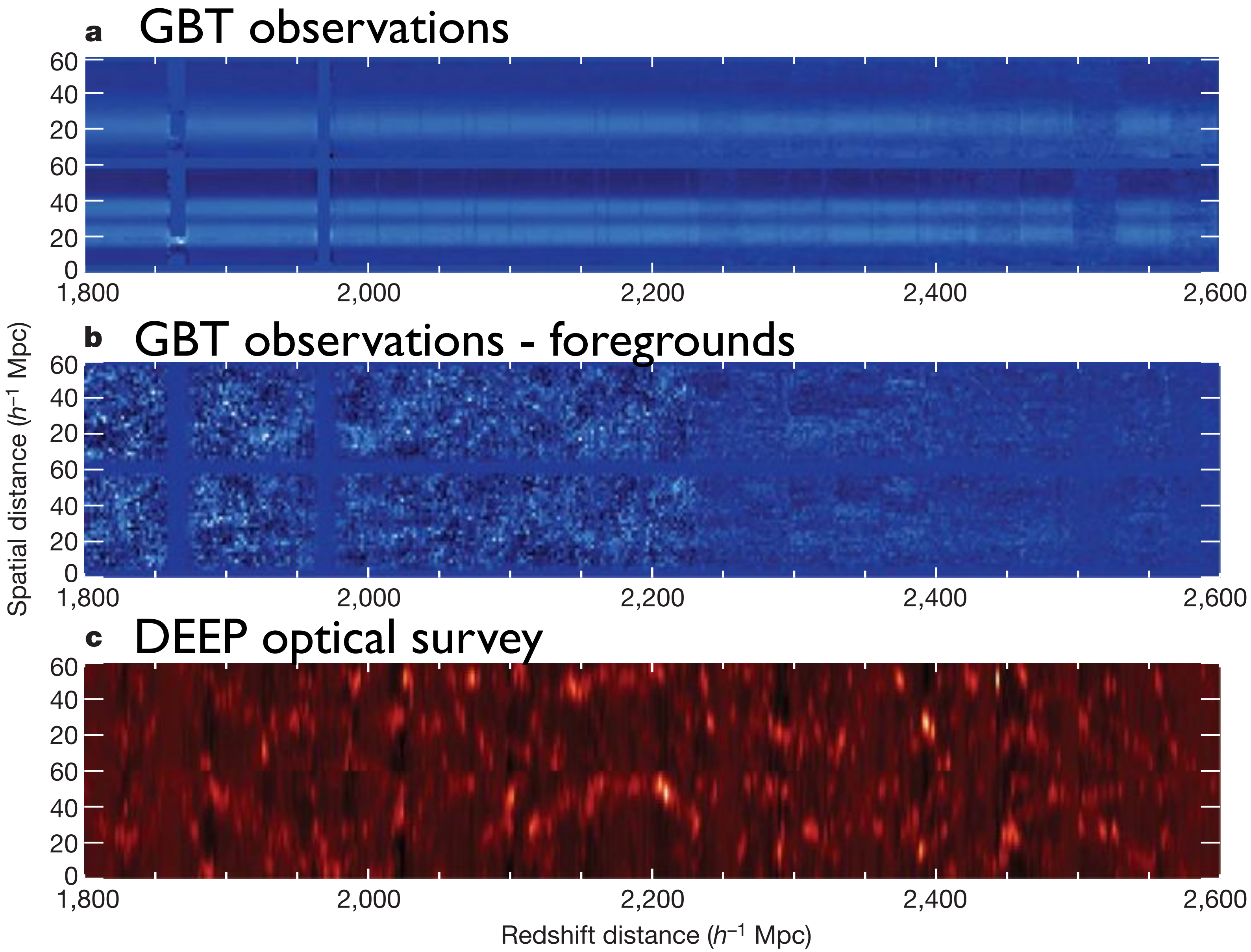


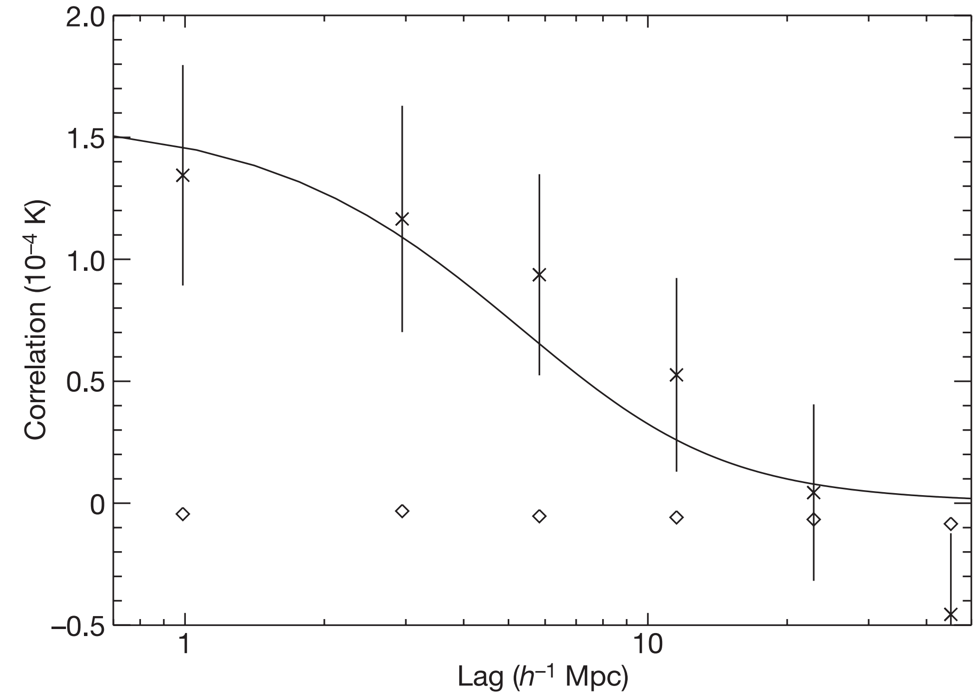
bandwidth=200MHz

GBT results

Chang+ 2010

GBT x DEEP => HI at z=0.8





$$\Omega_{\rm HI} = (5.5 \pm 1.5) \times 10^{-4} \times (1/rb)$$

Masui+ 2012 Improved results with GBT x WIGGLEZ

Radio Cosmology at z<6

21 cm intensity mapping offers efficient probe of LSS at high-z
BINGO/GBT z<1, SKA1/CHIME z<2.5, SKA2 z<5

Large volume accessible for cosmology; spectroscopic for RDS
=> promise for dark energy constraints

Potential to access largest scales to constrain non-G, relativistic effects, …

Competitive with other more traditional LSS probes

SKA2:

- HI redshift survey (billion galaxy survey) will be state of art
- Radio lensing competitive with optical e.g. Euclid

General:

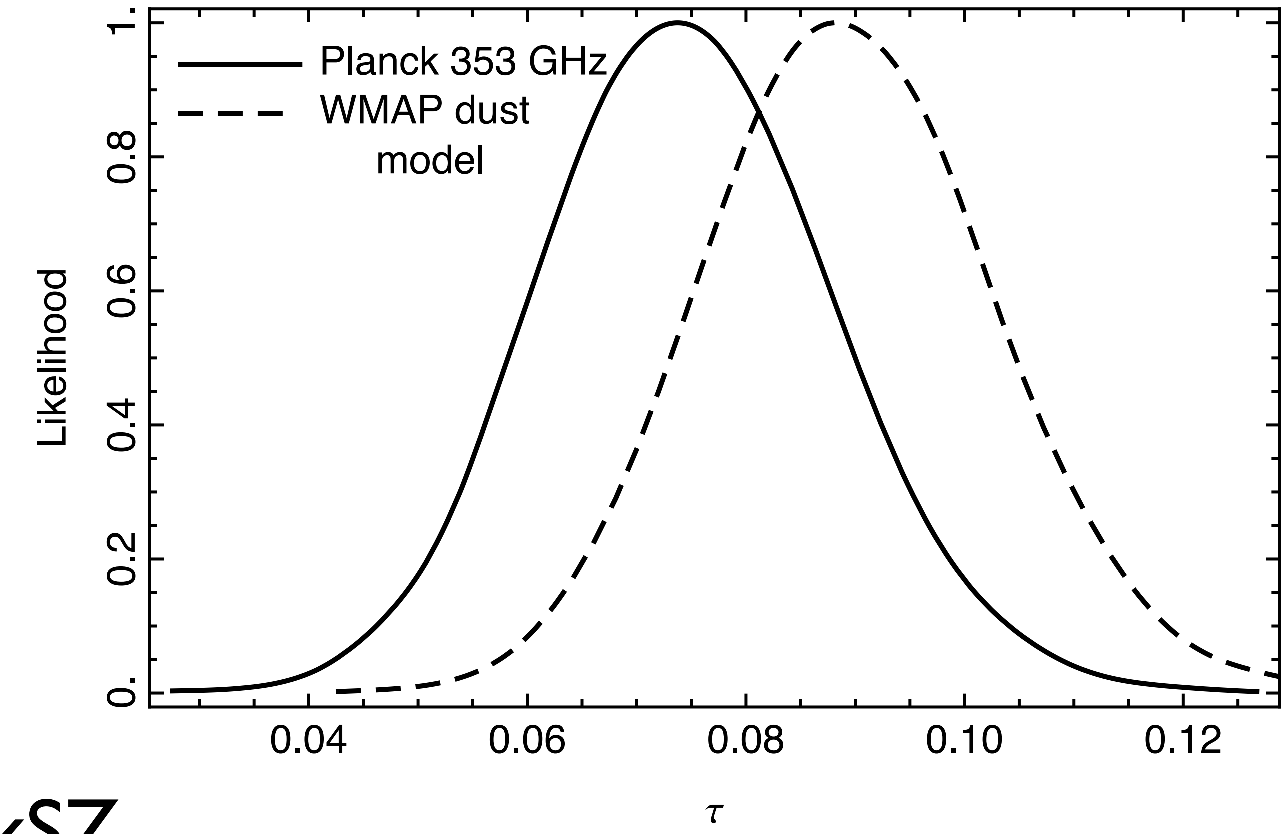
- Radio gives different systematics to optical/IR

Cosmology from Epoch of Reionization/Cosmic Dawn

with K. Ichiki, A. Mesinger, B. Metcalf, M. Santos for Cosmology and EoR Science Teams

CMB and reionization

Optical depth



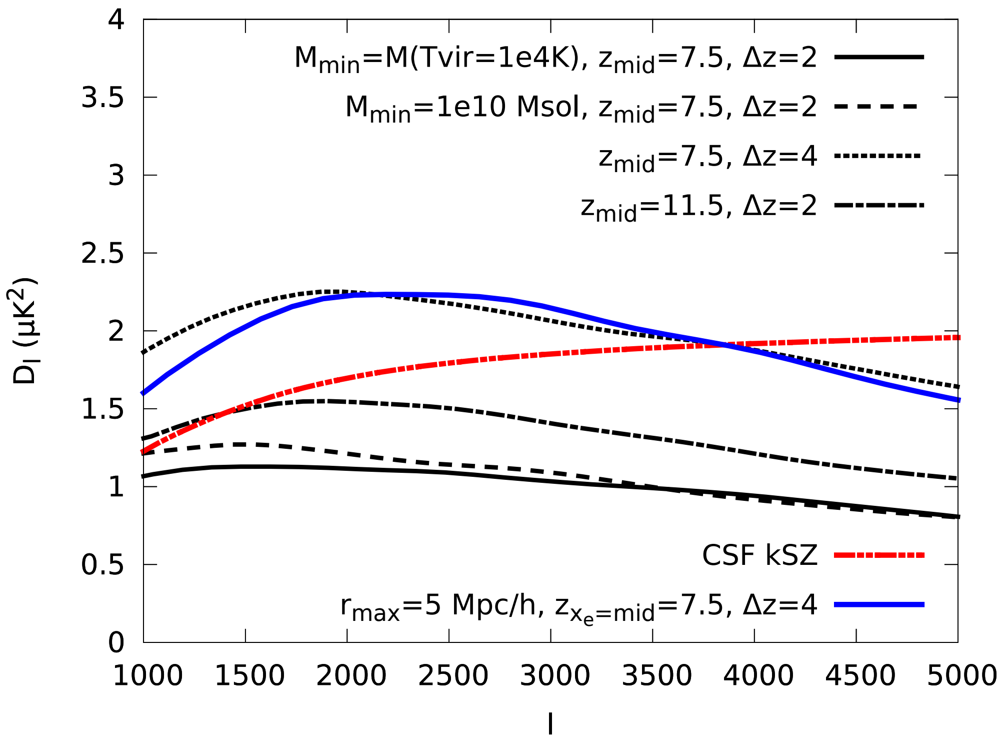
Planck XV (2013)

$$\tau = 0.089 \pm 0.013$$

$$\tau = 0.075 \pm 0.013,$$

~ constrains midpoint of reionization

kSZ



Zahn+ 2012

kSZ band power at l~3000

~ constrains duration of reionization

(see Mesinger+ 2012 for caveats)

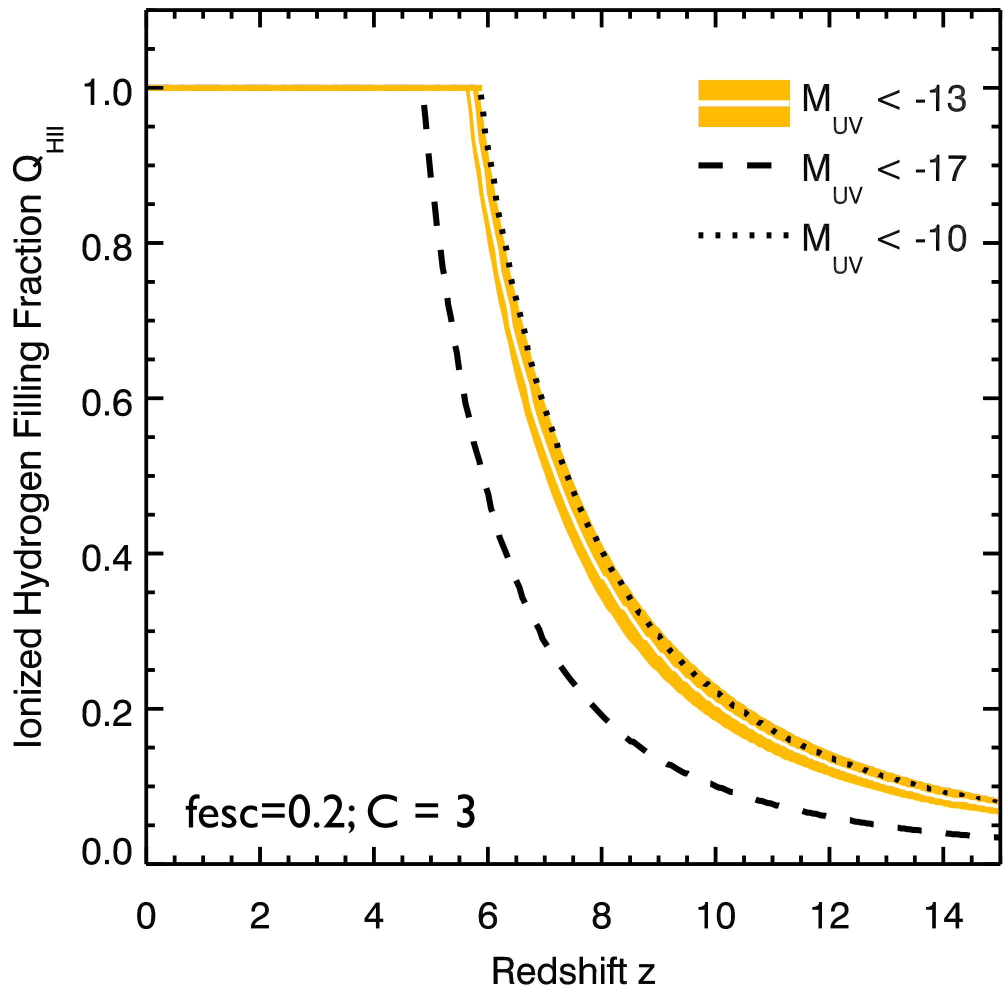
Planck and reionization

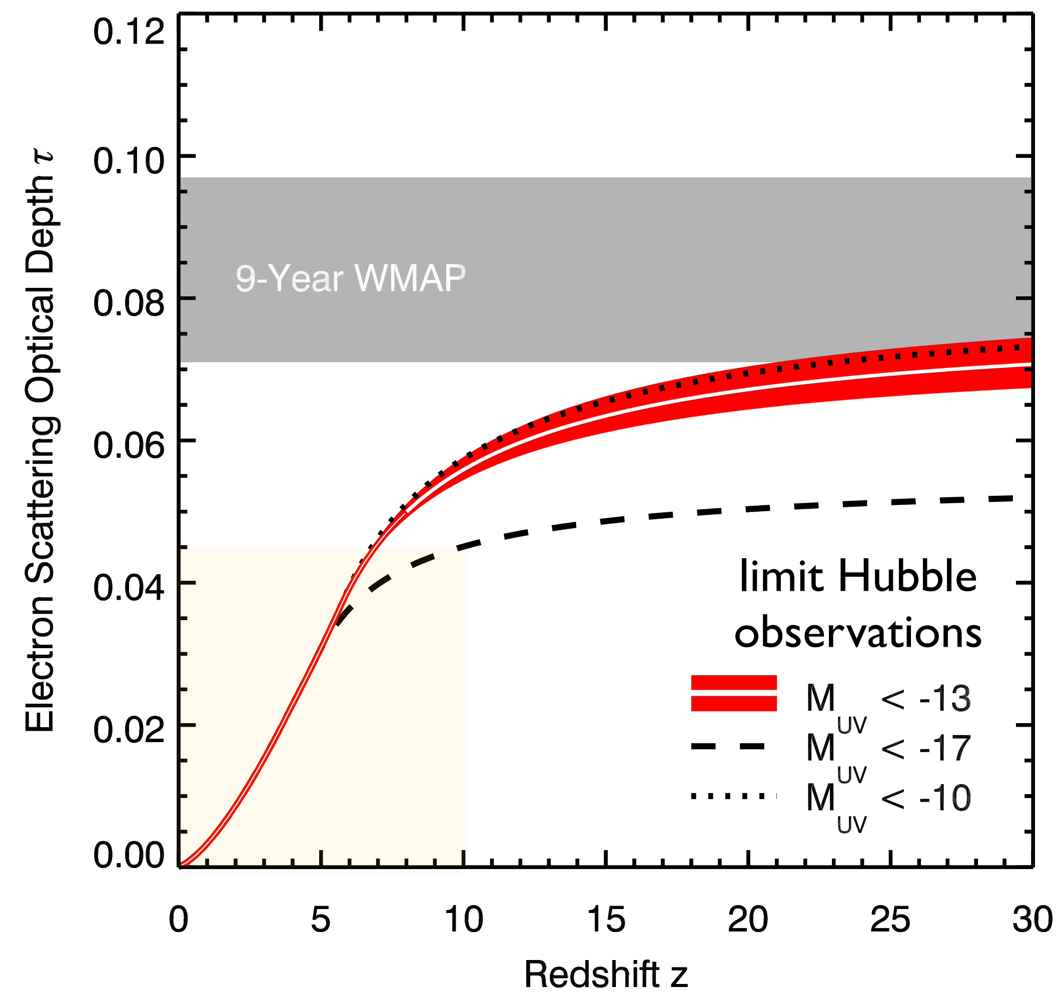
Robertson+2013

$$\dot{Q}_{\rm HII} = \frac{\dot{n}_{\rm ion}}{\langle n_{\rm H} \rangle} - \frac{Q_{\rm HII}}{t_{\rm rec}}$$

$$\dot{n}_{\rm ion} = f_{\rm esc}\xi_{\rm ion}\rho_{\rm UV}$$

$$\rho_{\rm UV}(z) = \int_{-\infty}^{M_{\rm UV}} \Phi(M)L(M)dM,$$



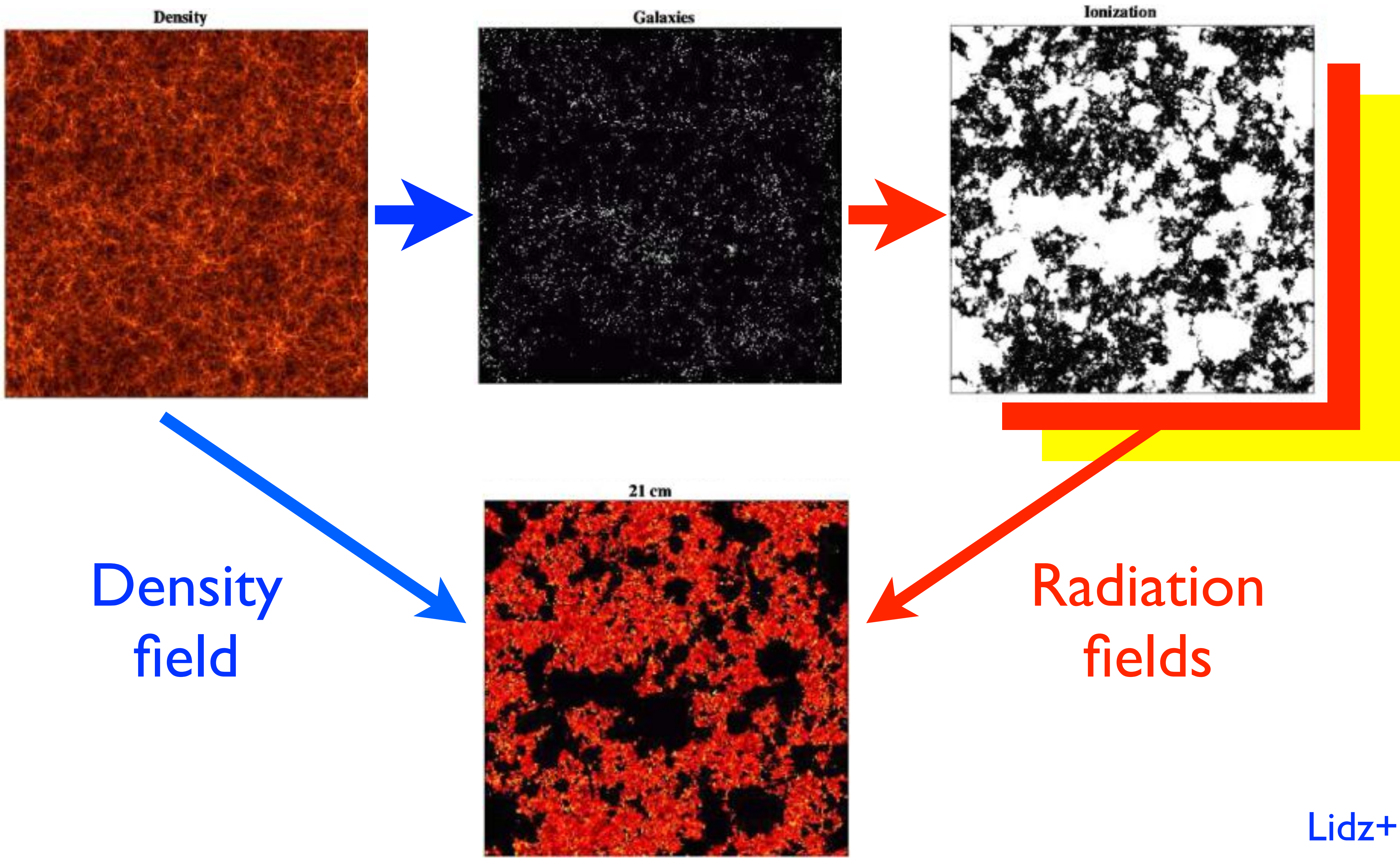


Optical depth >0.07 tends to require earlier population of fainter galaxies

21 cm signal

neutral fraction — baryon density — gas temperature +Lya flux — peculiar velocities

$$\delta T_B = 27 x_{HI} (1+\delta_b) \left(\frac{T_S - T_{\rm CMB}}{T_S}\right) \left(\frac{1+z}{10}\right)^{1/2} \left[\frac{\partial_r v_r}{(1+z)H(z)}\right]^{-1} \text{mK}$$

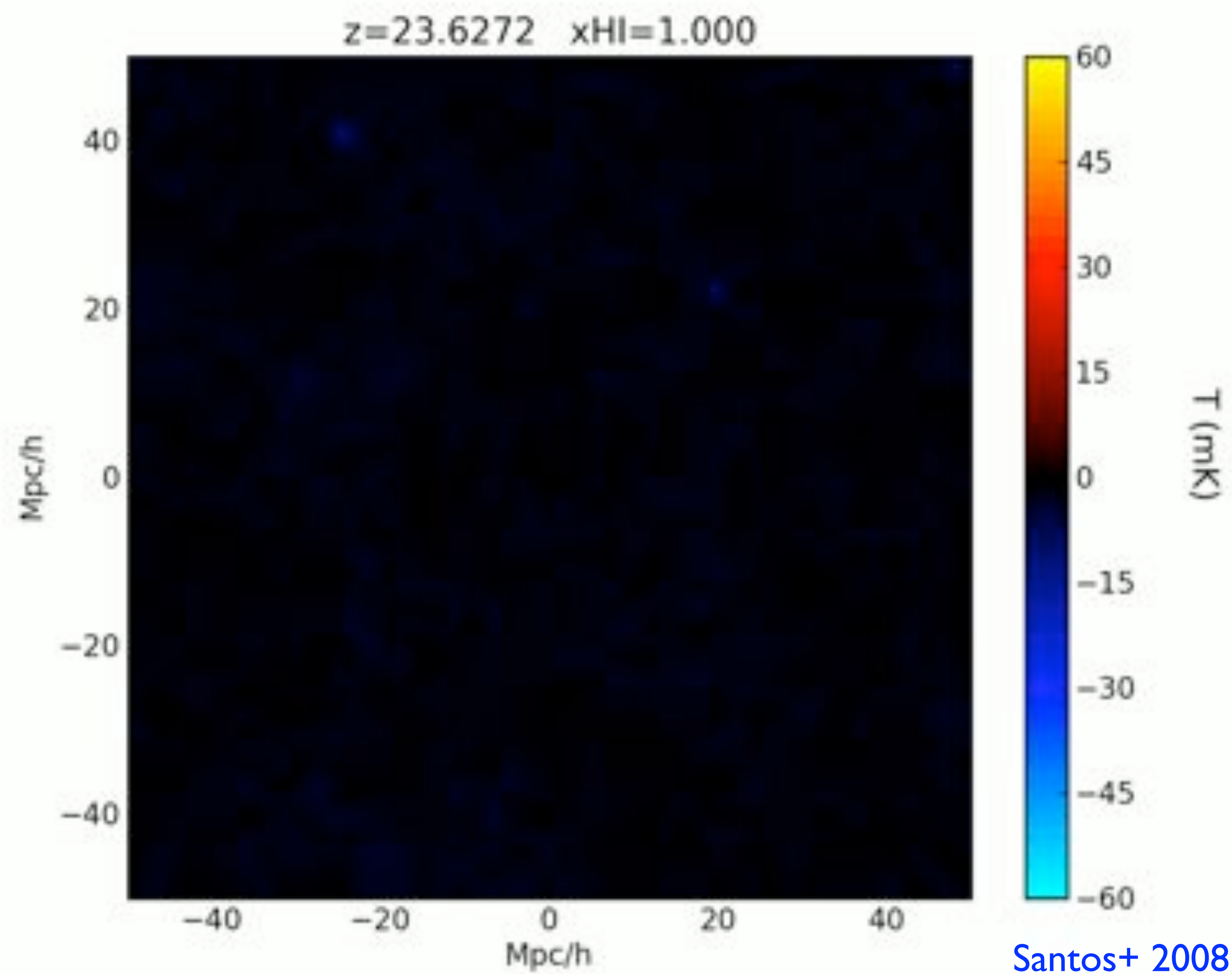


Density field

Radiation fields

Lidz+ 2009

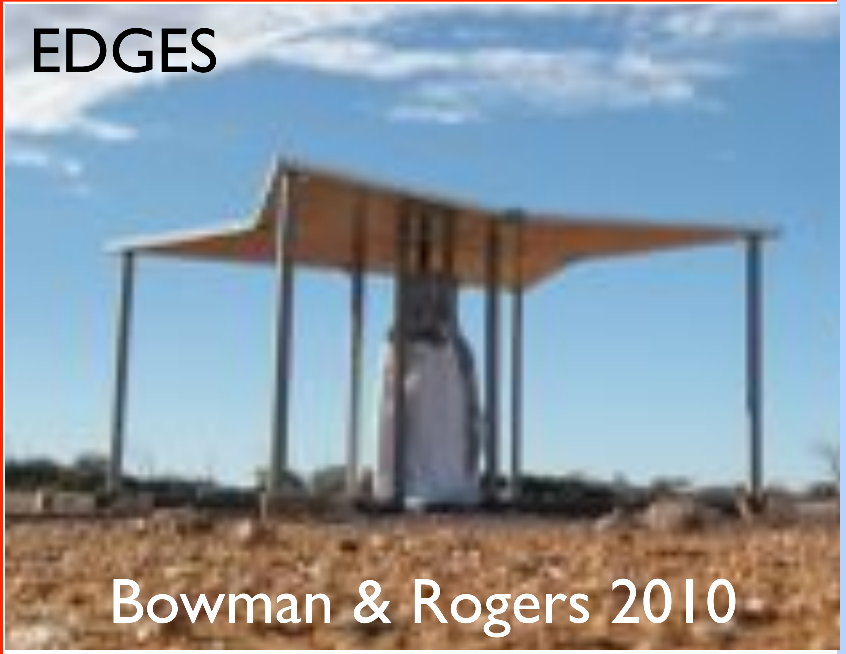
Numerical simulation



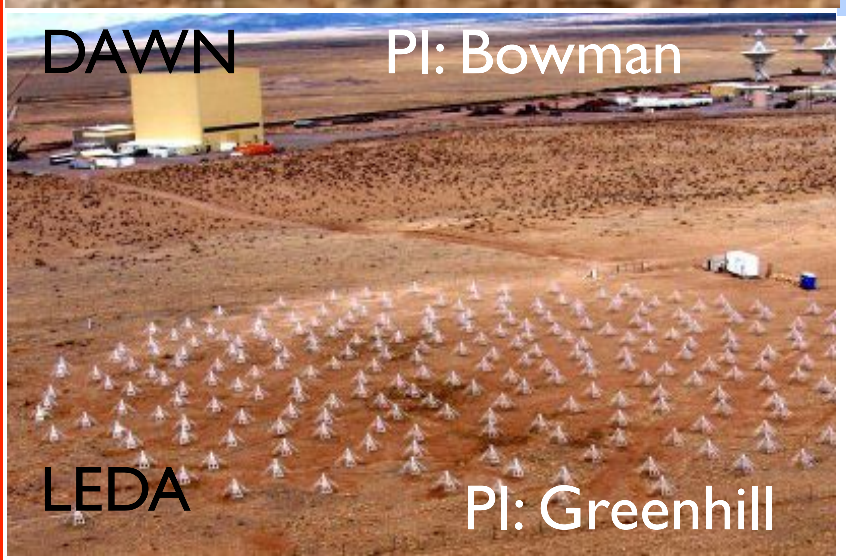
Santos+ 2008

Sky averaged mean 21 cm signal

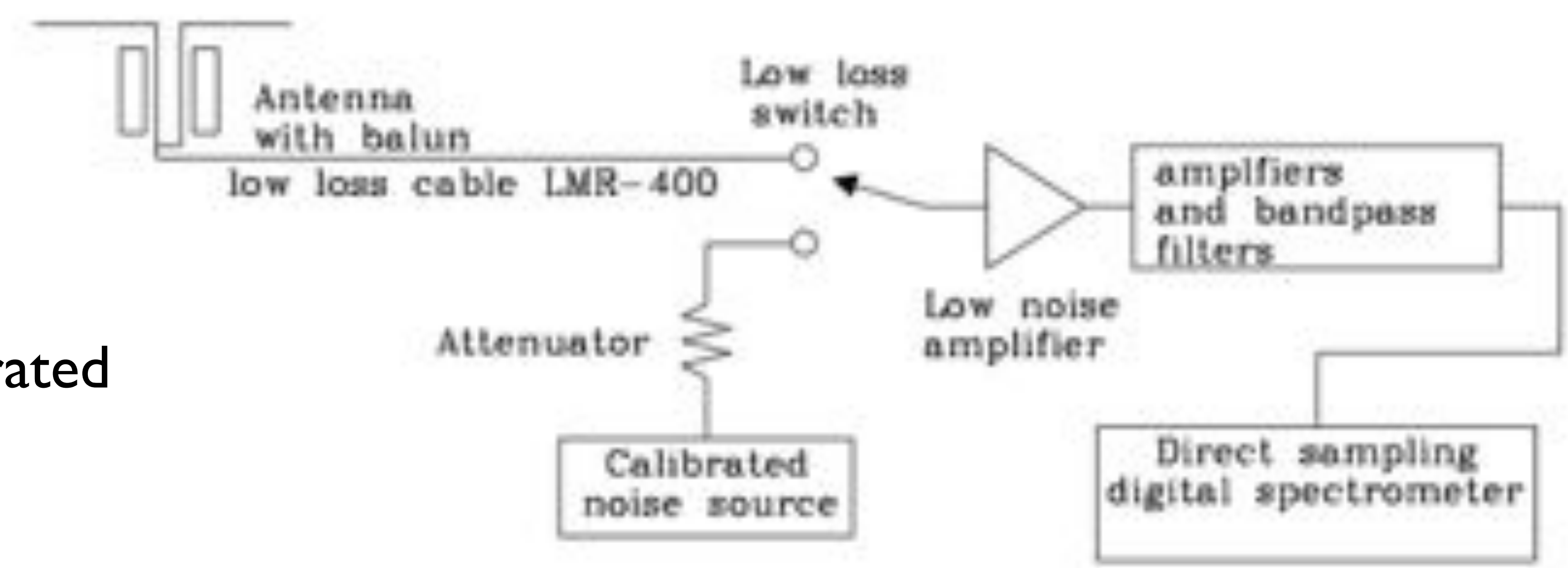
Imperial College London



Burns+



also CoRE - Ekers+ LOFAR-LOCOS - PI: Koopmans

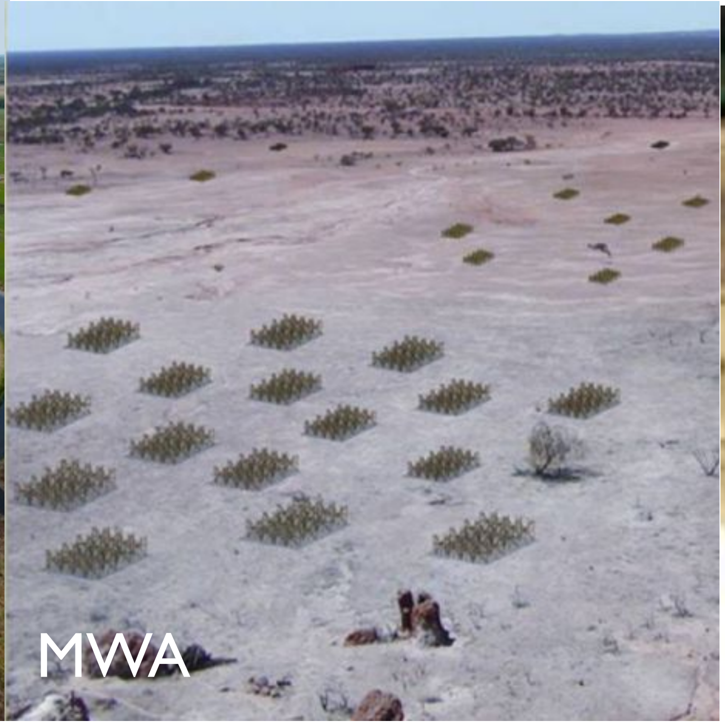


Switch between sky and calibrated reference source

Foregrounds and calibration are key issues

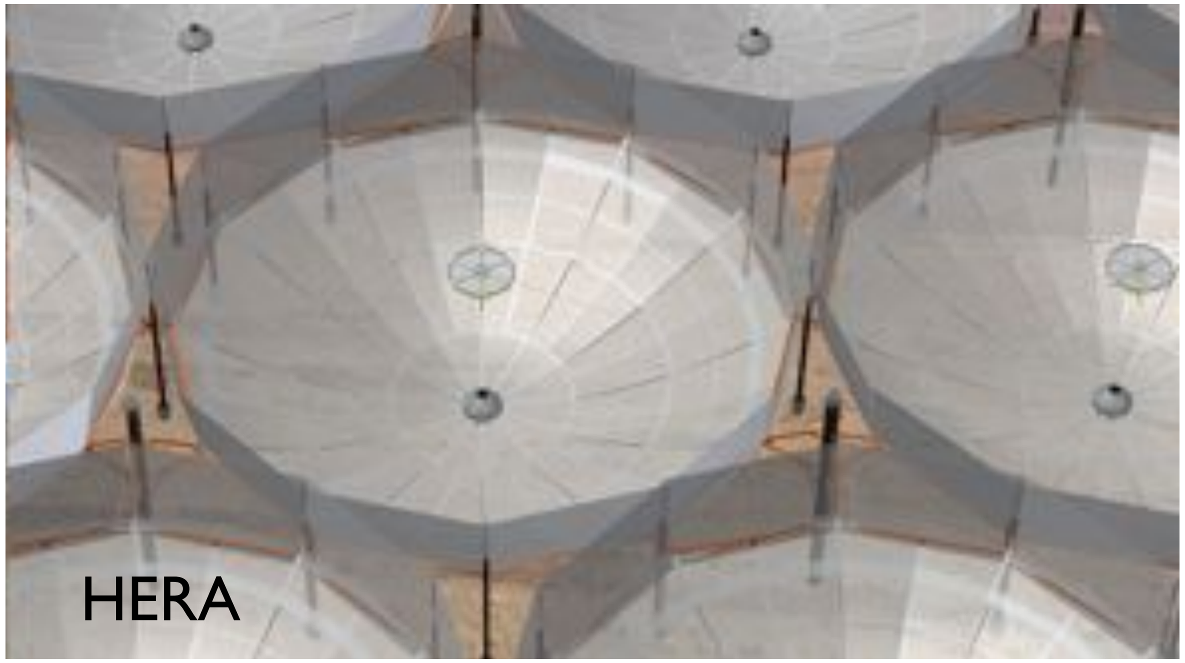
Harker+ 2011, Liu+2013

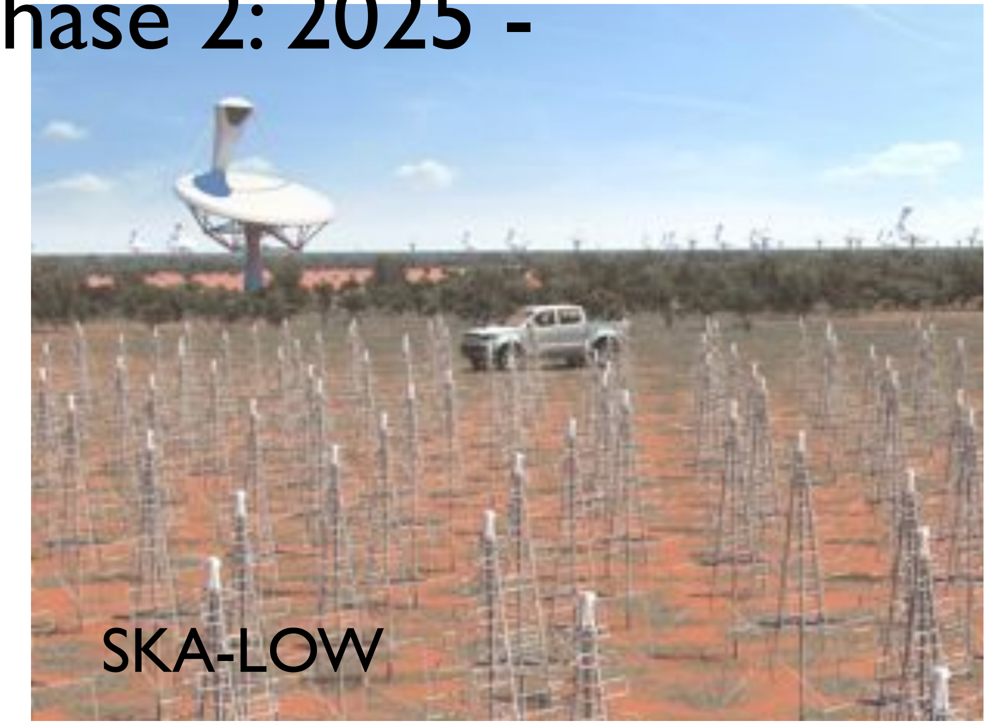
Fluctuation Experiments



Phase1: 2020 onwards
Phase 2: 2025 -

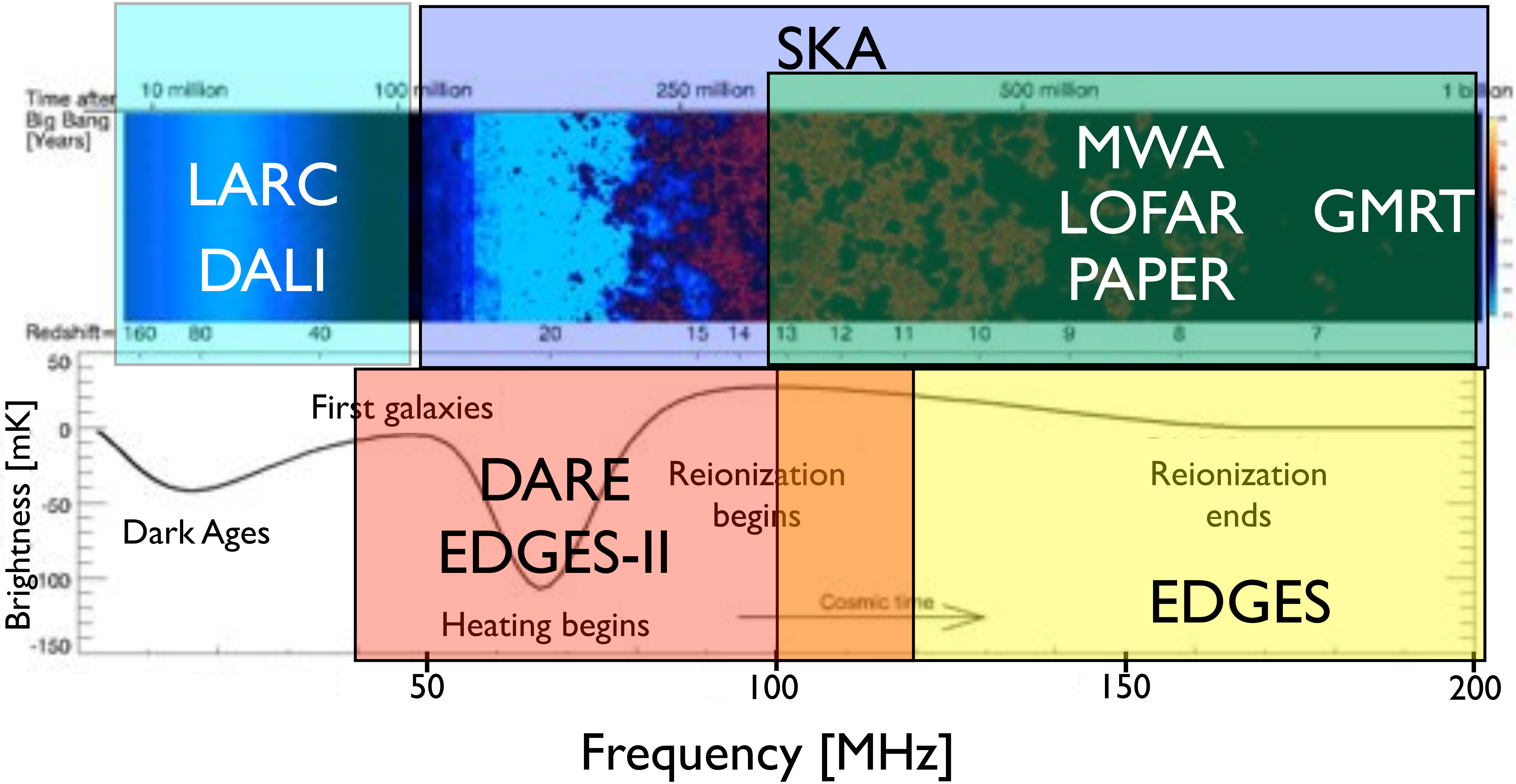
~2017-18 (?)





21 cm summary

Pritchard & Loeb 2010

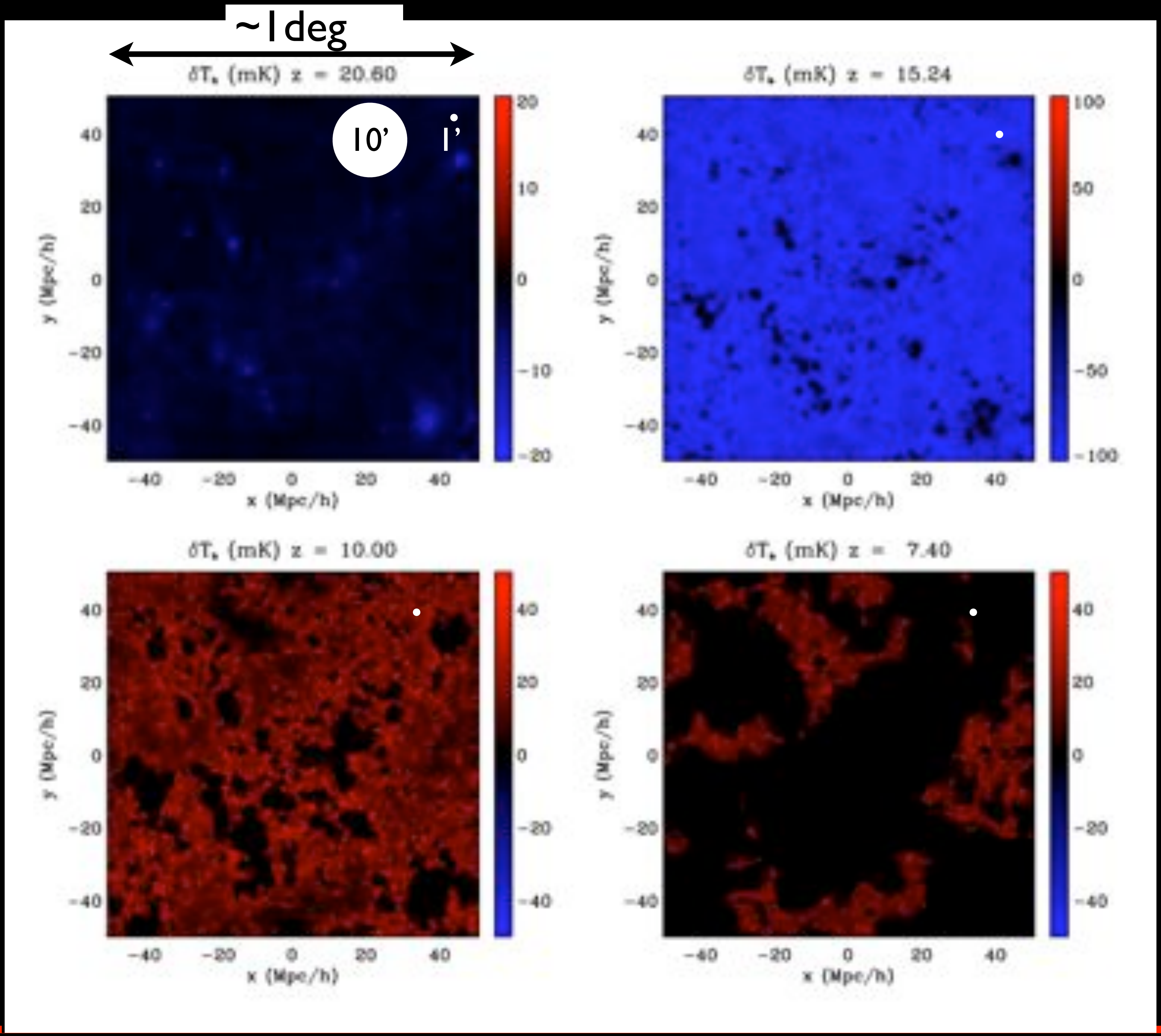


Systematic path to probing different epochs

SKA will image reionization

SKA will be first instrument with sensitivity for imaging
=> map topology of reionization

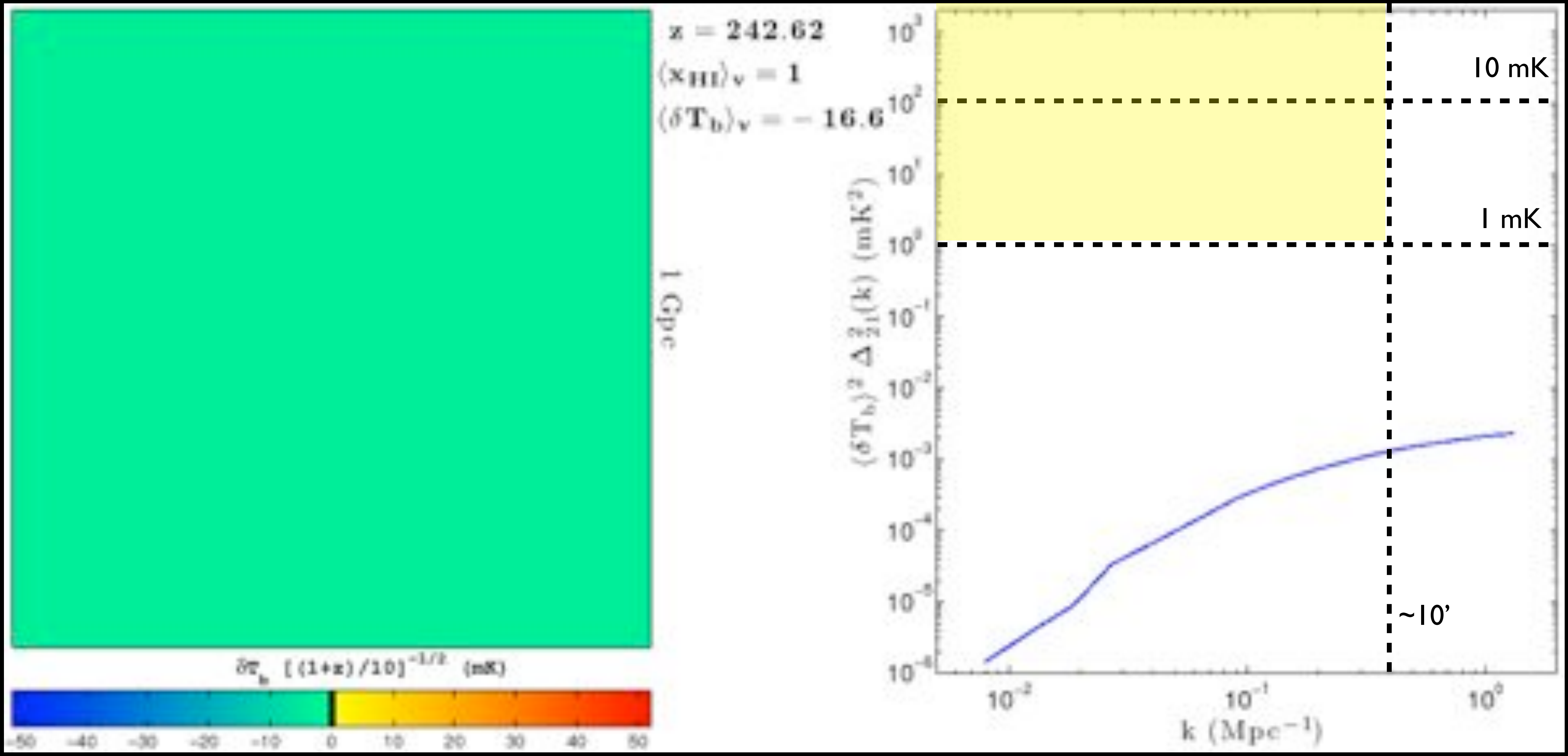
Mellema+ 2013



SKA FOV~ $20deg^2$

Evolution of the power spectrum

Mesinger+ 2010



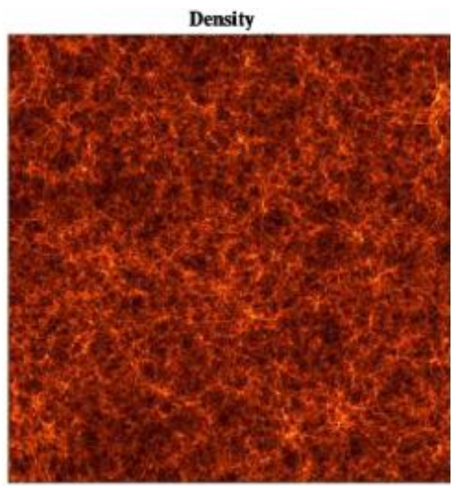
Measure power spectrum from z=27 to z~6
=>traces onset of star formation and IGM heating

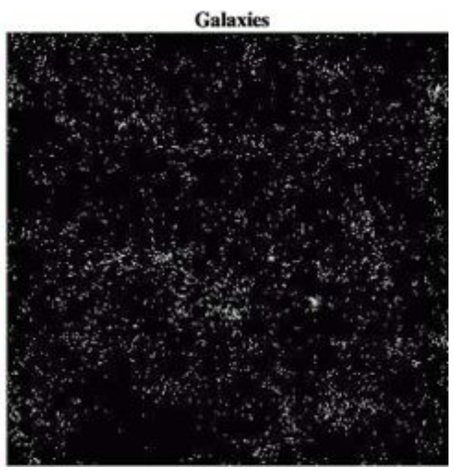
Paths to cosmology

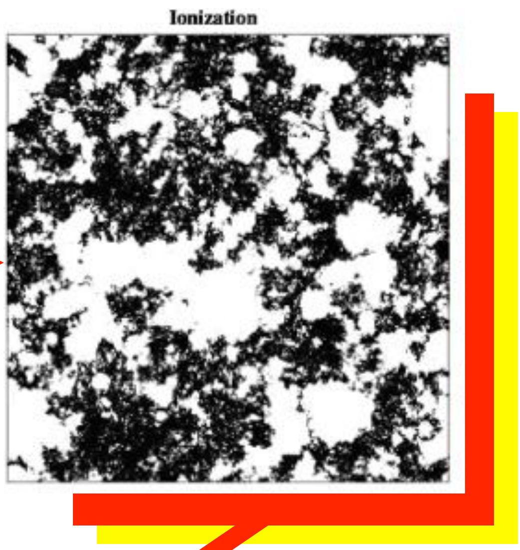
Imperial College London

Lidz+ 2009

2) Heating by exotic sources

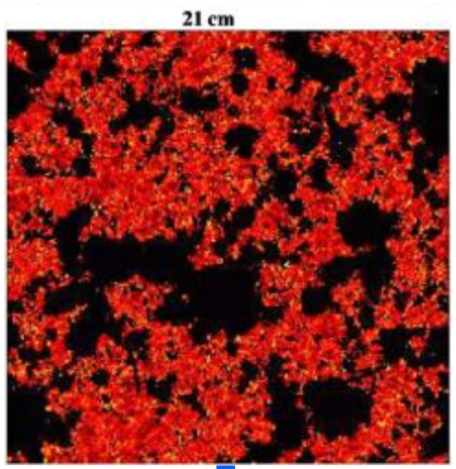






1) Infer density directly

3) Ionization pattern traces sources traces density



4) Weak lensing by matter along LoS

5) Other?

Separating cosmology & astrophysics is hard

Desiderata:
1) $T_S >> T_{CMB}$
(requires effective gas heating)

2) $J_\alpha >> J_{crit}$
(requires stellar Lya sources)

3) $x_{HI}=1$
(requires no ionizing radiation)

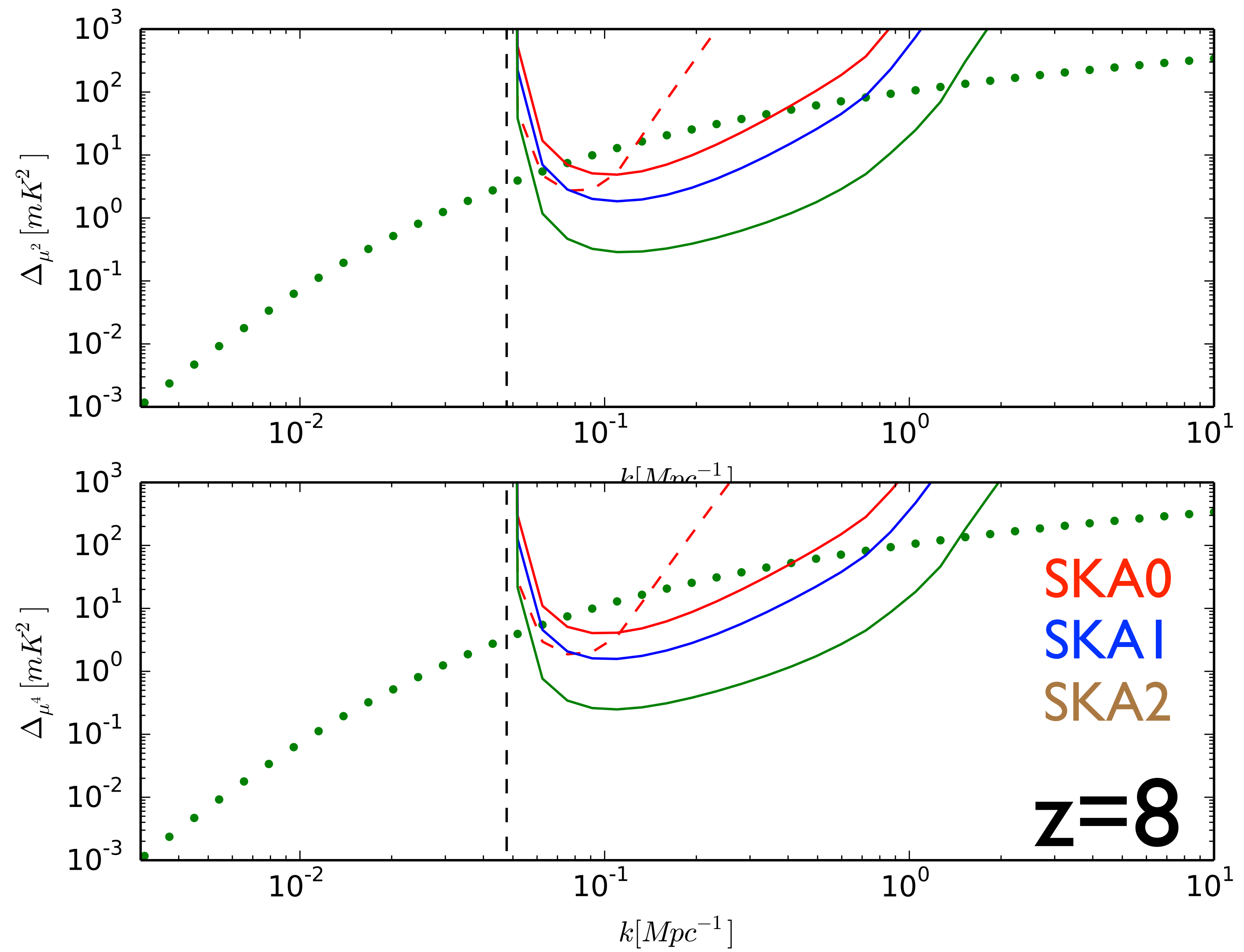
Extremely unlikely to satisfy all three since sources for (1) and (2) will likely produce ionizing radiation violating (3)

Strategy:
a) Avoid astrophysics where possible
b) Model astrophysics
c) Exploit RSD for more info

Redshift space distortions/peculiar velocities
=> P(k) angular dependence

$$P(k) = P_{\mu^0}(k) + P_{\mu^2}\mu^2 + P_{\mu^4}\mu^4$$

SKA will allow reasonable sensitivity for first time
BUT not enough for precision cosmology



Power spectrum & parameters

Mao+ 2008

Vanilla alone

		$\Delta\Omega_\Lambda$	$\Delta\ln(\Omega_m h^2)$	$\Delta\ln(\Omega_b h^2)$	Δn_s	$\Delta\ln A_s$	$\Delta\tau$	$\Delta\bar{x}_H(7.0)$[a]	$\Delta\bar{x}_H(7.5)$	$\Delta\bar{x}_H(8.0)$	$\Delta\bar{x}_H(9.2)$	$\Delta\Omega_k$	Δm_ν (eV)	$\Delta\alpha$
Planck		0.0070	0.0081	0.0059	0.0033	0.0088	0.0043	...	...	...	...	0.025	0.23	0.0026
+LOFAR	All OPT	0.0044	0.0052	0.0051	0.0018	0.0087	0.0042	0.0063	0.0063	0.0063	0.0063	0.0022	0.023	0.000 73
	All MID	0.0070	0.0081	0.0059	0.0032	0.0088	0.0043	0.18	0.26	0.23	...	0.018	0.22	0.0026
	All PESS	0.0070	0.0081	0.0059	0.0033	0.0088	0.0043	...	51	49	...	0.025	0.23	0.0026
+MWA	All OPT	0.0063	0.0074	0.0055	0.0024	0.0087	0.0043	0.0062	0.0062	0.0062	0.0062	0.0056	0.017	0.000 54
	All MID	0.0061	0.0070	0.0056	0.0030	0.0087	0.0043	0.32	0.22	0.29	...	0.021	0.19	0.0026
	All PESS	0.0070	0.0081	0.0059	0.0033	0.0088	0.0043	...	29	30	...	0.025	0.23	0.0026
+SKA	All OPT	0.000 52	0.0018	0.0040	0.000 39	0.0087	0.0042	0.0059	0.0059	0.0059	0.0059	0.0011	0.010	0.000 27
	All MID	0.0036	0.0040	0.0044	0.0025	0.0087	0.0043	0.0094	0.014	0.011	...	0.0039	0.056	0.0022
	All PESS	0.0070	0.0081	0.0059	0.0033	0.0088	0.0043	...	1.1	1.0	...	0.025	0.23	0.0026

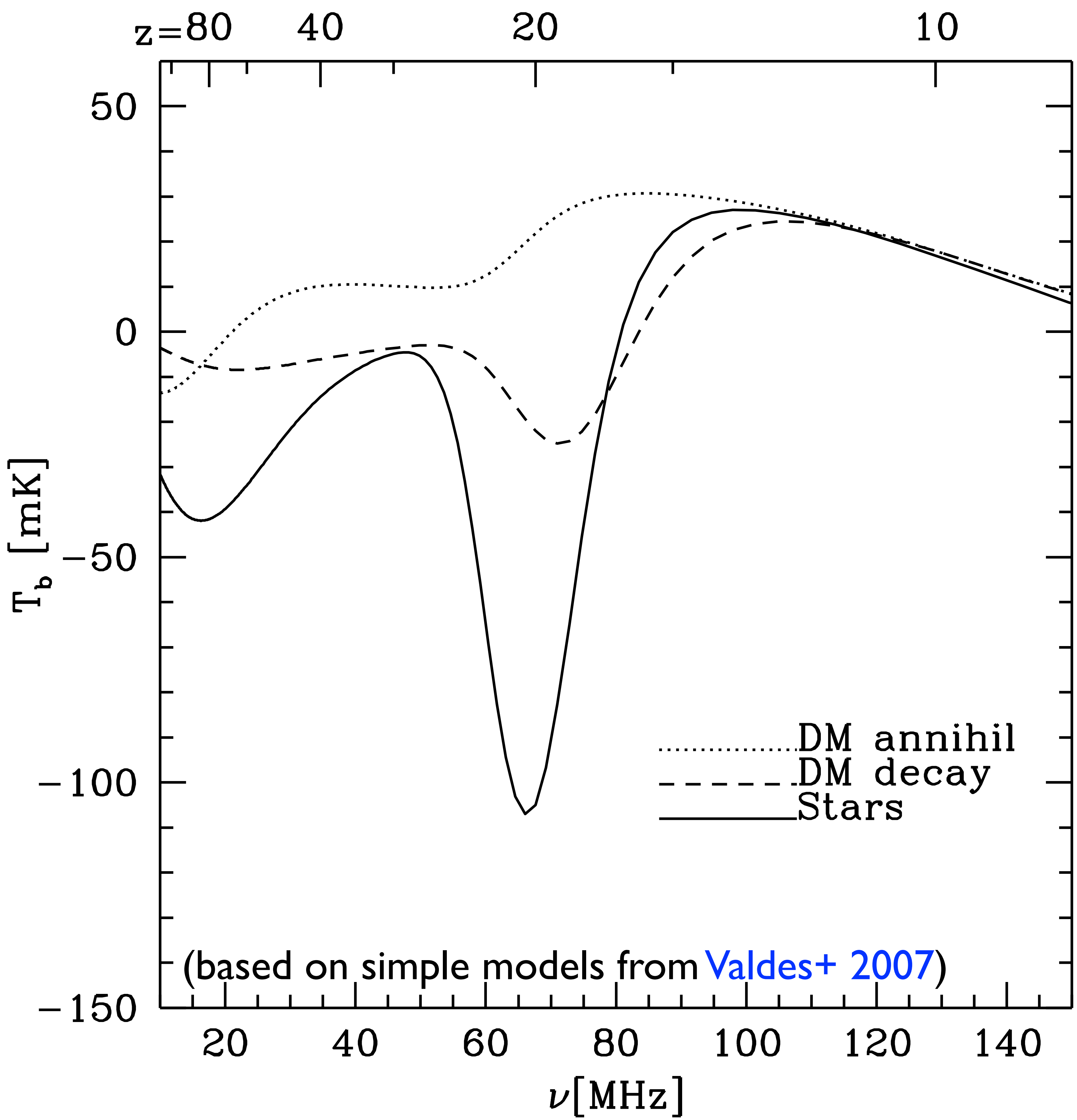
Planck does such a good job, hard for SKA to compete!

Enough raw sensitivity to density field to have a big impact - OPT
But need to account for foregrounds and astrophysics - MID
And worst case is only get info from linear peculiar velocities - PESS

Key gain is from adding small scales in linear regime - sensitive to k_{max} assumption

Key uncertainty is how well contribution from reionization/spin-temperature can be modelled

Calorimetry and exotic physics



(based on simple models from Valdes+ 2007)

Dark matter decaying after recombination might impact thermal history

Possibilities for exotic energy injection:

DM annihiliation/decay
Furlanetto+ 2006
Valdes+ 2007

Excited DM relaxation
Finkbeiner+ 2008

Evaporating primodial BH
Mack+ 2008

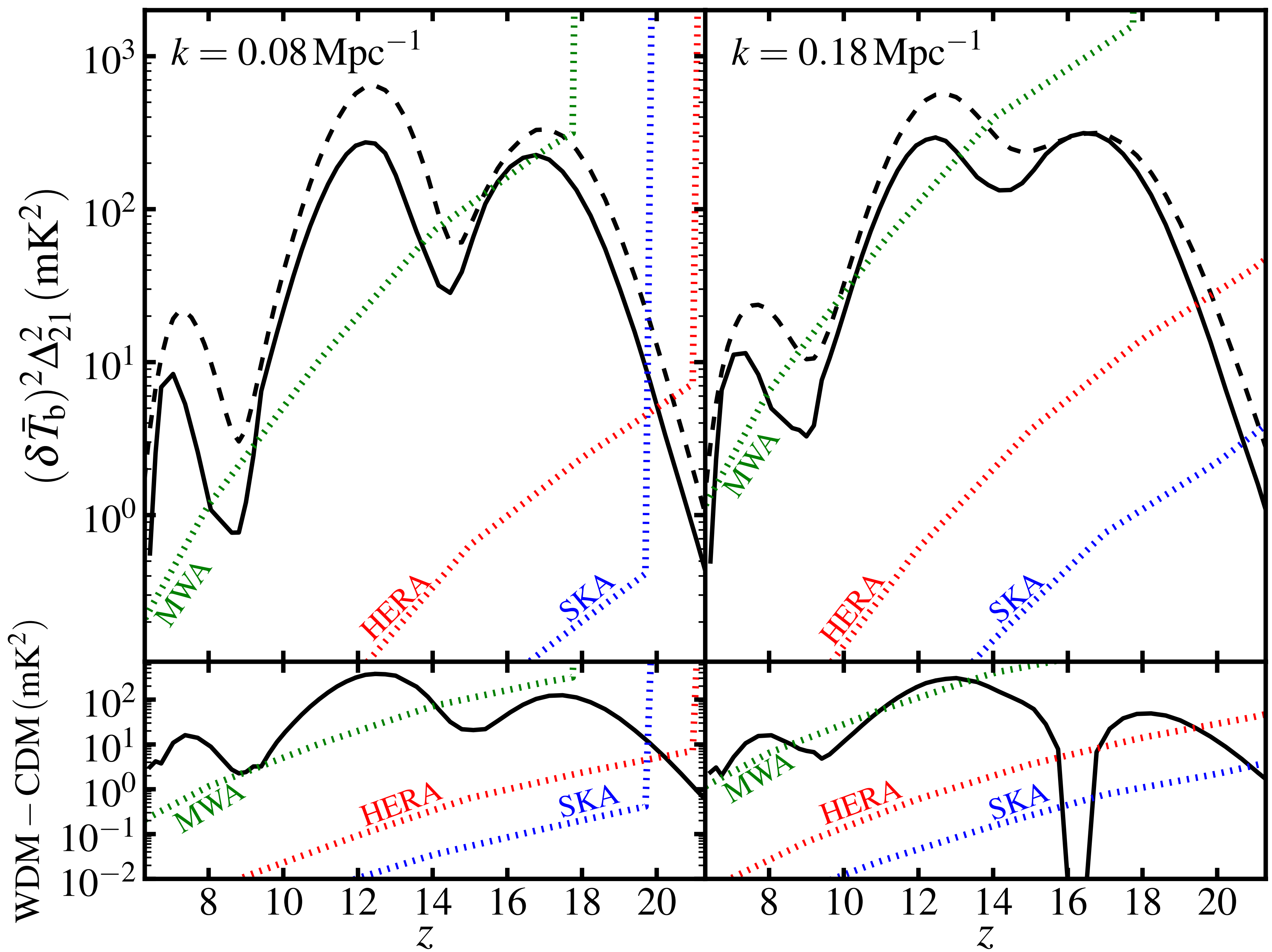
Cosmic string wakes
Brandenburger+ 2010

primordial magnetic fields
Shiraishi & Tashiro

...

Heating and WDM

Heating by dark matter annihilation could give insight into DM properties: CDM vs WDM



CDM=solid
WDM=dashed

m_X=2keV

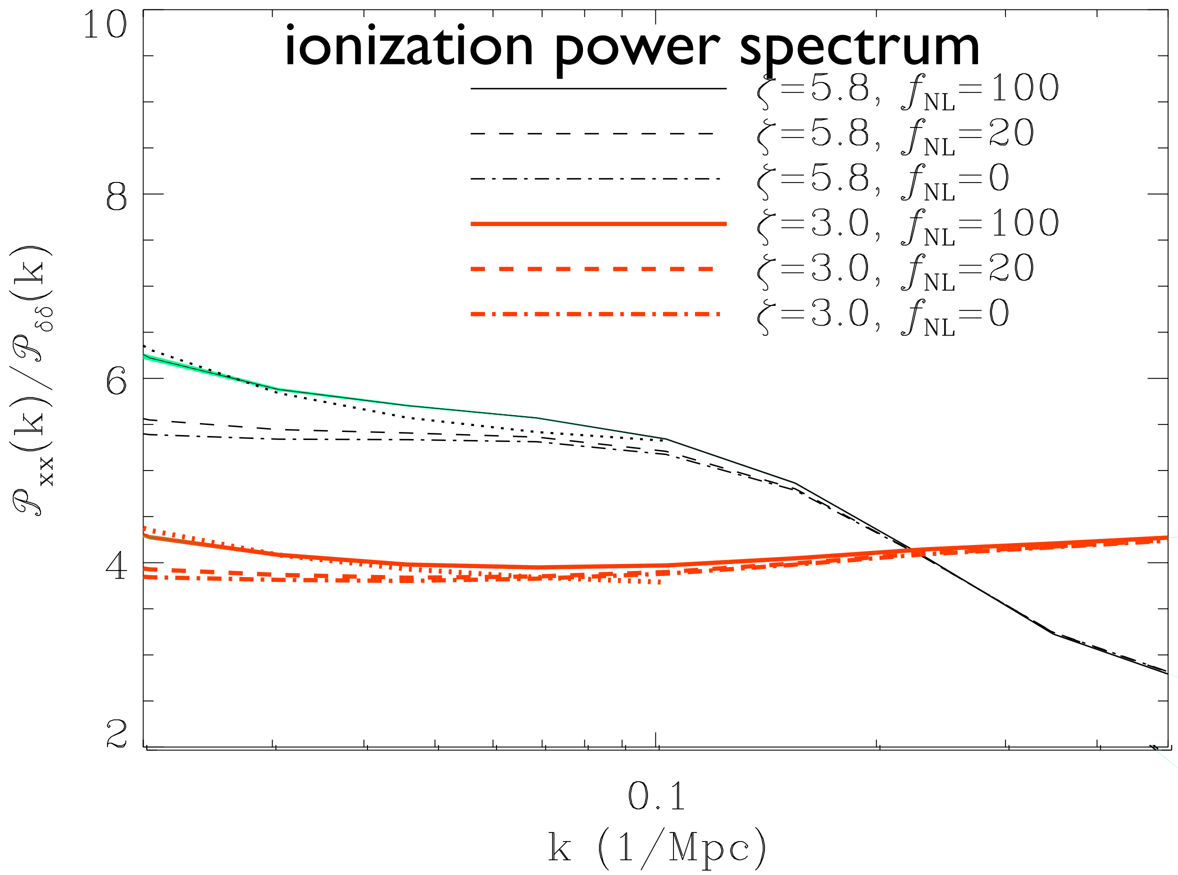
Sitwell+ 2014

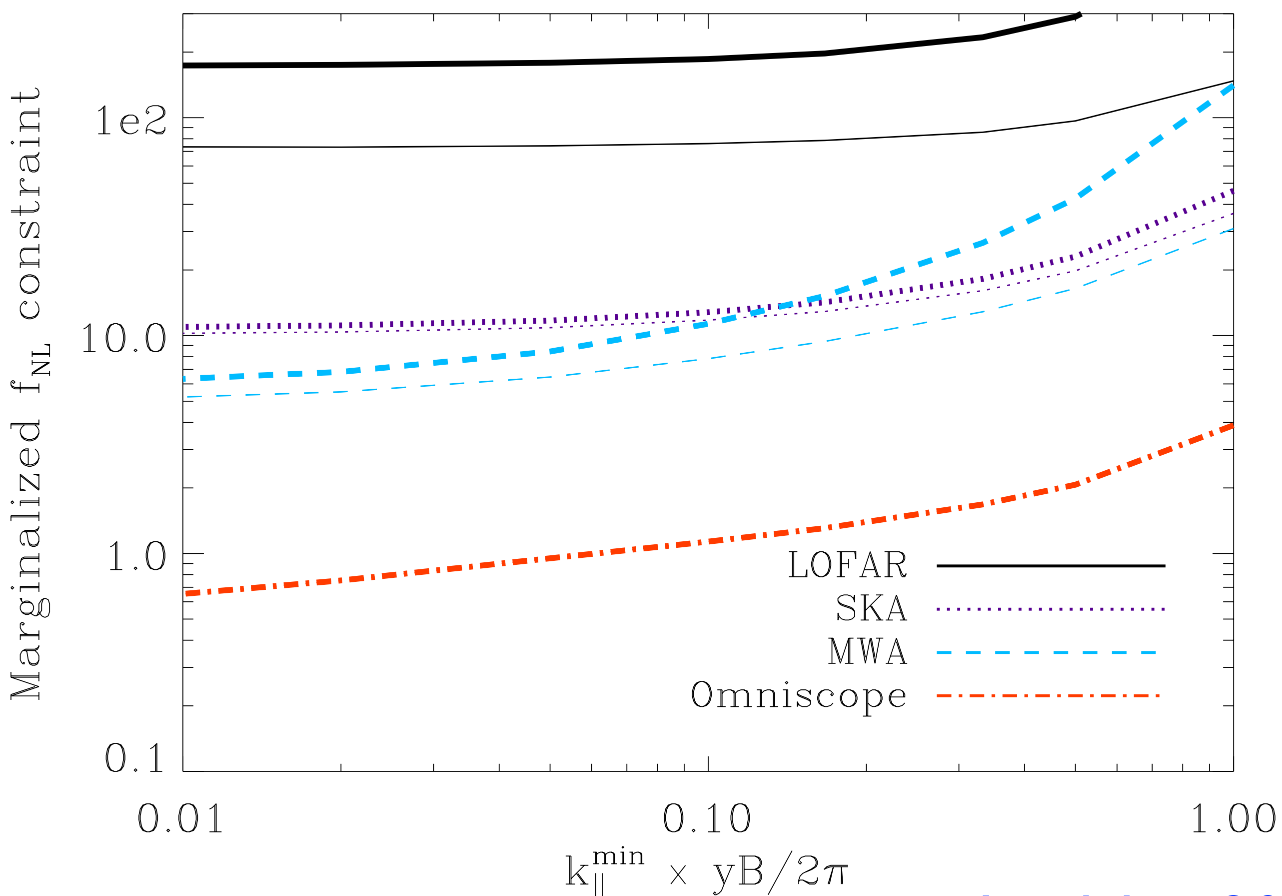
Non-Gaussianity

Density distribution can modify source population
=> signature in ionization field

E.g. Scale dependent bias from primordial non-Gaussianity

$$\Delta b_x(k,z) = 3(b_x - 1) f_{\rm NL} \Omega_m H_0^2 \bar{\delta}_B / \big(D(z) k^2 T(k)\big)$$





Joudaki+ 2011

Scale dependent bias from primordial non-Gaussianity is one example
Others: WDM, ...

Cosmic shear

Weak lensing by matter between 21cm and observer
=> probes normal regions of sky

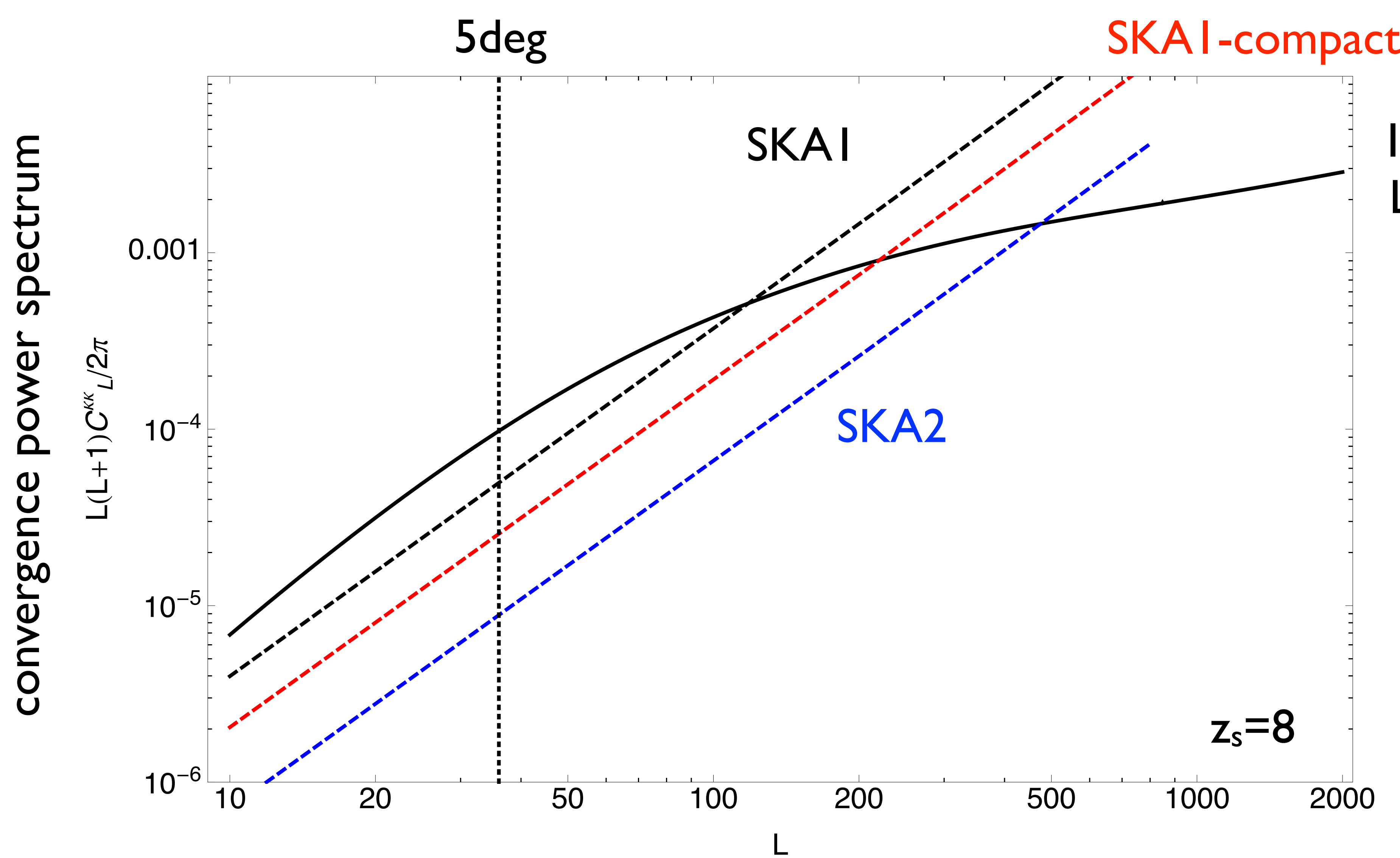


Image dark matter along LoS to 25 deg^2 patch on ~10 arcmin scales

deep 100deg^2 to shallow 10,000 deg^2 survey

$$C_\ell^{\rm N} = \frac{(2\pi)^3 T_{\rm sys}^2}{B t_{\rm obs} f_{\rm cover}^2 \ell_{\rm max}(\nu)^2}\,,\qquad N(L,\nu) = \left[\sum_{j=1}^{j_{\rm max}} \frac{1}{L^4}\int \frac{d^2\ell}{(2\pi)^2} \frac{[\mathbf{l}\cdot\mathbf{L}C_{\ell,j} + \mathbf{L}\cdot(\mathbf{L}-\mathbf{l})C_{|\ell-L|,j}]^2}{2C^{\rm tot}_{\ell,j}C^{\rm tot}_{|\mathbf{l}-\mathbf{L}|,j}}\right]^{-1}$$

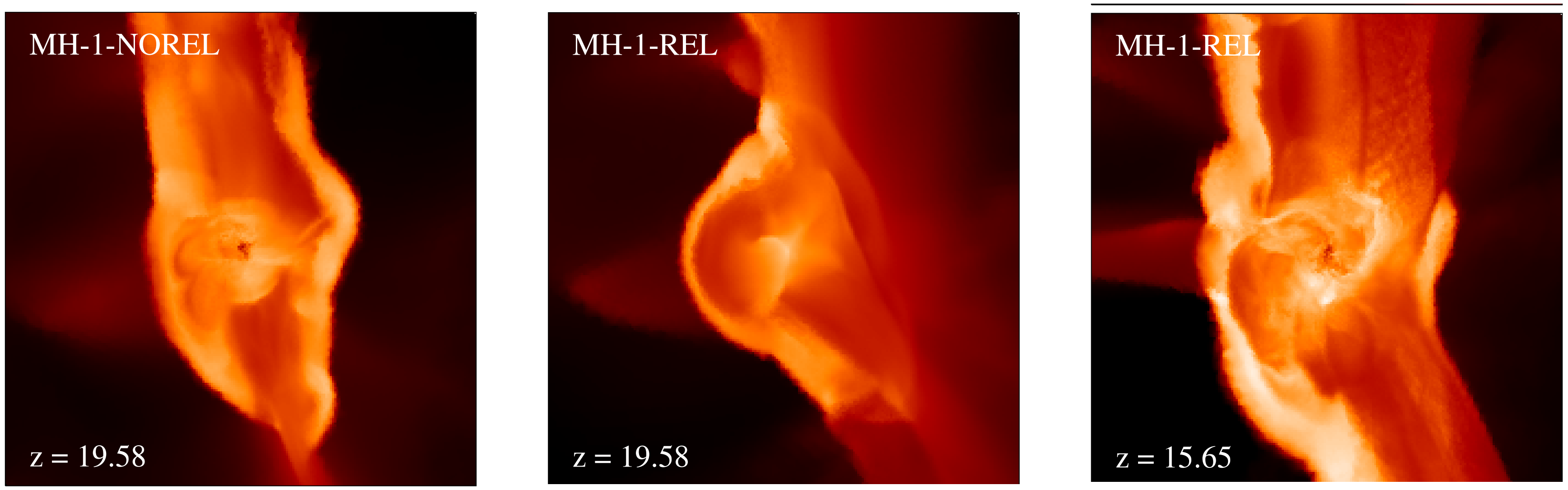
Metcalf & Pourtsidou 2014

How the wind blows?

Recombination leads to sudden drop in sound speed
=> coherent supersonic relative motion of baryons and dark matter

Tseliakhovich & Hirata 2010

No-rel: galaxy forms at z~20 | Rel: snapshot at z~20 | Rel: gal formation delayed to z~16



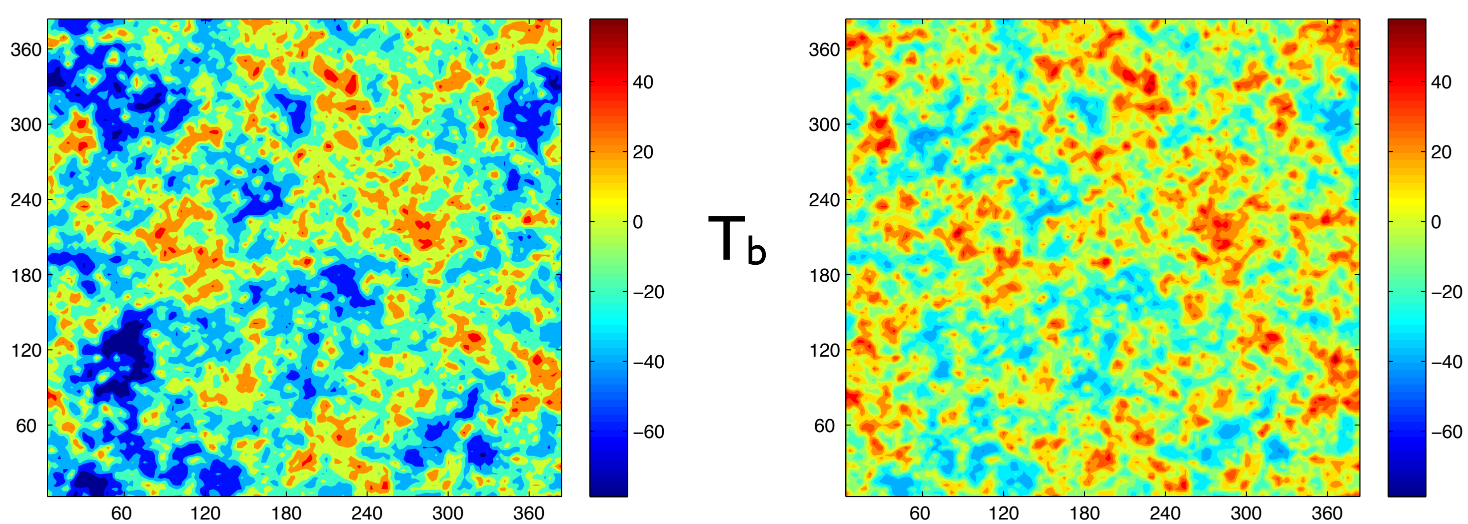
flow

Greif+ 2011

Galaxy formation in low mass $<10^8$ Msol halos delayed

Little effect on high mass halos
=> importance of effect decreases at late times

Maio+2010, Greif+2011, Stacey+2011



With v | z=20 | Without v

Visbal+ 2012

Coherence of velocity field leads to boost in 21cm fluctuations
=> much more detectable signal
+ enhanced BAO signature

IF star formation in low mass halos important

Summary

21 cm observations will transform our understanding of galaxy formation and astrophysics during first billion years

We still don't really know how well we will be able to separate cosmology from astrophysics (How will imaging help? Mask astrophysics?)

Cosmology requires some degree of inventiveness:
1) Infer density field directly (avoid + model astro, RSD)
2) Heating driven by exotic sources (DM annihilation,primordial BH, ...)
3) Impact of cosmology on sources (non-G, WDM, ...)
4) Lensing (map DM)

Other? e.g. varying constants, cosmic string wakes, CMB tau, ...

The Three faces of 21cm

21cm observations will transform cosmology!

f_{NL}~0.01, individual neutrino masses,
incredible precision on cosmological parameters,…

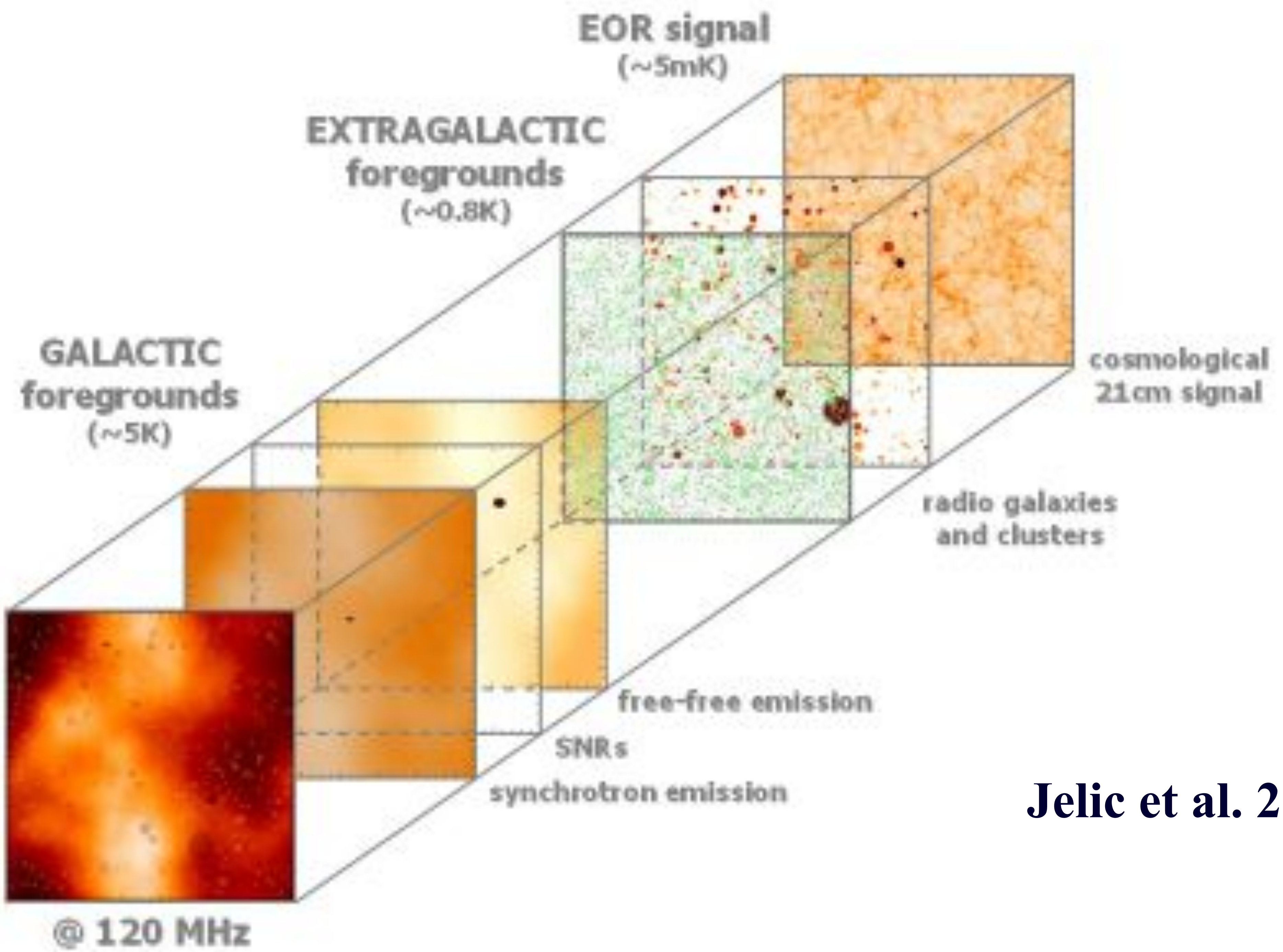
Foregrounds too big & messy
Instruments too complicated
Astrophysics contaminates everything

WAIT!

Status of observations

Foreground removal

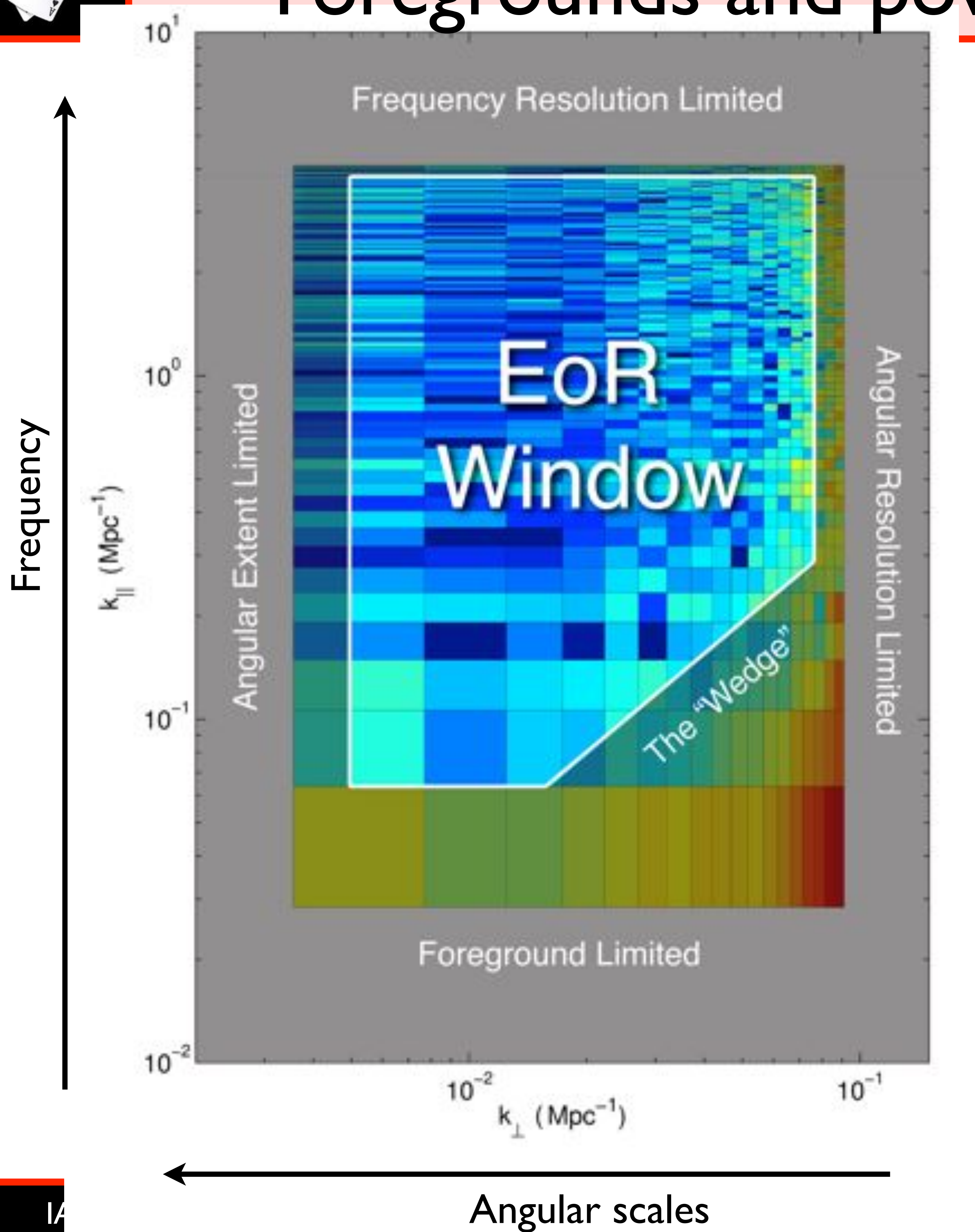
Foregrounds ~ 10^3-10^5 signal



Jelic et al. 2008

ICA, GMCA Chapman+ 2012, 2013 Quadratic estimators Liu+ 2012, Dillon+ 2013

Foregrounds and power spectrum



Instruments naturally probe narrow cylinder in Fourier space

EoR window set by:

k_perpendicular <=> angles
- low k: field of view set by station size
- high k: angular resolution set by long baselines

k_parallel <=> frequency
- low k: smooth foregrounds so mainly contaminate long wavelength modes
- high k: frequency resolution of instrument

The "Wedge"
- point source removal residuals and beam chromatic effects

Dillon+ 2013

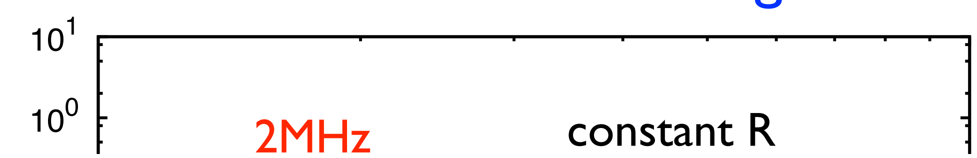
Giant Meterwave Radio Telescope

Pre-existing telescope

Sky map	Sky map - foregrounds	Sky map-foregrounds zoom

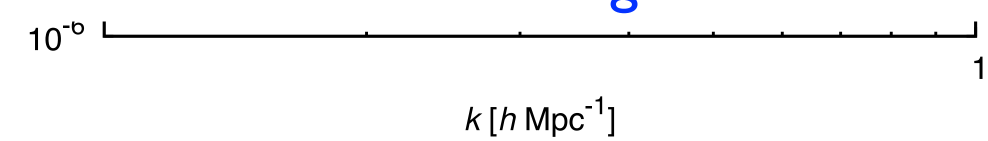
Claimed upper limits
on power spectrum of
cold IGM <$(70\text{mK})^2$ at z=8.5

Paciga+ 2010



Since retracted: ~80% signal removed too
now claim <$(248\text{mK})^2$ at k=0.50 hMpc^{-1} at z=8.6

Paciga+ 2013

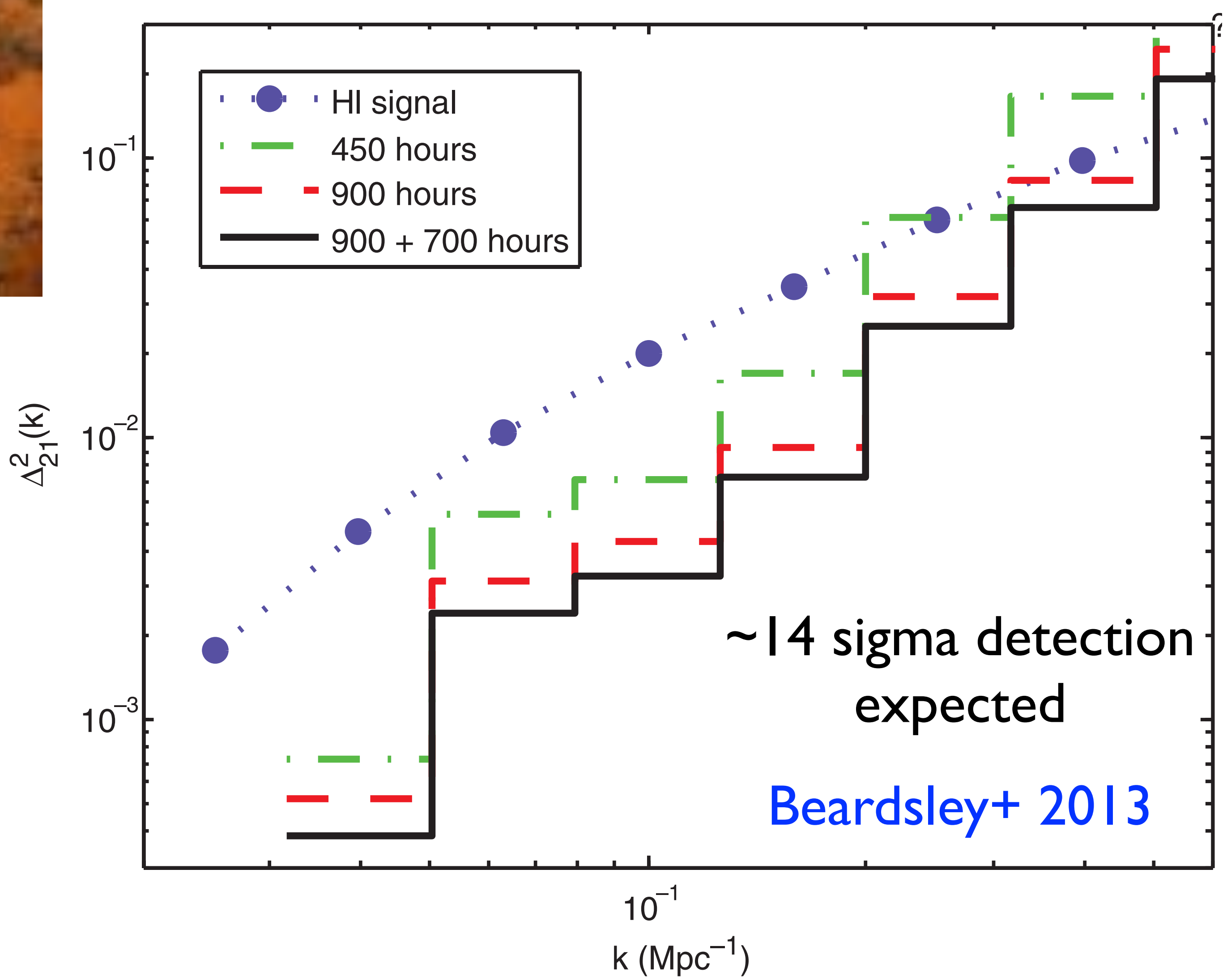


Data of the required sensitivity acquired with GMRT
=> first serious attempt at 21 cm signal at z~8.5

Murchison Widefield Array (MWA)

128 tiles of 16 dipoles

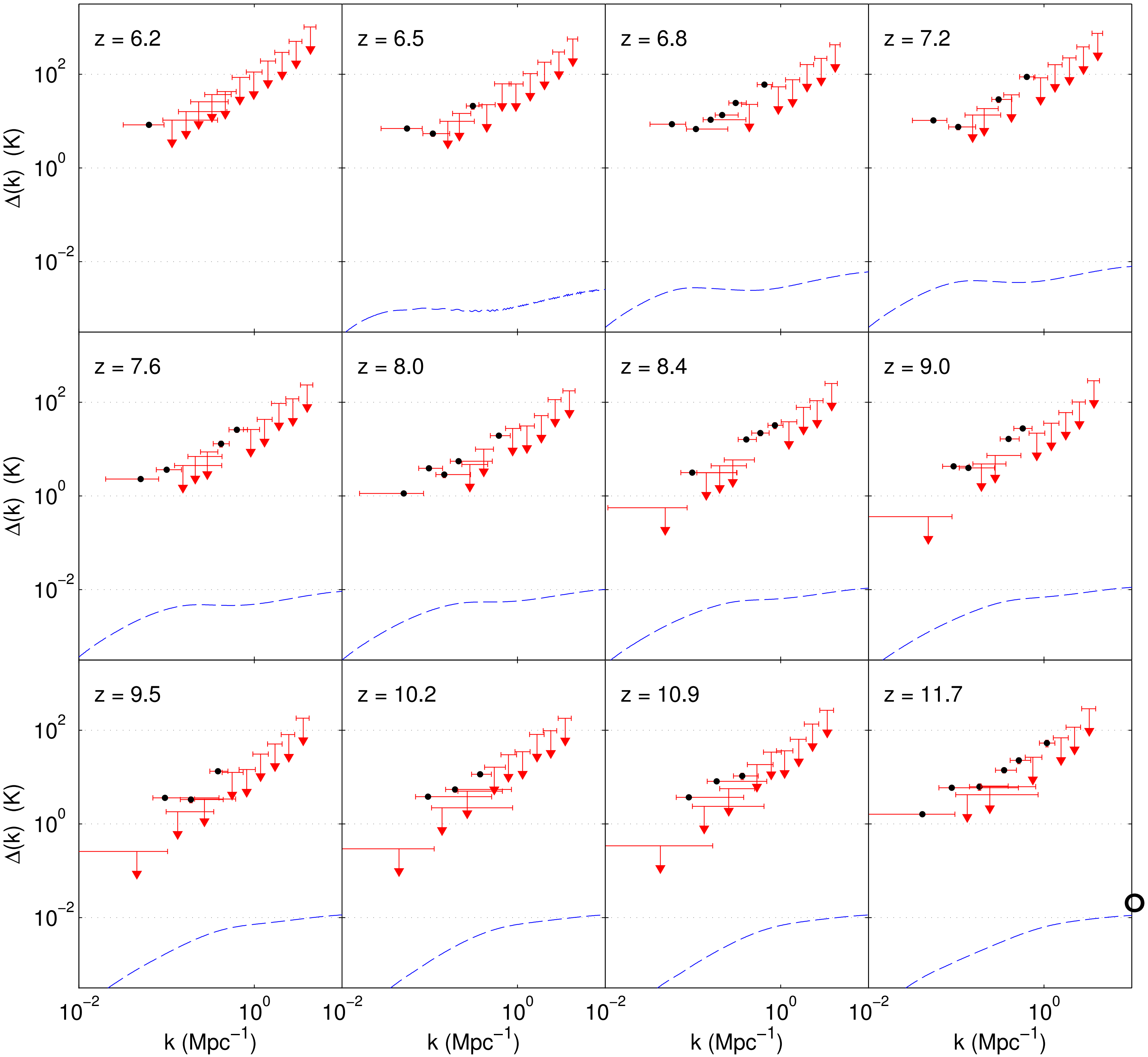
~1km long baselines



Compact array =>
- filled UV plane
- wide field of view for survey
- data rate requires real time calibration

MWA-32T constraints

Dillon+ 2013



Best limit <(300mK)^2 k=0.07hMpc^{-1} at z=9.5 similar constraints over range z=6.2-11.7

Two orders of magnitude to go (just 22hr & 32T)

MWA-128T commisioning underway with science observations earlier in the year

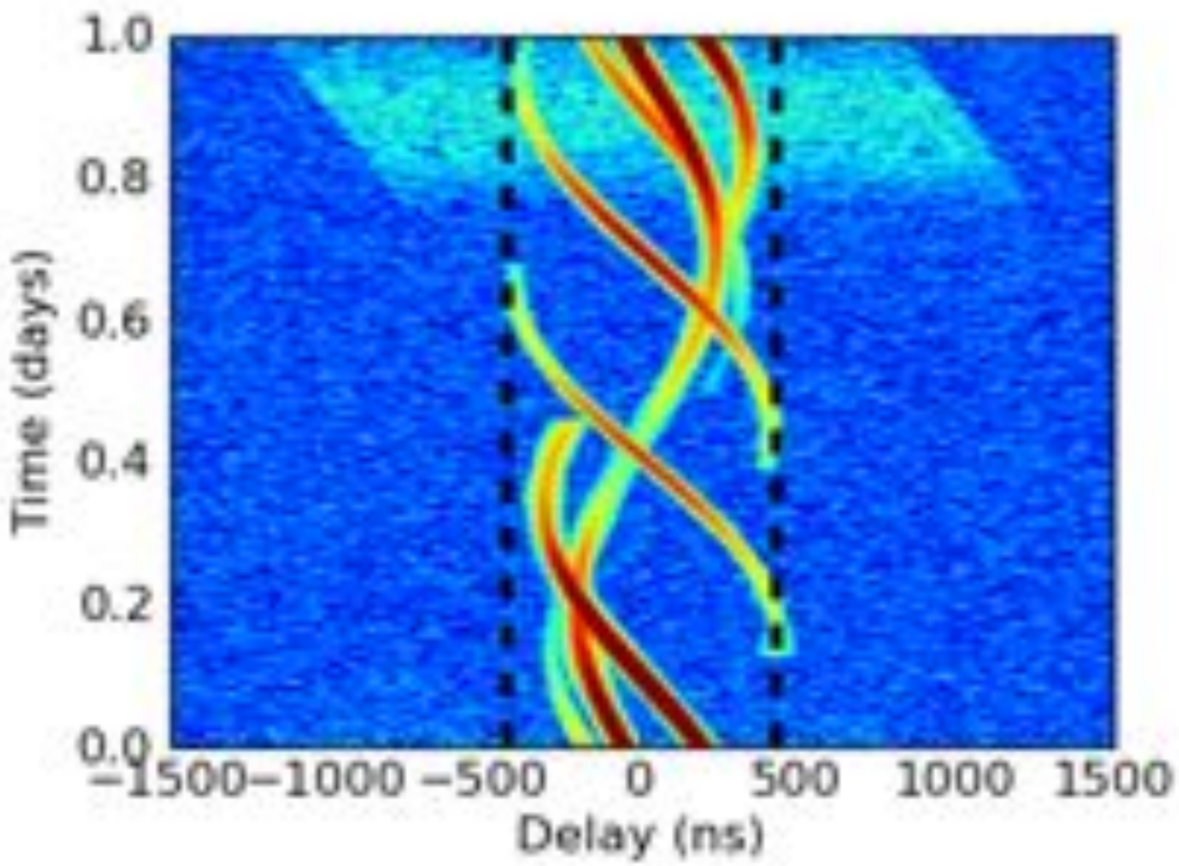
PAPER-32

64 simple dipoles - 128 since early 2014

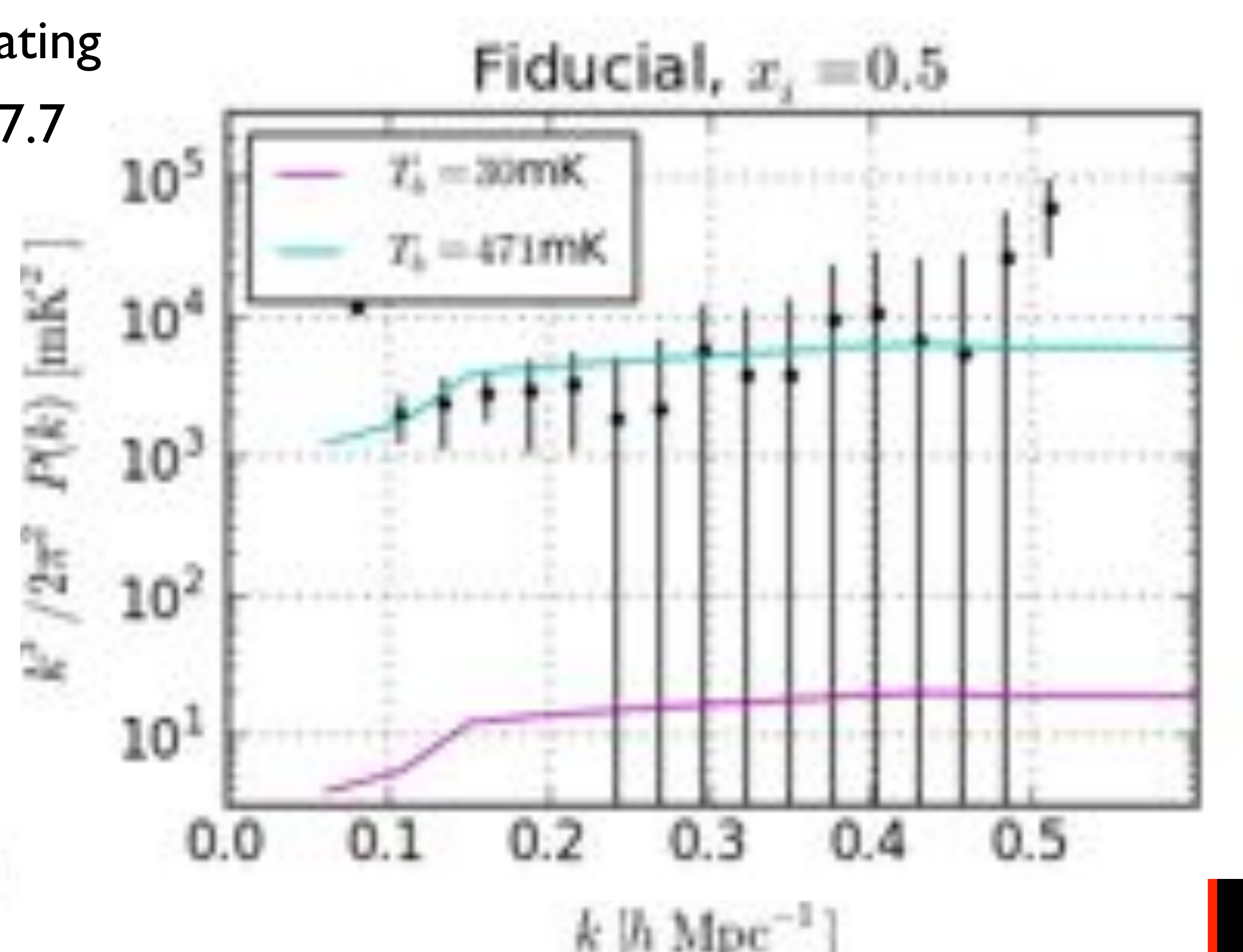
Small scale experiment
=> less collecting area than LOFAR/MWA
=> compensate by making very compact

Begins to constrain models with no X-ray heating

PAPER-32 <(52mK)^2 at k=0.11hMpc-1 at z=7.7



Delay-spectrum technique for foreground removal



Redundant configuration leads to narrow k-range of sensitivity

Parsons+ 2014

Low Frequency Array (LOFAR)

General purpose array:

Long baselines for point source removal

Smaller field of view, multiple beams

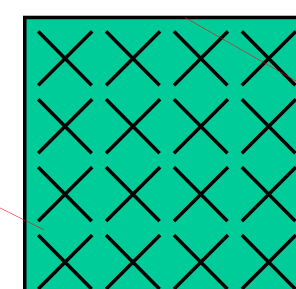
Initial data shows no show stoppers

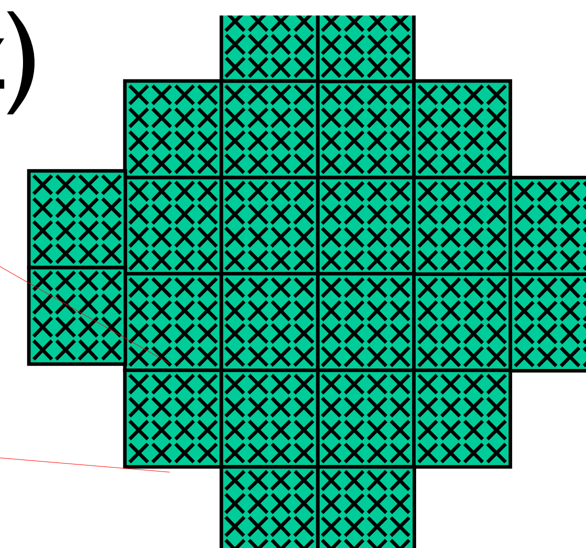
see Yatawatta+ 2013

100s hr data collected

LBA (10-80MHz)

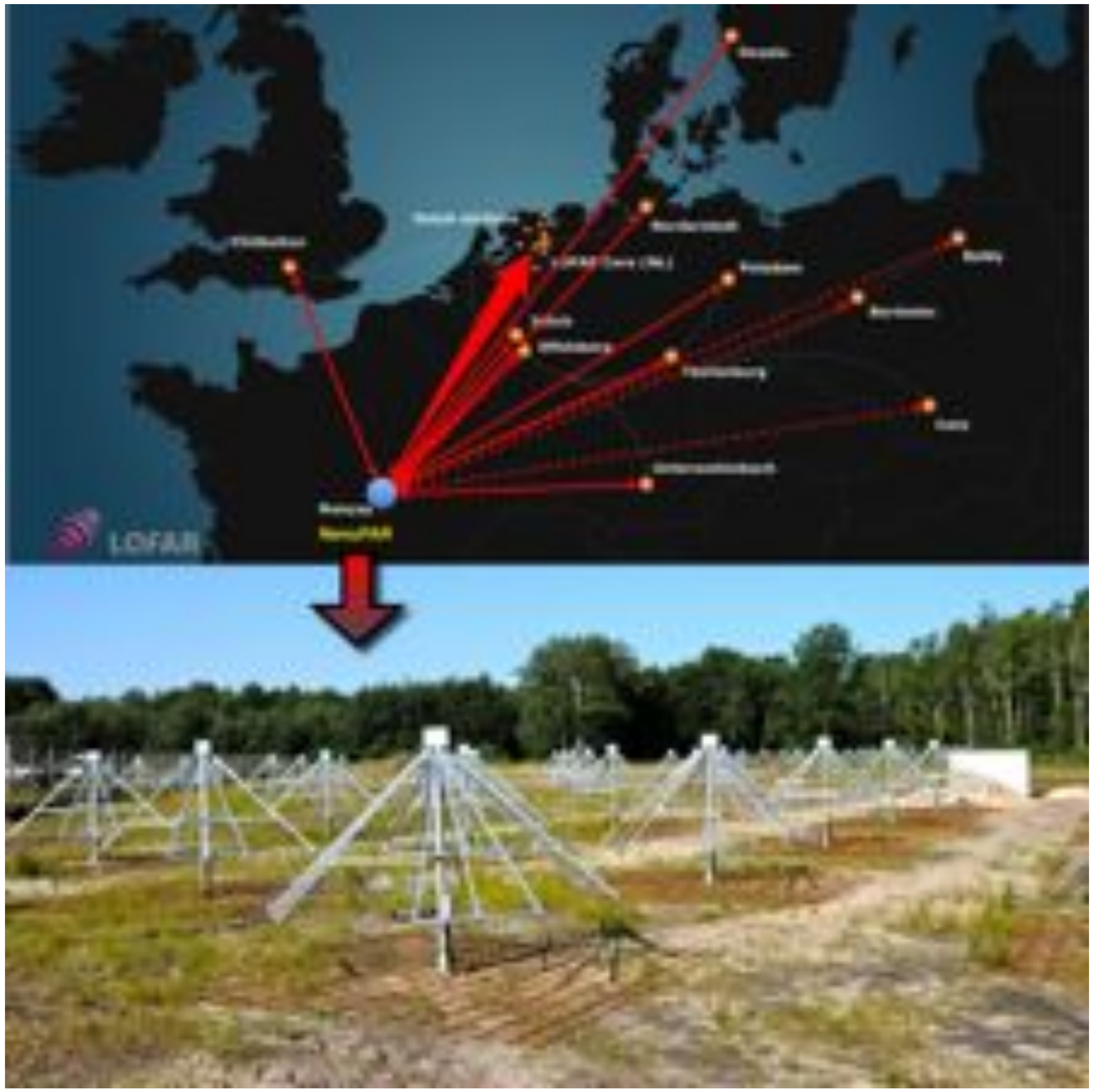
HBA (120-240 MHz)





NenuFAR - SKA pathfinder

NenuFAR=New extension in Nancay upgrading LOFAR

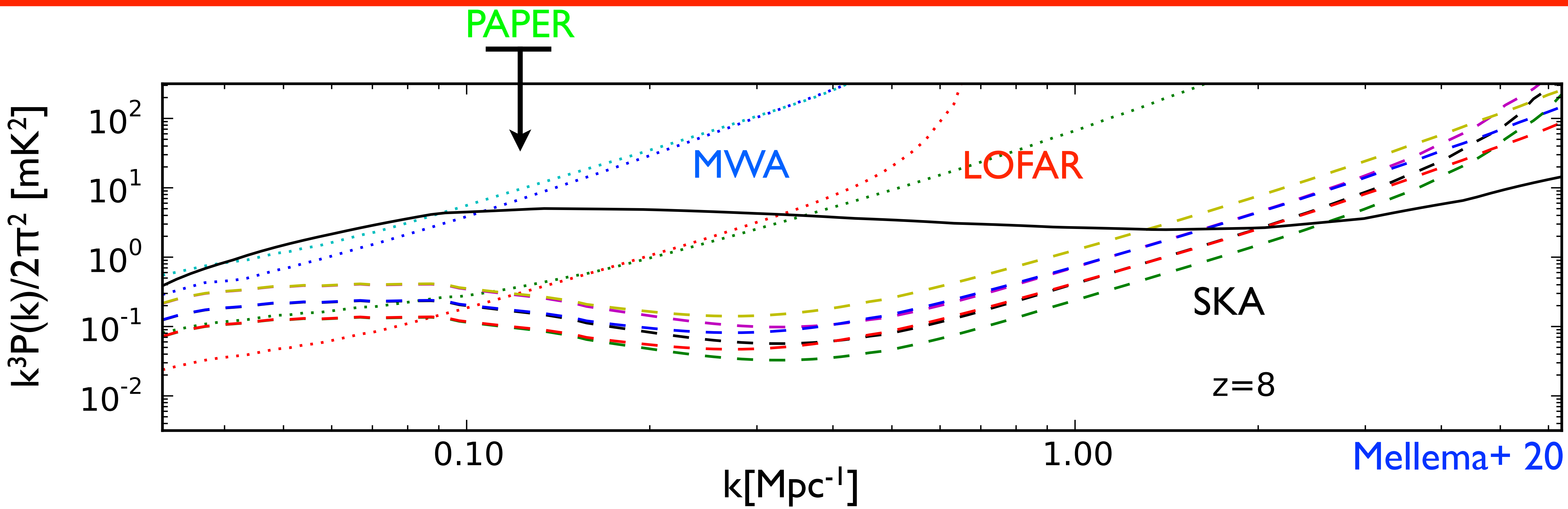


Sensitivity comparable w LOFAR core

Stand alone mode interesting for Cosmic Dawn observations

RIP Jean-Francois Denisse
16 May 1915-17 November 2014
Founded Nancay radio astronomy station in 1956

Summary of experiments



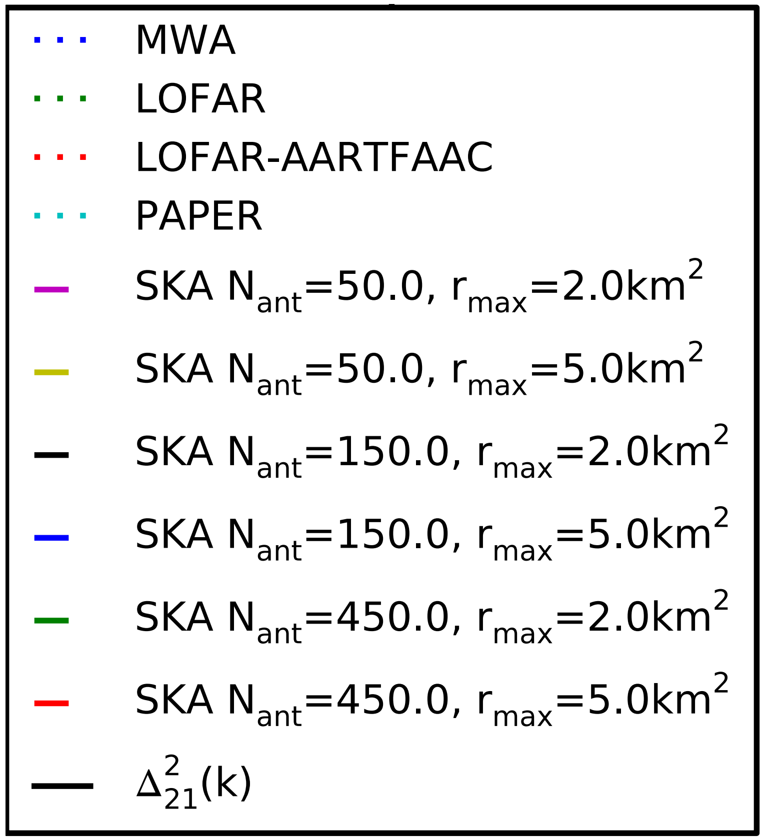
Mellema+ 2013

MWA-32T: <(300mK)^2 at k=0.07 hMpc^{-1} at z=9.5 Dillon+ 2013

GMRT: <(248mK)^2 at k=0.50 hMpc^{-1} at z=8.6 Paciga+ 2013
(previous claim was <(70mK)^2)

PAPER-32: <(52mK)^2 at k=0.11hMpc^{-1} at z=7.7 Parsons+ 2013

LOFAR: yet to be released but Yatawatta+ 2013



SKA status

SKA director general - Phil Diamond

SKA sites: South Africa - Karoo
Australia - Western Outback

SKA-LOW: 50-350 MHz (Australia)
SKA-MID: 350MHz-3GHz (SA)
SKA-SUR: 350MHz - (Australia)

Current

Rebaselining exercise underway to fit cost cap of €650M

Decision expected ~ March 2015

Watch arXiv for updated SKA Science Case ~ 150 chapters

Conclusions

Imperial College London

21cm intensity mapping powerful probe of LSS - competitive with optical and constrains higher reshifts

21cm EoR observations will shed light on Cosmic Dawn and Epoch of Reionization. Adds details to CMB constraints on reionization history

Cosmology from EoR requires first understanding astrophysics & foregrounds. Information from pathfinders will fill in gaps in current understanding.

EoR experiments have data => 1st detection expected soon

Exciting array of new instruments coming soon:
IM: BINGO, CHIME, SKA-MID, SKA-SUR
EoR: HERA, SKA-LOW, … … … Omniscope

Collectively 21cm observations offer a path to observe majority of cosmic volume - challenge is to learn how to exploit that

Fin