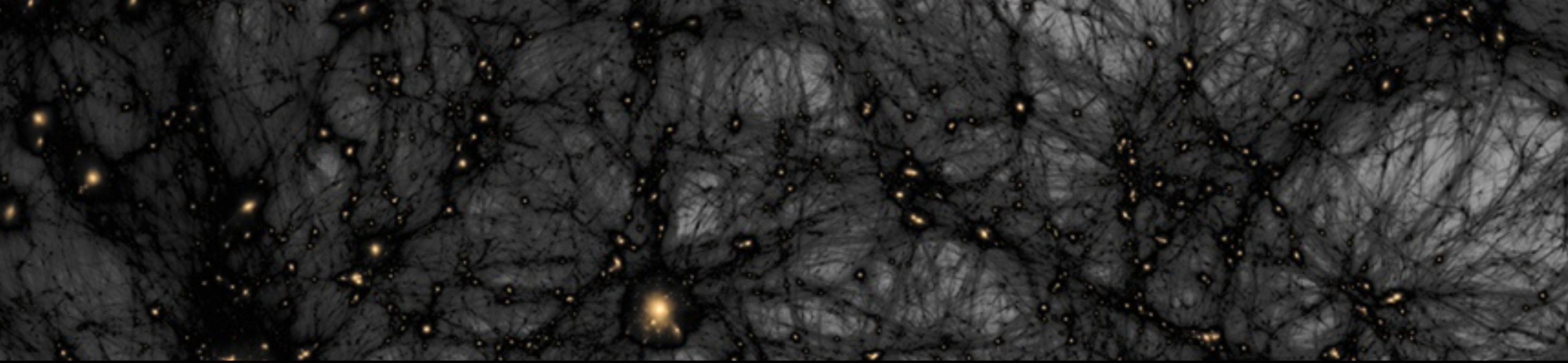


LECTURE III: 21cm INTENSITY MAPPING

Alkistis Pourtsidou

Queen Mary University of London

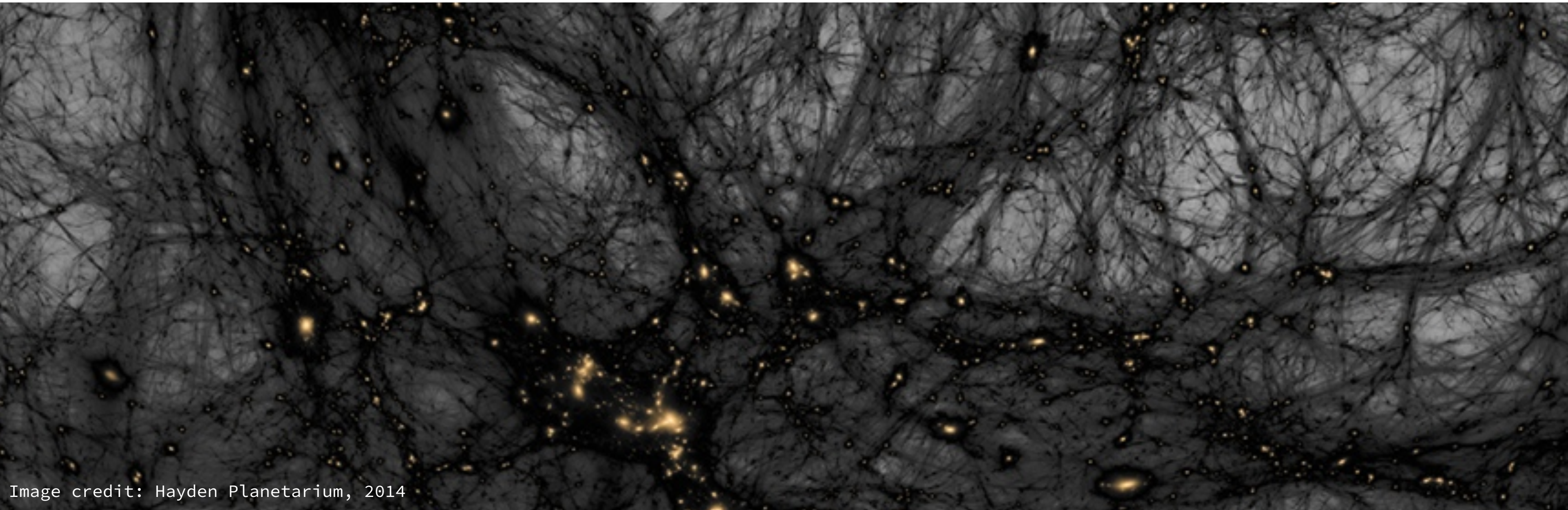
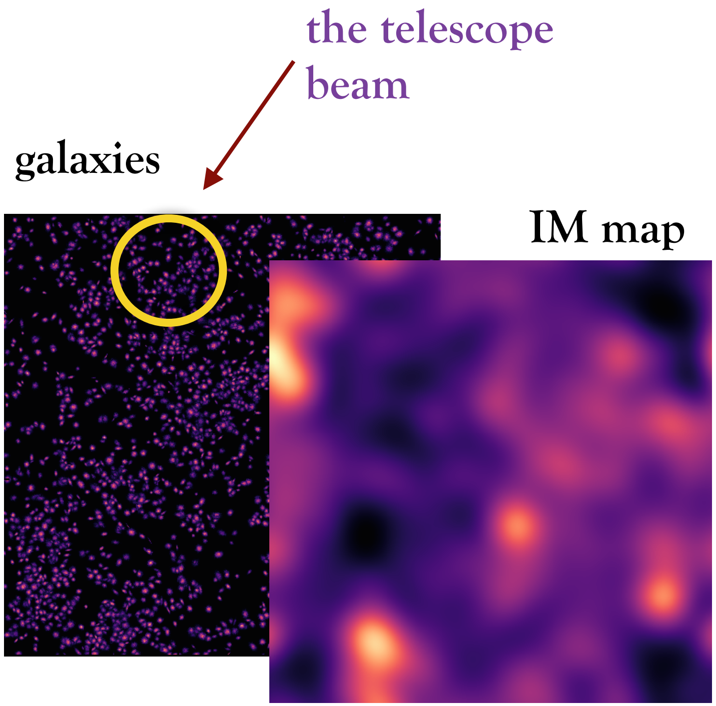


Image credit: Hayden Planetarium, 2014

RECAP: THE INTENSITY MAPPING METHOD

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



[Simulations by S. Cunnington]

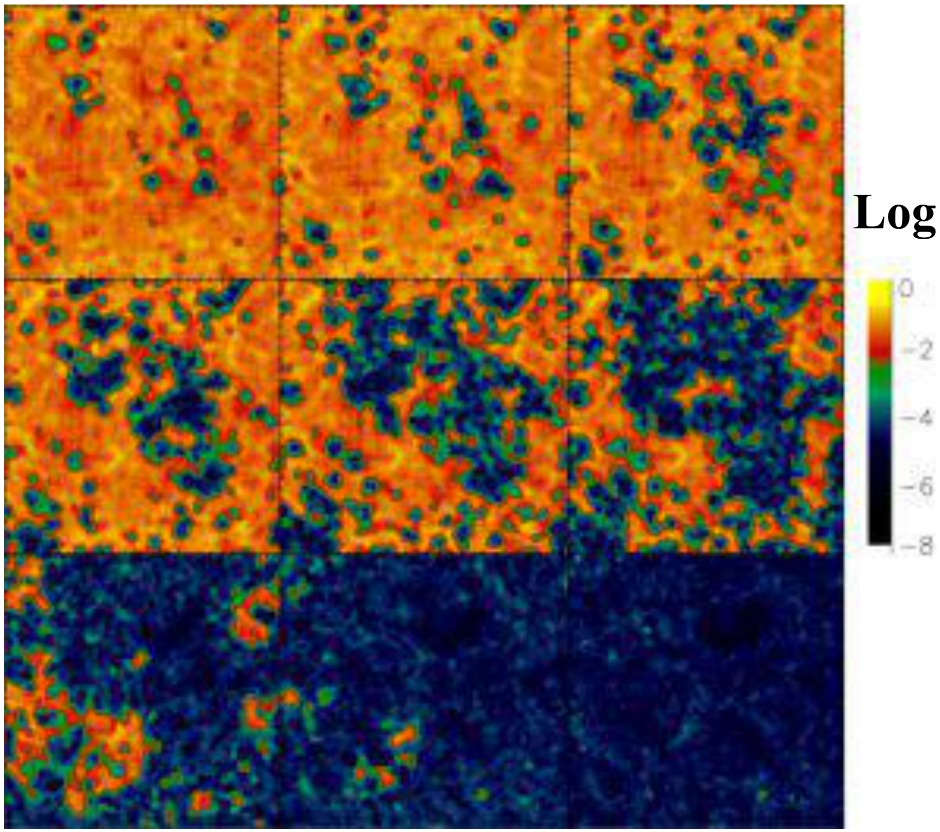
- Detecting HI (neutral hydrogen) galaxies via their 21cm emission line is very expensive
- But cosmological information is on large scales
- Get intensity map of the HI 21cm emission line - like CMB but 3D!
- Excellent redshift resolution
- **Signal of the order 0.1 mK – foregrounds much bigger**

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

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

21cm temperature fluctuations

z=13.5 **Ciardi et al.**



z=8

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

- 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

21CM OBSERVABLE UNIVERSE

Huge unexplored volume can be probed with 21cm!

Mao et al 2008

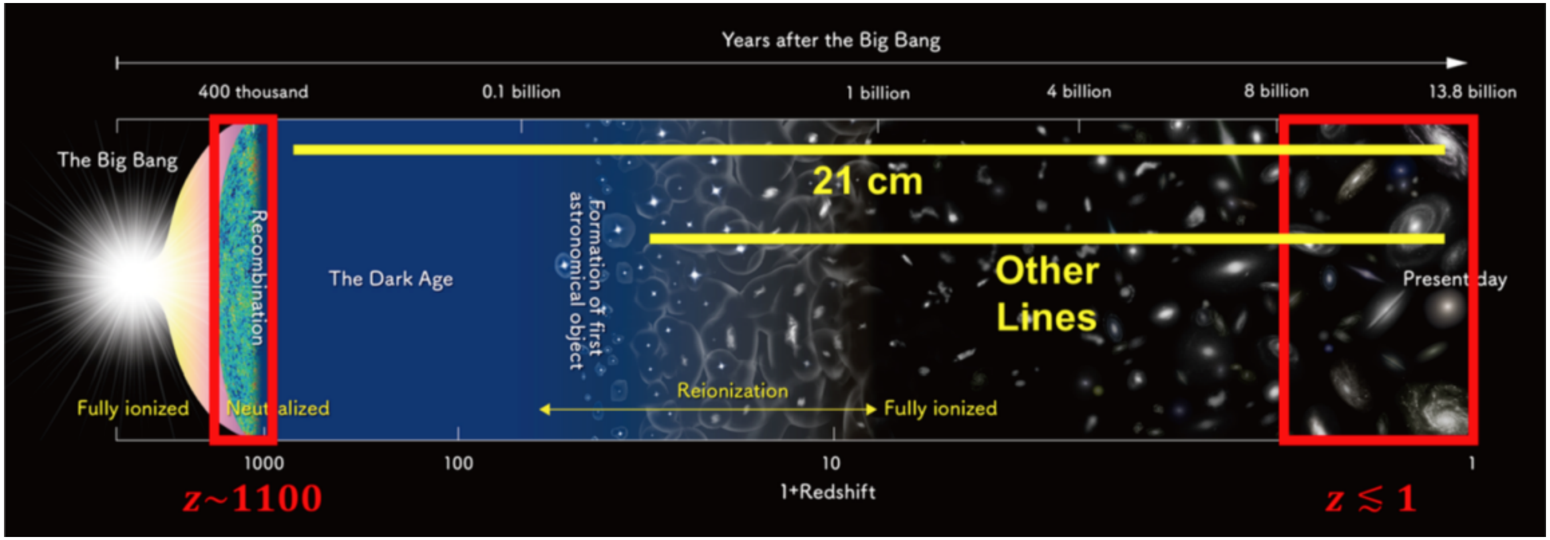


Image Credit: NAOJ [Kovetz et al. 2017 arXiv:1709.09066]

Single dish mode (auto correlation)

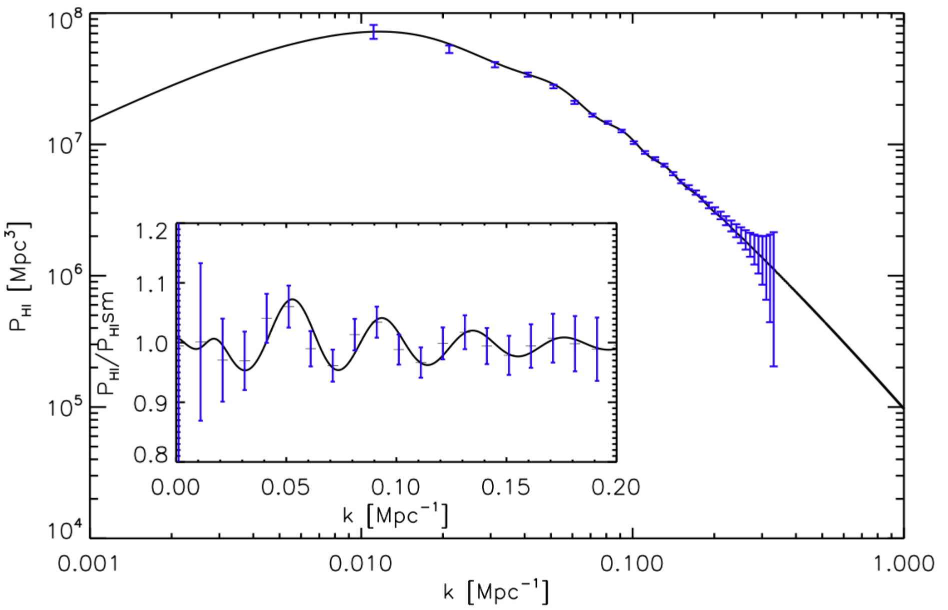
- The auto correlation signal from one or more dishes is considered
- Instrumental noise $1/N_{dish}$
- Smallest scale the array can probe is set by the beam
- Single dish mode can probe ultra-large scales (if it scans enough sky)

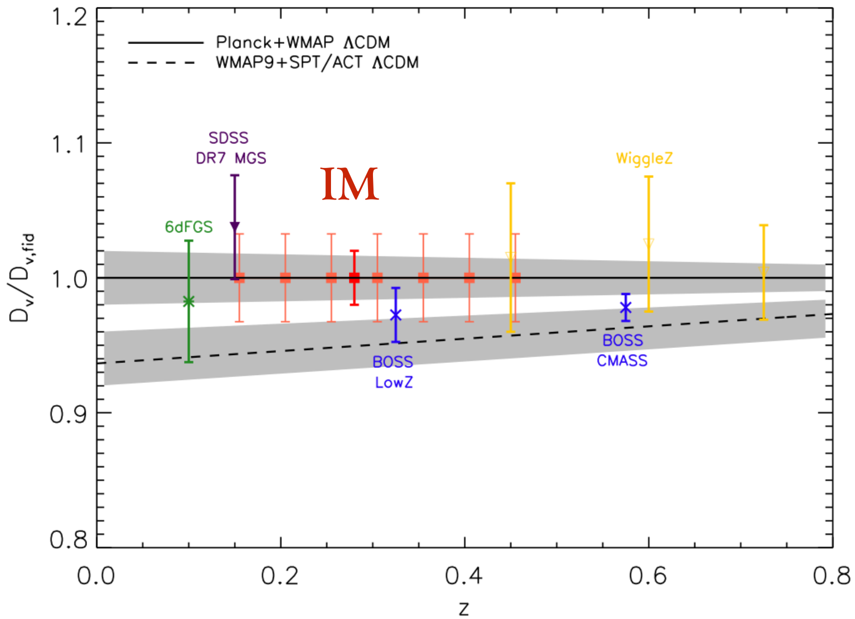
Interferometer mode

- The cross-correlation signal from the array elements is used
- Smallest scale the array can probe is set by the maximum baseline → can achieve very high angular resolution
- Largest scale given by the shortest baseline

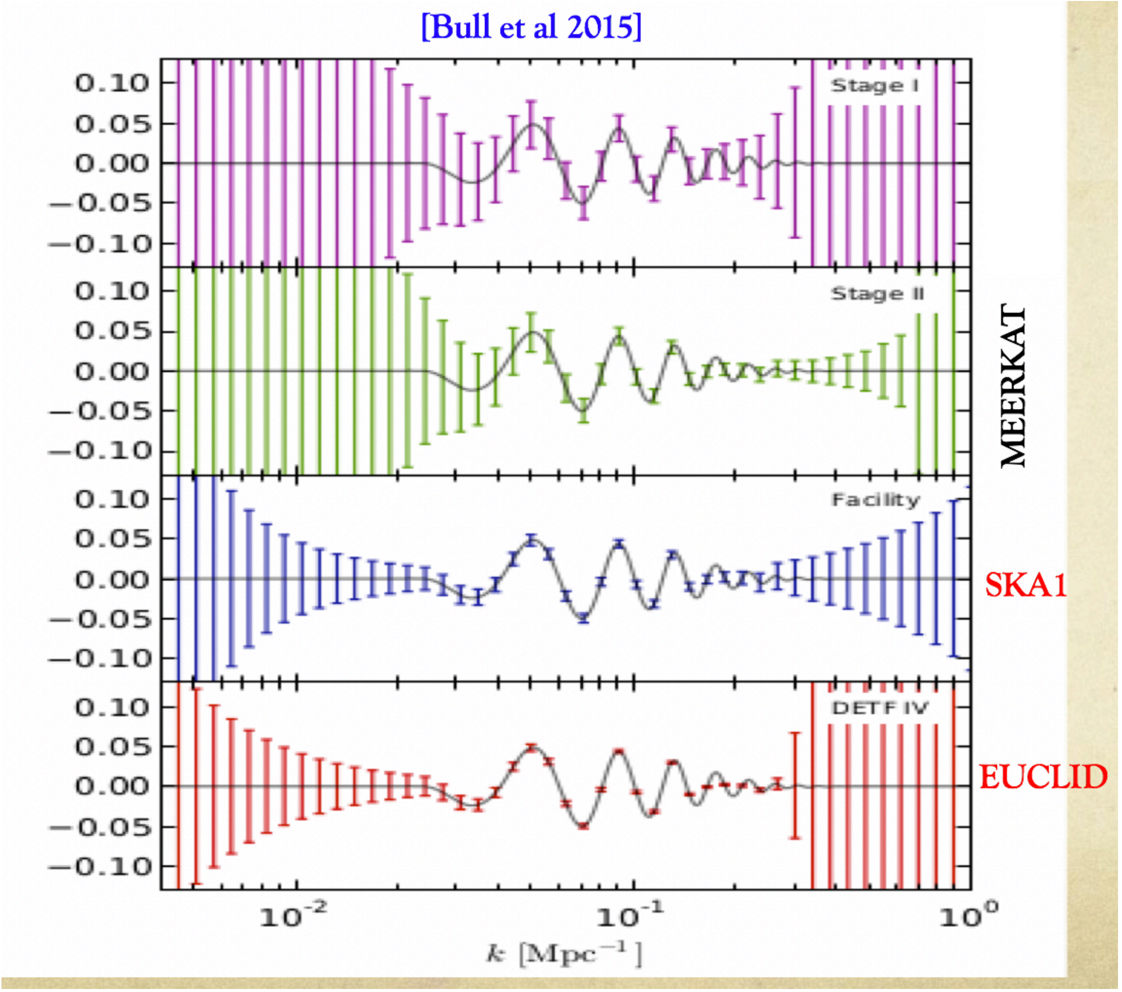
PRECISION COSMOLOGY IN THE RADIO: THE SINGLE DISH APPROACH

- **Problem:** For cosmology, we need to probe large volumes fast - interferometers not good at that (not at low z at least)
- **Solution:** Precision cosmology in the radio with the single-dish approach [Battye, AP et al 2013]
- A single 40m diameter dish, with a multi-feed (multi-beam) system, can be competitive with current optical galaxy surveys





MEERKAT AND SKA PHASE 1 IN SINGLE-DISH MODE: LOOKS PRETTY GOOD!



- Let's see how single-dish intensity mapping can do that!

CHARACTERISING THE HI SIGNAL

The mean observed brightness temperature due to the average HI density in the Universe can be written as:

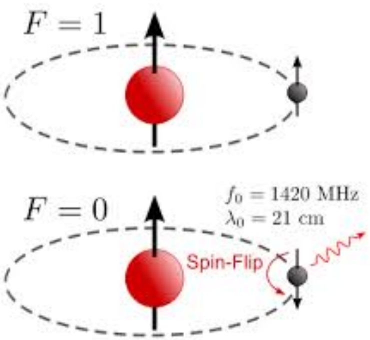
Emission coefficient

Average HI density

$$\bar{T}_{\mathrm{obs}}(z) = \frac{\bar{T}_{\mathrm{emit}}(z)}{1+z} = \left(\frac{\hbar c^3}{k}\frac{3A_{21}}{16 f_{\mathrm{emit}}^2 M_{\mathrm{H}}}\right)\left(\frac{\rho_{\mathrm{HI}}(z)}{1+z}\right)\frac{dl}{dv}$$

peculiar velocities term

Mass of hydrogen atom



$$f_{\mathrm{emit}} = 1420.4\,\mathrm{MHz} \qquad f_{\mathrm{obs}} = \frac{1420}{1+z}\,\mathrm{MHz}$$

The last term, dl/dv, relates the line sight distance to the recession velocity and is given by $1/H_0$ in the local Universe

CHARACTERISING THE HI SIGNAL

To compute dl/dv, we need the comoving volume element:

$$\frac{dV}{dz d\Omega} = \frac{cr^2}{H(z)} = c\left(\frac{r}{1+z}\right)^2 \frac{(1+z)^2}{H(z)} = c\,[d_{\rm A}(z)]^2 \frac{(1+z)^2}{H(z)}$$

$$r(z) = c\int_0^z \frac{dz'}{H(z')} \qquad d_{\rm A}(z) = r(z)/(1+z)$$

We can also write: $dV = d_{\rm A}^2\, dl\, d\Omega$

Hence: $\dfrac{dl}{dz} = \dfrac{c}{H(z)}(1+z)^2$

Therefore, using $dv/c = dz/(1+z)$, we find that

$$\boxed{\frac{dl}{dv} = \frac{(1+z)^3}{H(z)}.}$$

CHARACTERISING THE HI SIGNAL

Substituting the above and using the HI density

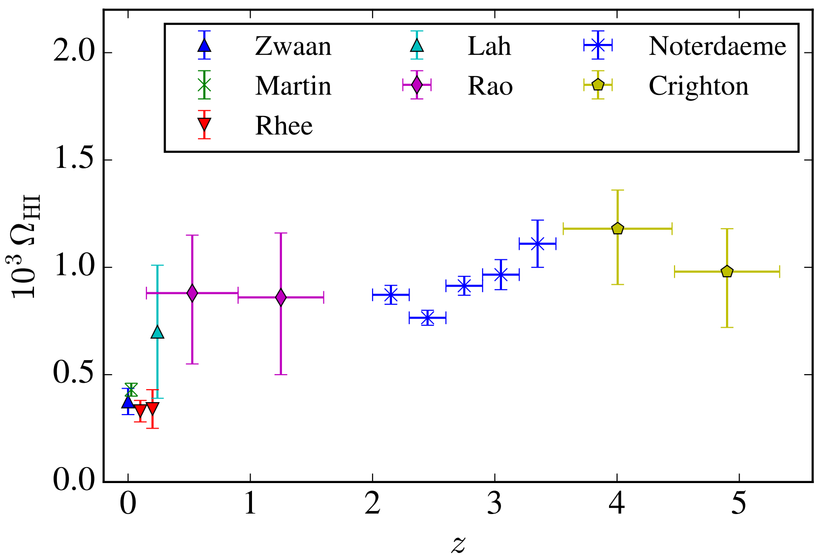
$$\Omega_{\rm HI}(z) = 8\pi G\rho_{\rm HI}(z)/(3H_0^2)$$

we get a simple expression:

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

where $h = H_0/100\,{\rm km\,sec^{-1}\,Mpc^{-1}}$

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



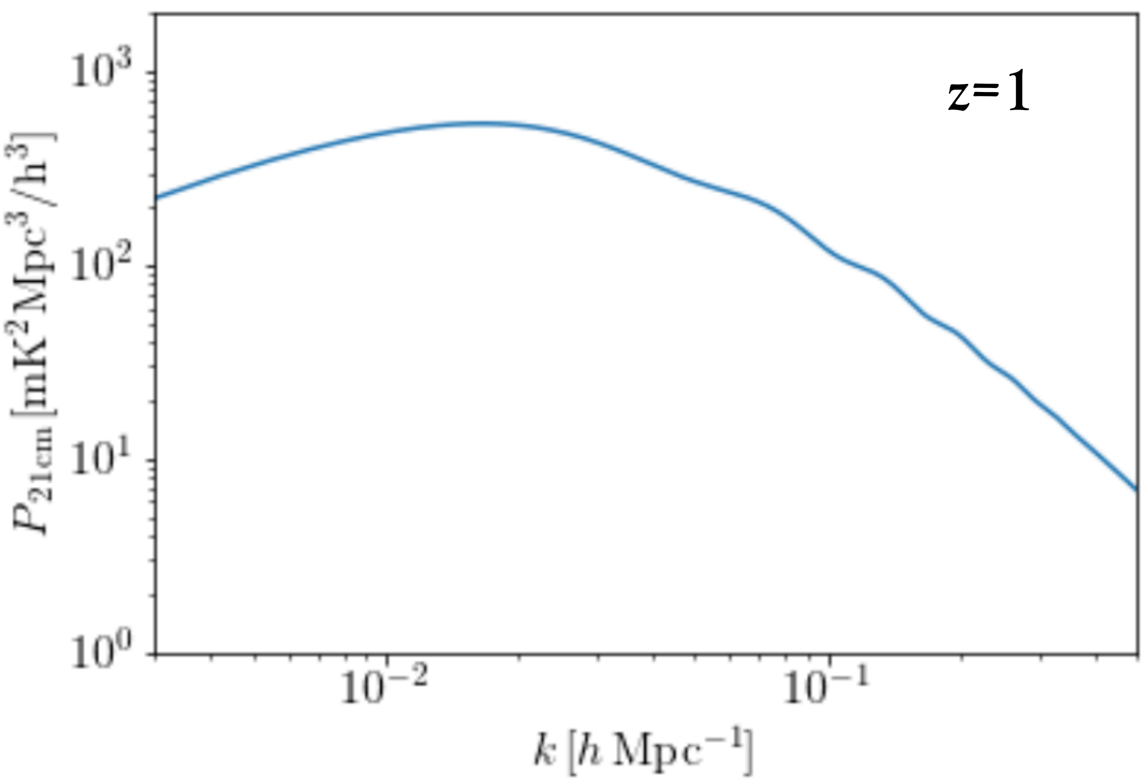
As you can see, the HI density is not very well constrained…later we'll see how HI intensity mapping can help with that!

THE 21CM POWER SPECTRUM

The 3D 21cm power spectrum can be written as $\delta_{21\mathrm{cm}} = \bar{T} b_{\mathrm{HI}} \delta_m$

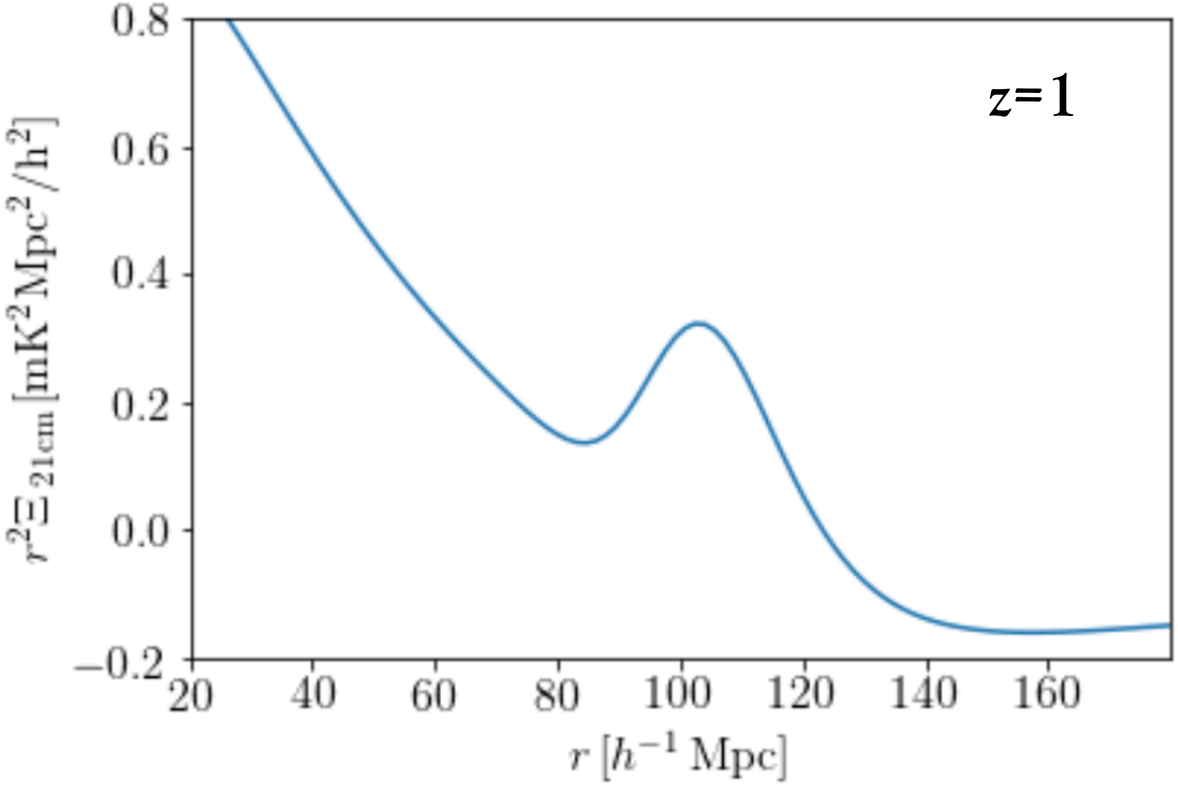
$$P_{21\mathrm{cm}} = \bar{T}(z)^2 b_{\mathrm{HI}}(z)^2 P_m(k, z)$$

Features like BAOs are there, of course; the question is, how well we can detect them!



THE 21CM CORRELATION FUNCTION

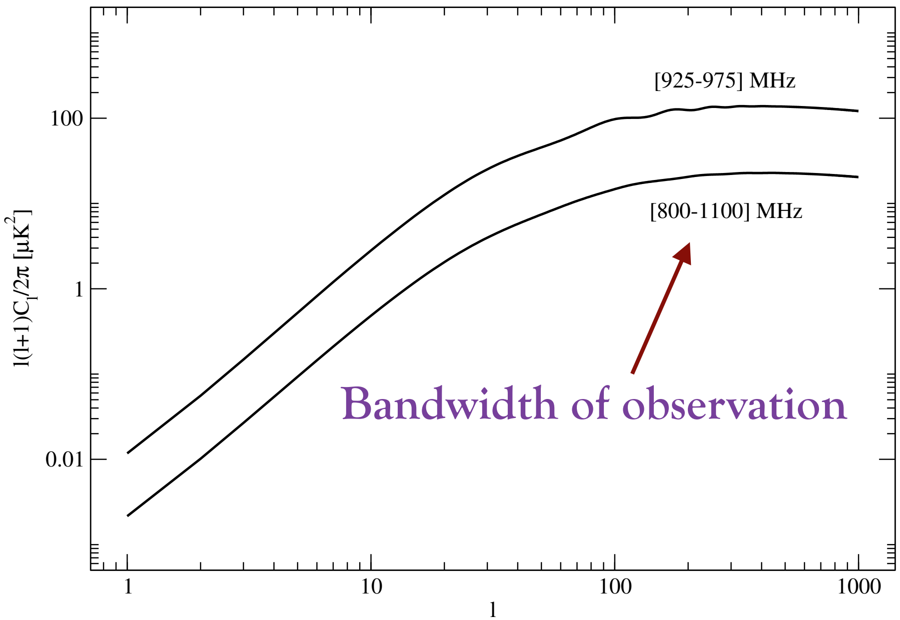
The correlation function at *z*=1 (you will need this for the working group exercise 1.2)



THE 21CM ANGULAR POWER SPECTRA

Angular power spectra are calculated via expansion in spherical harmonics.

[Battye et al. 2013]



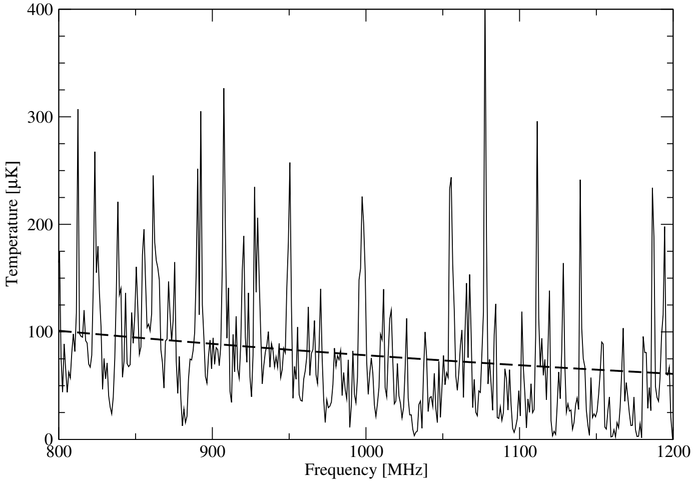
The HI angular power spectrum for the same central frequency, 950 MHz, but for two different ranges 925–975 MHz and 800–1100 MHz. The signal amplitude increases with decreasing the frequency range and the BAOs become more prominent. As the frequency range increases the size of the region probed becomes larger implying that the fluctuations will decrease.

Simulating the signal

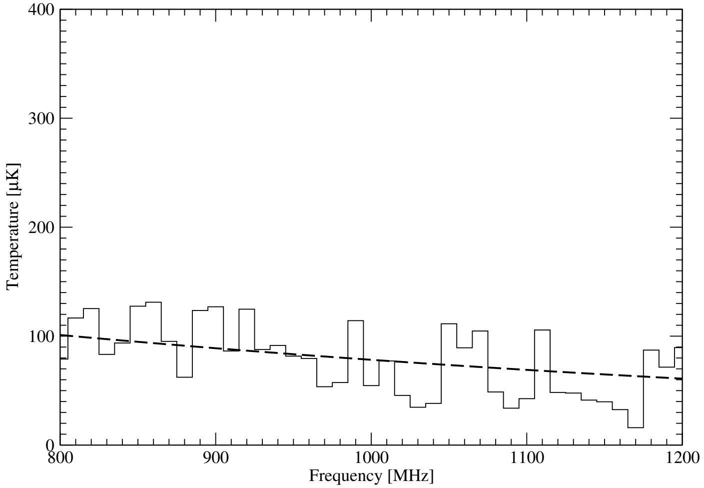
- The S^3 simulations [Obreschkow et al. 2009] are semi-analytic simulations of HI emission based on catalogues of galaxies whose properties are evolved from the Millennium simulation.

- We can calculate the integrated HI flux and HI line width, from which we get the HI brightness temperature contributed by galaxies in some frequency range as it would be observed by a telescope with a given beam.

[Battye et al. 2013]



(a) $\Delta f = 1\,\mathrm{MHz}, \theta_{\mathrm{FWHM}} = 60\,\mathrm{arcmin}$



(b) $\Delta f = 10\,\mathrm{MHz}, \theta_{\mathrm{FWHM}} = 60\,\mathrm{arcmin}$

THE NOISE

- **Using intensity mapping we basically have no shot noise!**
- **Instead, we have instrumental noise, the thermal noise of the telescope.**
- **Let's see how this noise is modelled.**

The frequency (redshift) resolution of single-dish IM surveys is excellent, but not the angular resolution! Hence, we have a response function in the transverse direction:

$$W^2(k) = \exp\left[-k_\perp^2 r(z)^2 \left(\frac{\theta_{\rm B}}{\sqrt{8\ln 2}}\right)^2\right]$$

$$\theta_B = \lambda / D_{\rm dish} \qquad \lambda = 21(1+z)\,{\rm cm}$$

- Example: MeerKAT has dishes with diameter 13.5 m

THE NOISE

The pixel thermal noise is given by

receiver temperature

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

channel width

observing time

pixel/survey (total) area

- 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)

THE NOISE

The noise power spectrum is then given by

$$P^{\rm N}(k) = \sigma_{\rm pix}^2 V_{\rm pix} W^{-2}(k)$$

The error on a power spectrum measurement averaged in a k-bin is:

$$\frac{\sigma_P}{P} = \sqrt{2\frac{(2\pi)^3}{V_{\rm sur}}\frac{1}{4\pi k^2 \Delta k}}\left(1 + \frac{\sigma_{\rm pix}^2 V_{\rm pix}}{[\bar{T}(z)]^2 W(k)^2 P}\right)$$

The first term is the usual cosmic variance contribution.

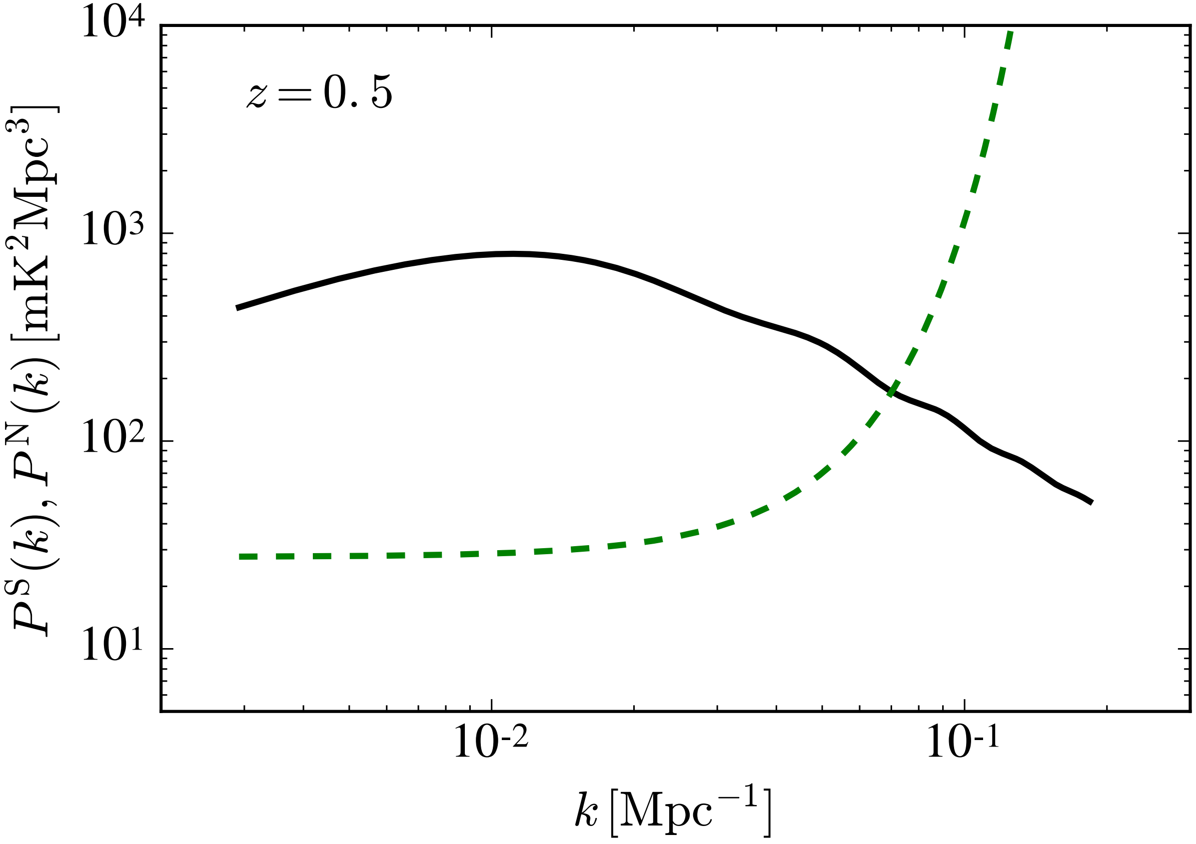
$$V_{\rm sur} = \Omega_{\rm sur}\int_{z_{\rm min}}^{z_{\rm max}} dz \frac{dV}{dz d\Omega}$$

where

$$\frac{dV}{dz d\Omega} = \frac{c r(z)^2}{H_0 E(z)} \, .$$

SIGNAL VS THERMAL NOISE

[MeerKAT IM example]



Detection prospects

[MeerKAT IM example]

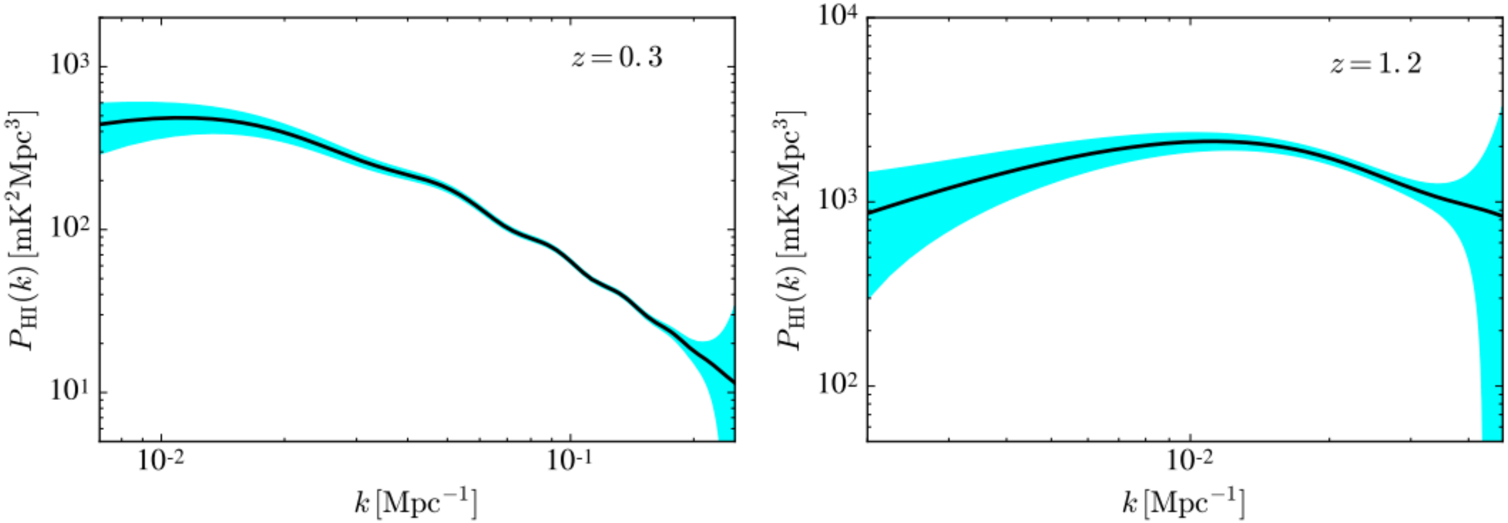
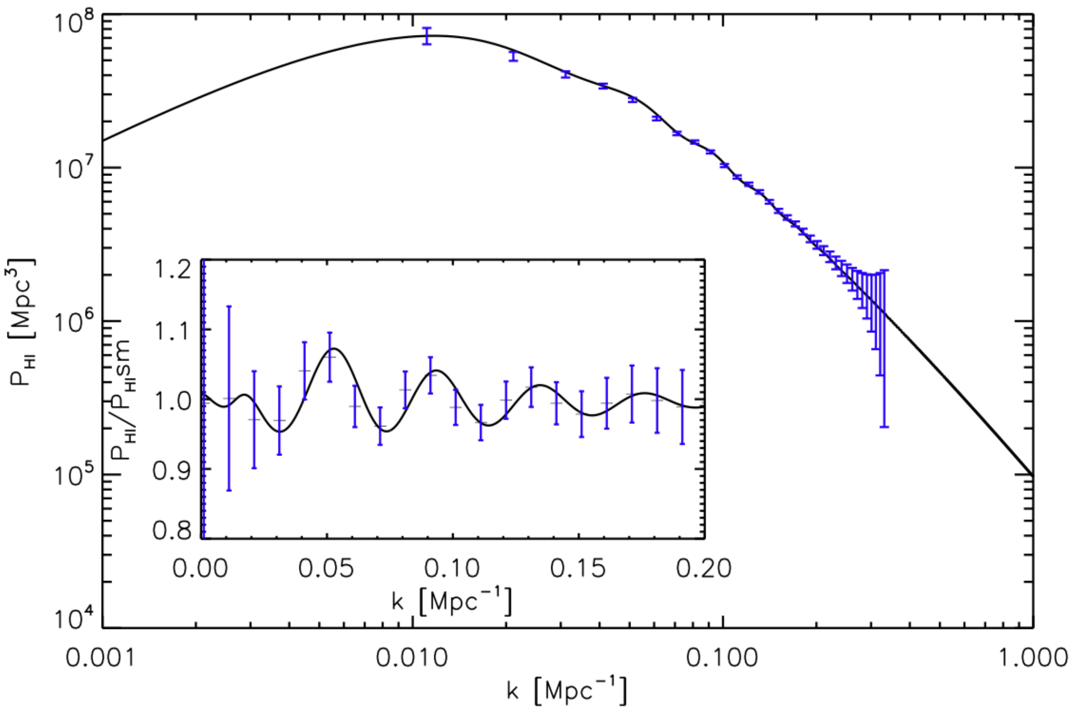


Figure 1: HI detection in autocorrelation with a 4000 deg^2 survey using MeerKAT. The black solid line is the predicted power spectrum $P_{\rm HI}(k,z)$ at $z = 0.3$ (left) and at $z = 1.2$ (right). Note that $z = 0.3$ is in the L-band while $z = 1.2$ is in the UHF band. The cyan area represents the measurement errors for a total observation time of ~ 5 months. The width of the bins is $\Delta z = 0.1$ and we have used a k-binning $\Delta k = 0.01$ Mpc^{-1}.

MEASURING THE BAO SCALE

In Battye et al. 2013 we implemented this formalism (and an optimisation study - see Exercise 1.1) to get forecasts for detecting the BAO.



This data would give a 2.4% measurement of the BAO scale, competitive with optical surveys like WiggleZ or BOSS.

Phased Array Feeds (PAFs):

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

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

They allow extremely rapid imaging!

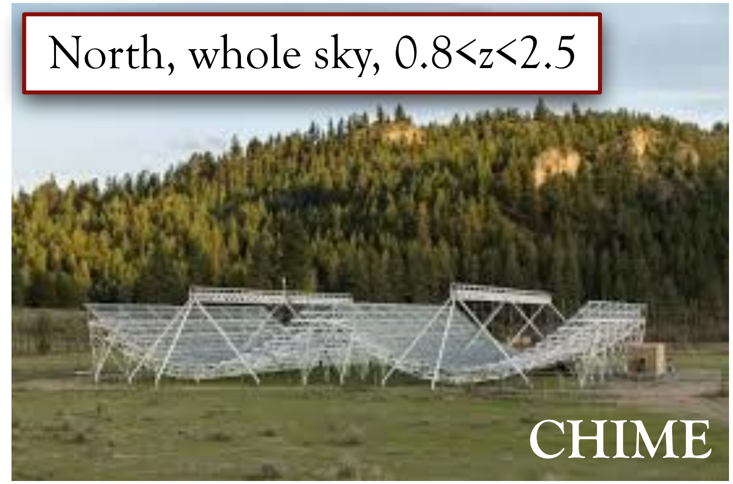
Applications outside physics (e.g. medical imaging)

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

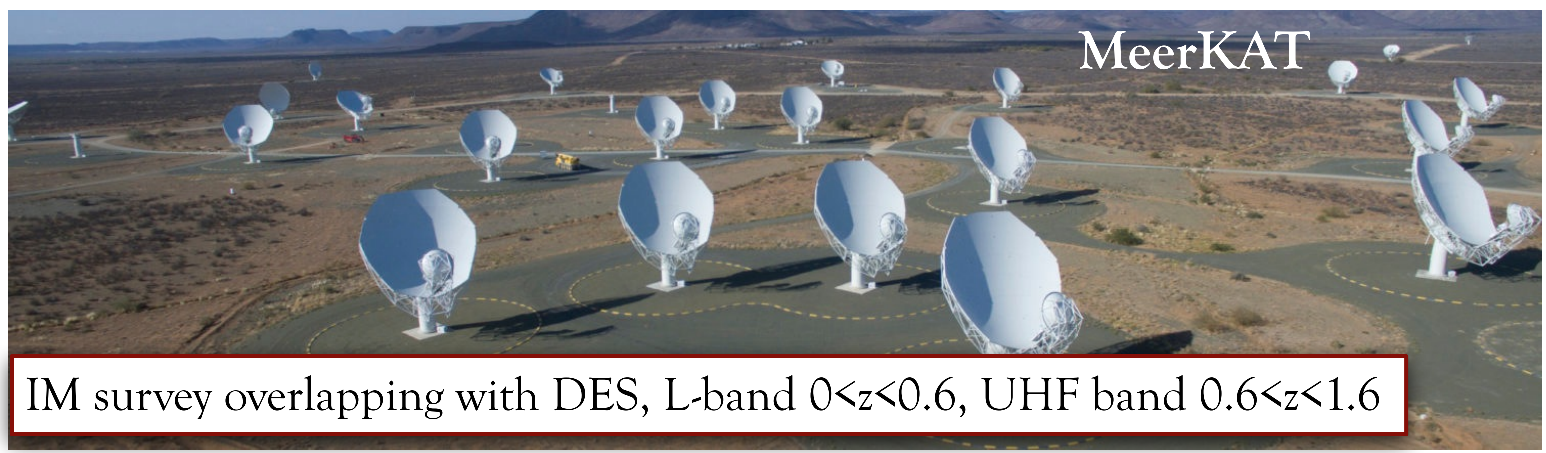
Already installed and operational in ASKAP, the SKA's Australian precursor [see Wolz, Blake and Wyithe 2017 for intensity mapping applications]

INTENSITY MAPPING: PAST, CURRENT AND FORTHCOMING SURVEYS

First detection in x-cross with optical



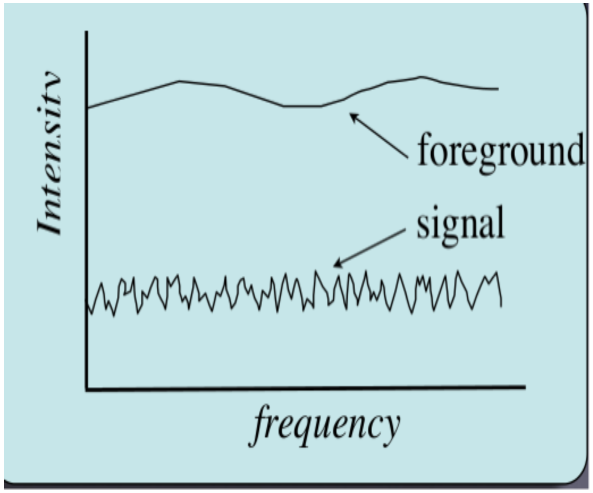
North, whole sky, $0.8<z<2.5$



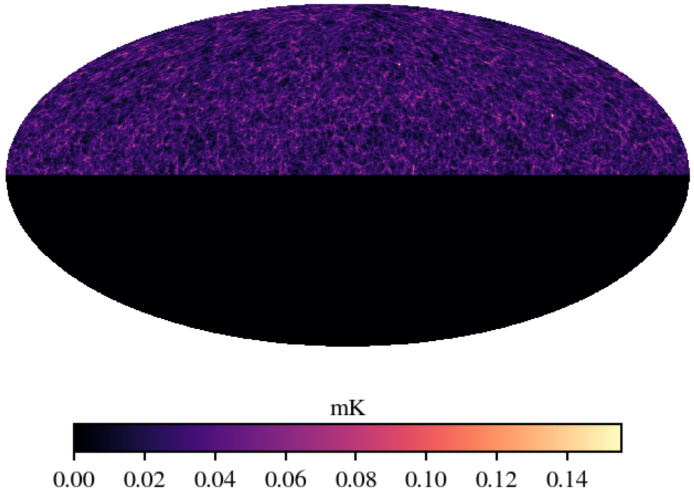
IM survey overlapping with DES, L-band $0<z<0.6$, UHF band $0.6<z<1.6$

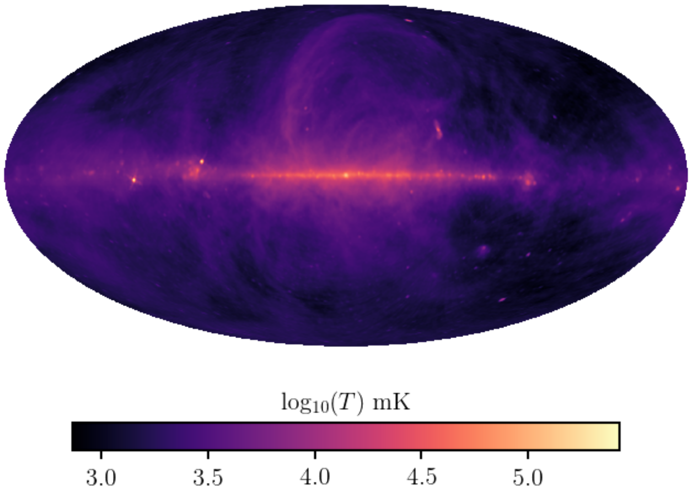
THE FOREGROUND PROBLEM

- Foreground contamination is a big problem in intensity mapping measurements
- Foregrounds can be 1000 times bigger than the signal
- But they are smooth in frequency, so we can remove them
- We use techniques similar to the ones applied on the CMB data (e.g. independent component analysis)



Simulations: S. Cunnington





21CM FOREGROUNDS

Slide from S. Cunnington

Model:

$$C_\ell(\nu_1,\nu_2) = A\left(\frac{\ell_{\mathrm{ref}}}{\ell}\right)^{\beta}\left(\frac{\nu_{\mathrm{ref}}^2}{\nu_1\nu_2}\right)^{\alpha}\exp\left(-\frac{\log^2(\nu_1/\nu_2)}{2\xi^2}\right)$$

Then simulate using Gaussian realisations for each 'type' of foreground:

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

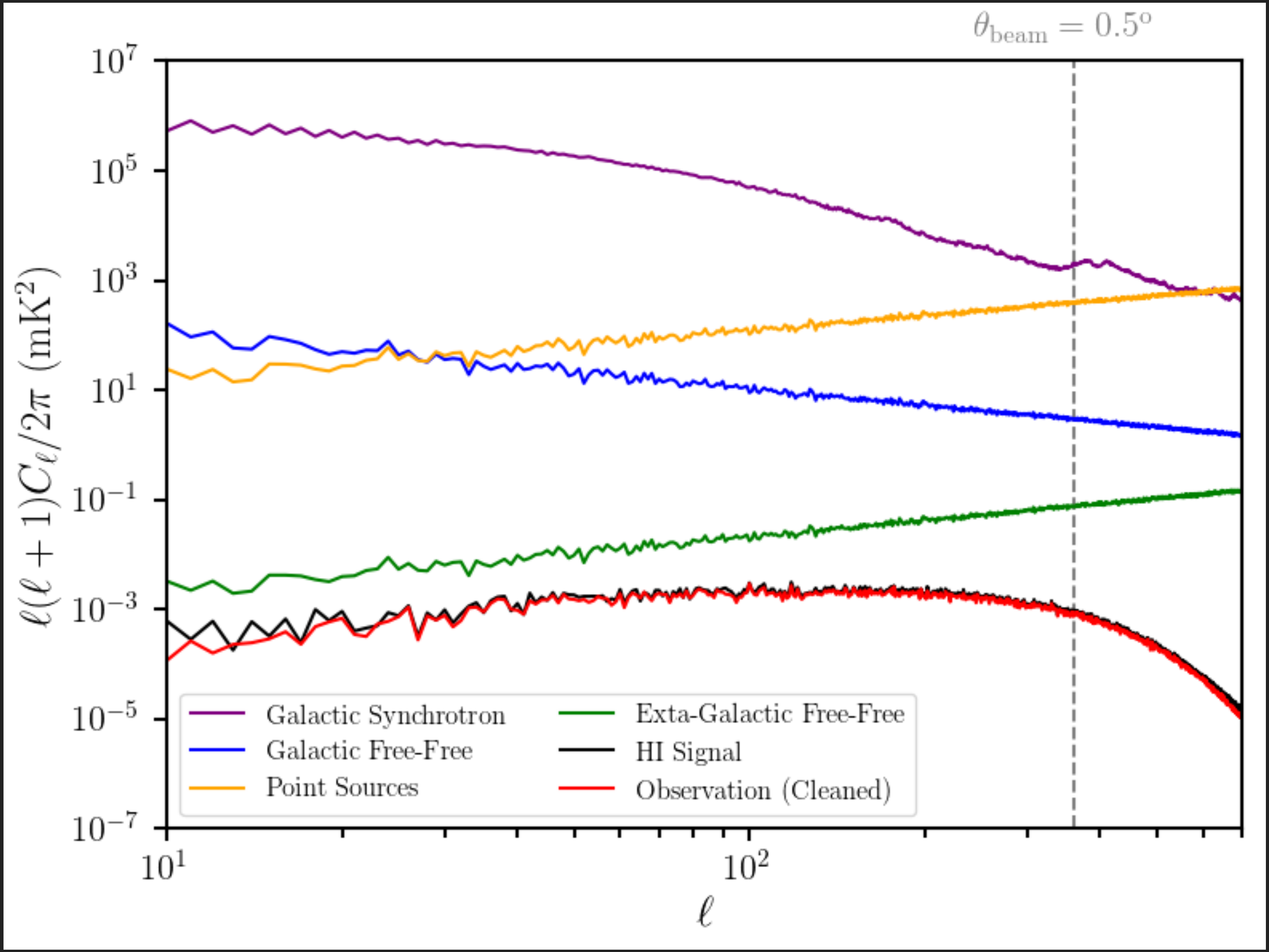
(ii) Extra-galactic point sources - objects beyond our own galaxy emitting signals close to 21cm signal, a typical example our AGNs

(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

Foreground	A	β	α	ξ
Galactic synchrotron	700	2.4	2.80	4.0
Point sources	57	1.1	2.07	1.0
Galactic free-free	0.088	3.0	2.15	35
Extra-galactic free-free	0.014	1.0	2.10	35

Slide from S. Cunnington



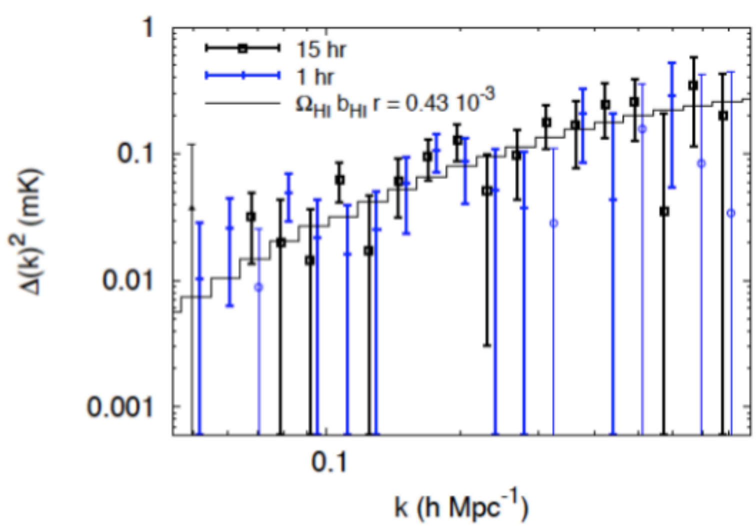
DETECTIONS WITH RADIO IM-OPTICAL CROSS-CORRELATIONS

- Systematic effects are a big challenge for IM
- **GBT x WiggleZ** showed that cross-correlating with optical can mitigate this!
- **2dF x Parkes** detection a couple of months ago!
- **GBT x eBOSS** project under way **(Wolz, AP, et al.)**

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

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

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

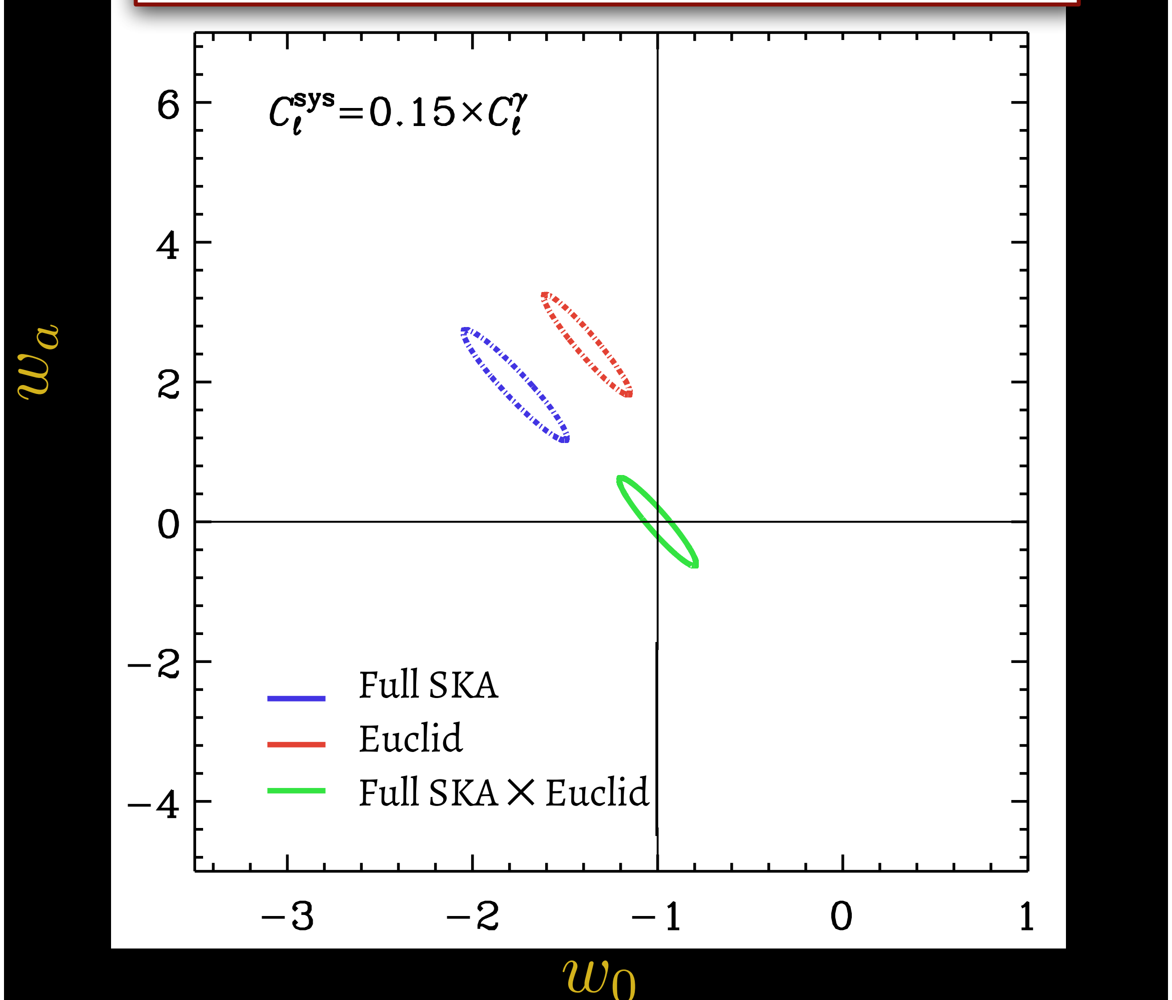


Masui, et al., ApJ 2012,
Chang et al., Nature 2010

LESS IS MORE

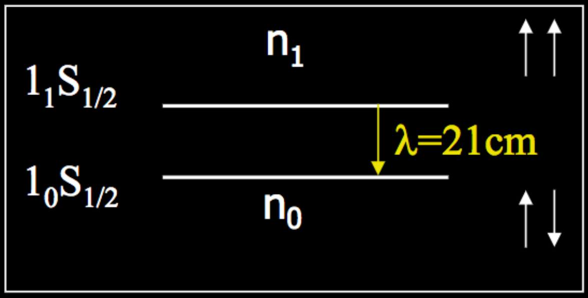
Less systematics to worry about: the cosmic shear case

[Camera, Harrison, Bonaldi & Brown 2016]



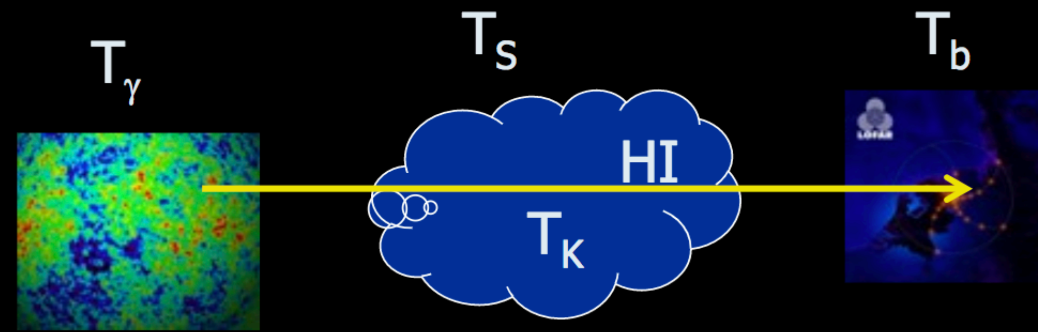
[Slide from Jonathan Pritchard]

- HI hyperfine structure



$n_1/n_0=3\,\exp(-h\nu_{21cm}/kT_s)$

- Use CMB backlight to probe 21cm transition



z=13
f_{21cm}=1.4 GHz

z=0
f_{obs}=100 MHz

- 3D mapping of HI possible - angles + frequency
- 21 cm brightness temperature

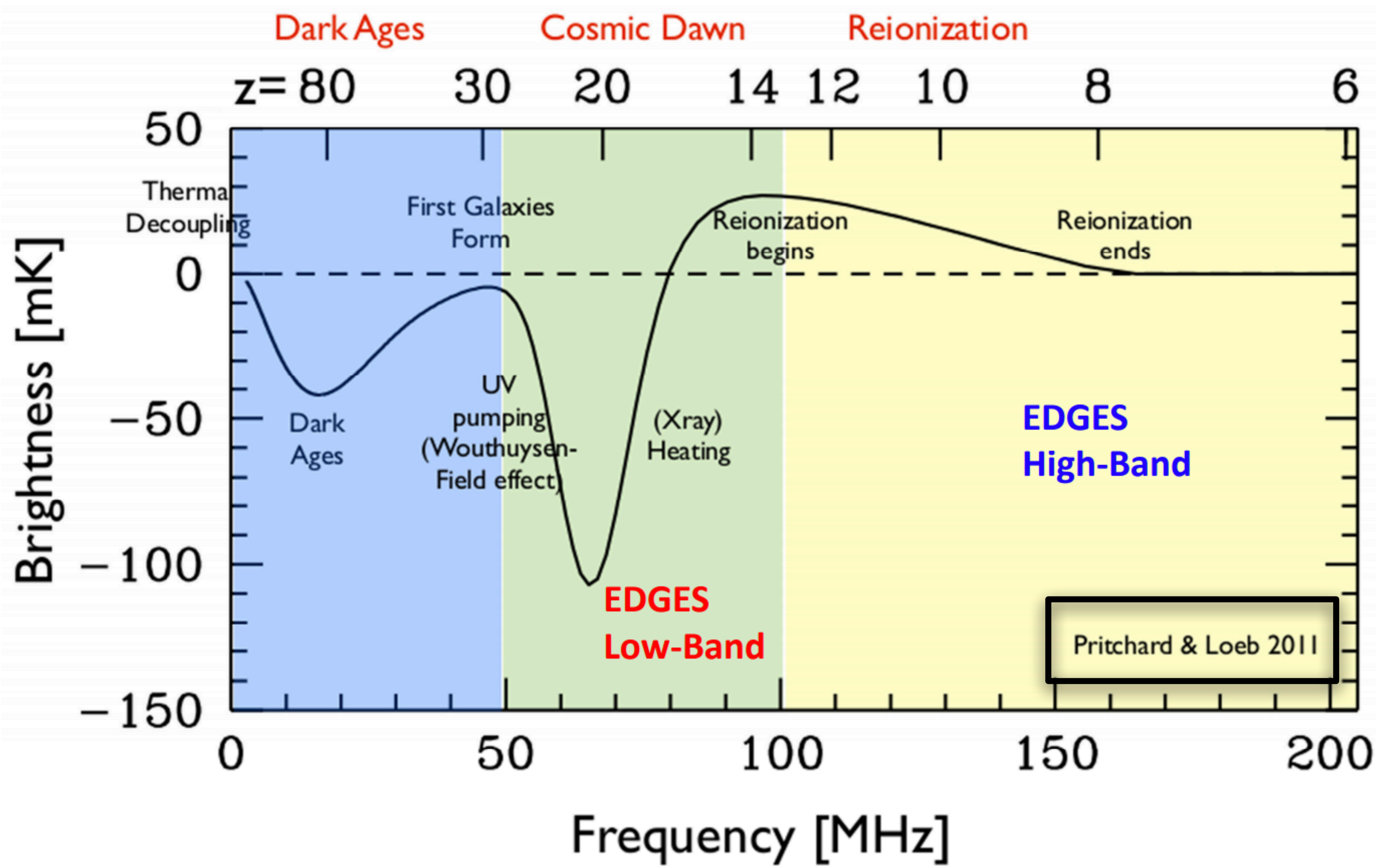
$$T_b = 27 x_{\rm HI}(1+\delta_b)\left(\frac{T_S - T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2}\,\mathrm{mK}$$

- 21 cm spin temperature

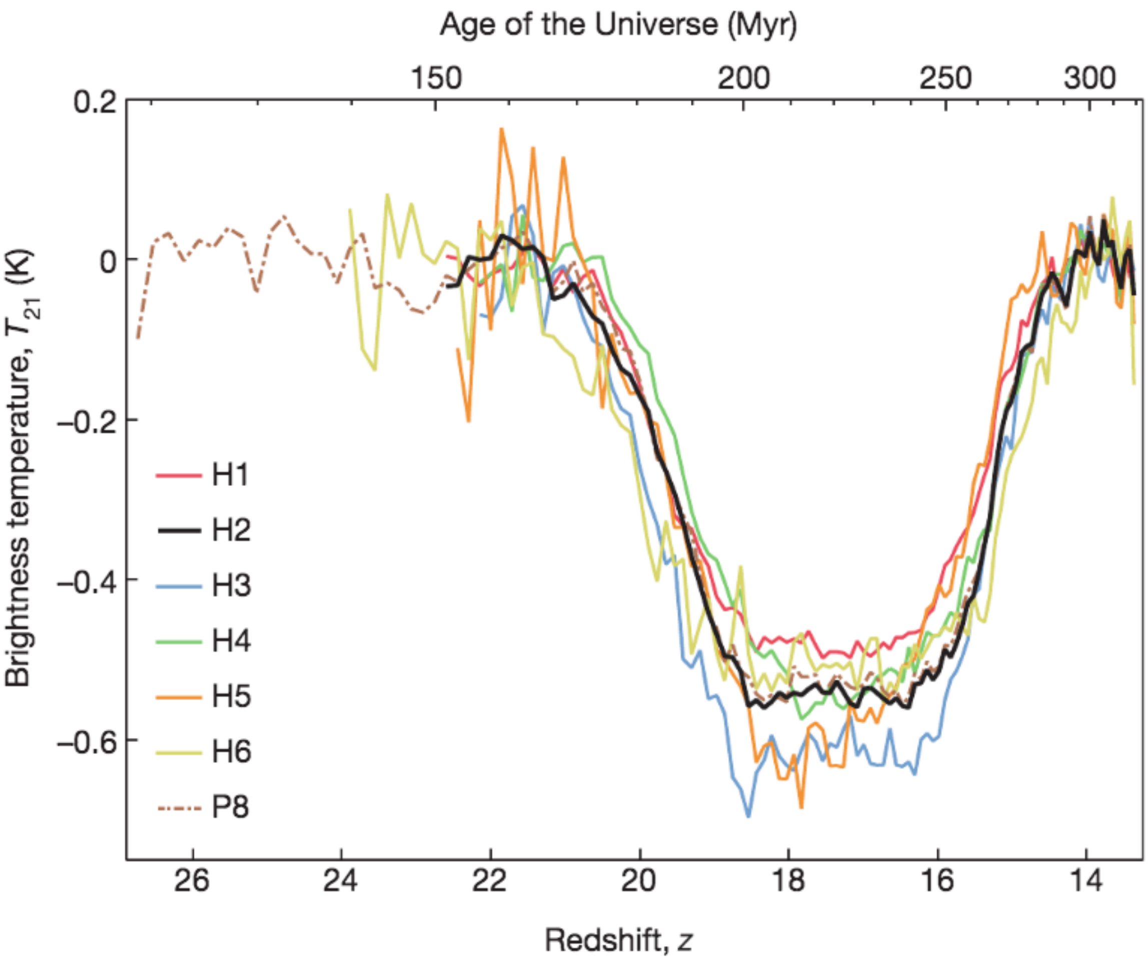
$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

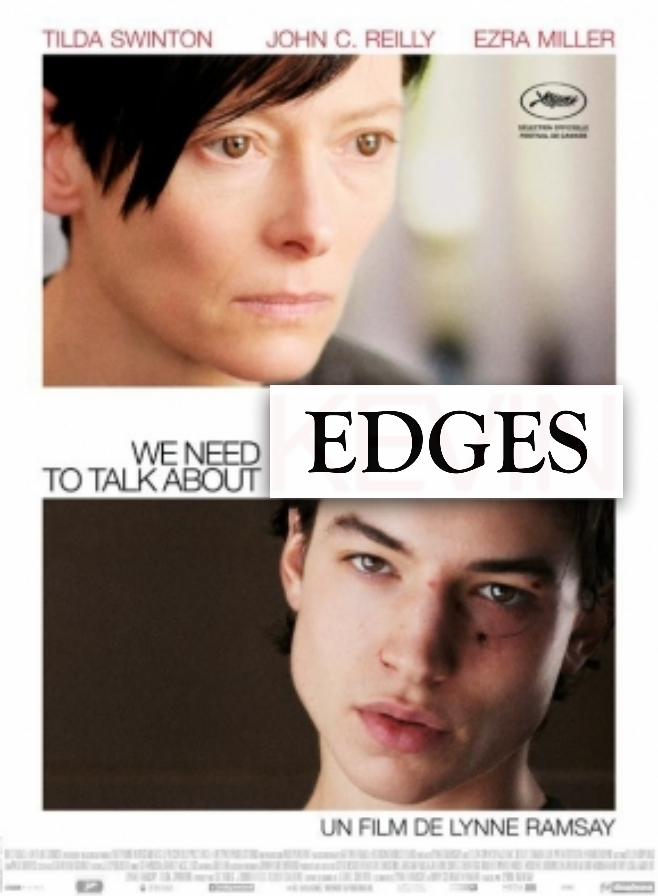
Coupling mechanisms:
Radiative transitions (CMB)
Collisions
Wouthuysen-Field

DARK AGES, COSMIC DAWN AND EOR



We need to talk about EDGES (see working group exercise 2)





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