TeVPA 2019

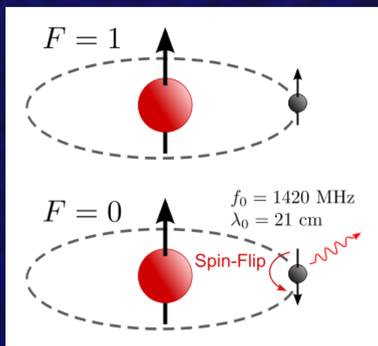
The 21cm probe of Cosmology

Xuelei Chen
National Astronomical Observatories
Chinese Academy of Sciences

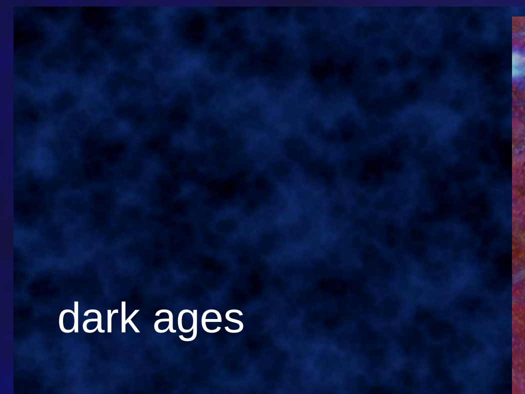
University of Sydney, 2019.12.03

What is the 21cm line

ground state hydrogen atom



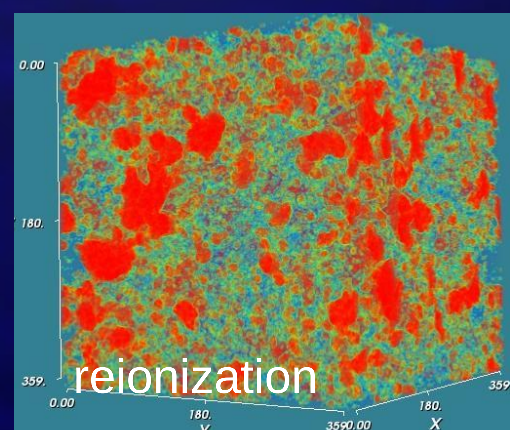
Redshifted to 21(1+z) cm

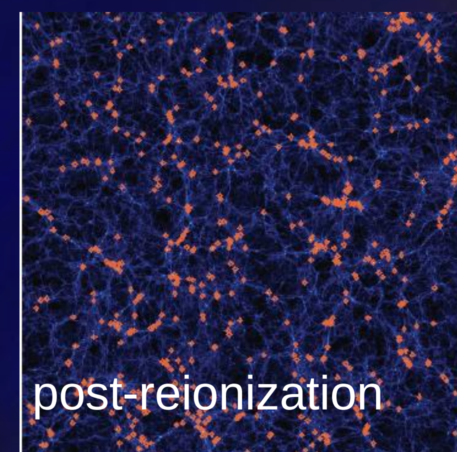


observe w.r.t. radio background:
spin temperature

$$\frac{n_1}{n_0} = 3e^{-\Delta E/k_B T_S} = 3e^{-T_*/T_S}$$

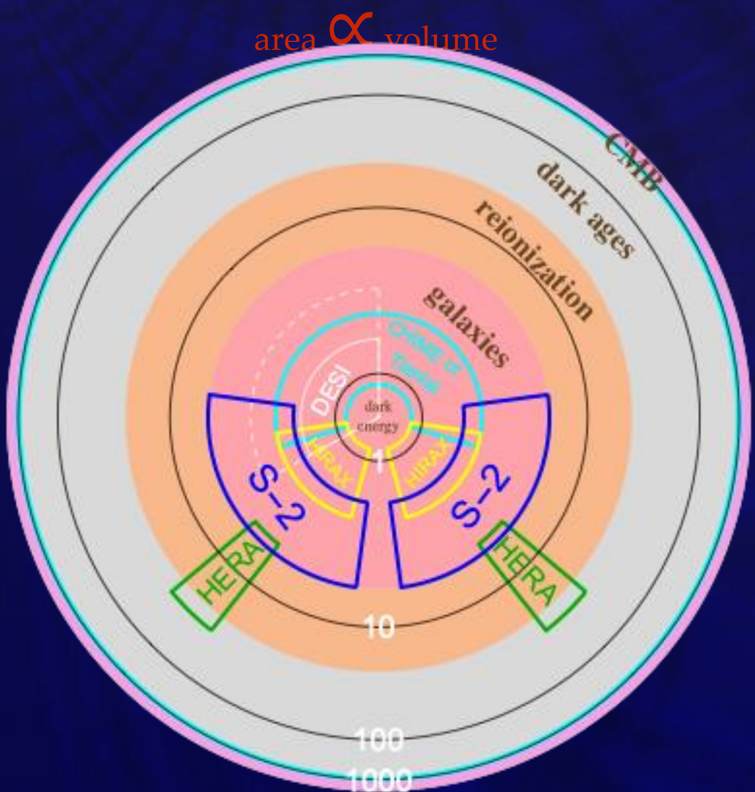
$$T_S = \frac{T_{CMB} + y_\alpha T_\alpha + y_c T_k}{1 + y_\alpha + y_c} \; ,$$





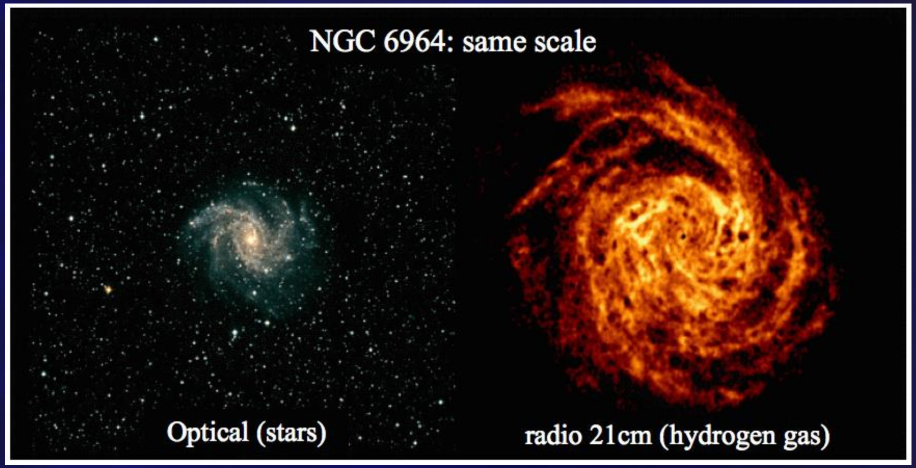
Why 21cm observation

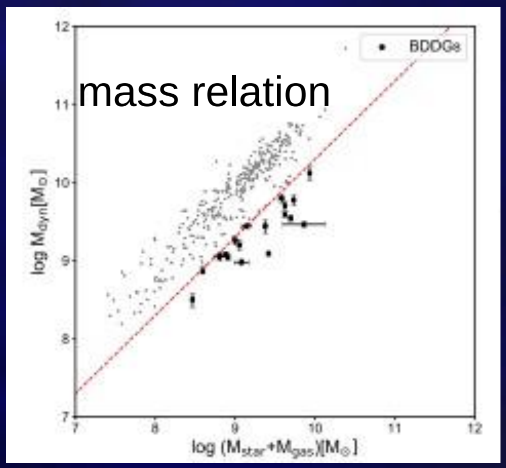
Ubiquitous: 76% of baryons

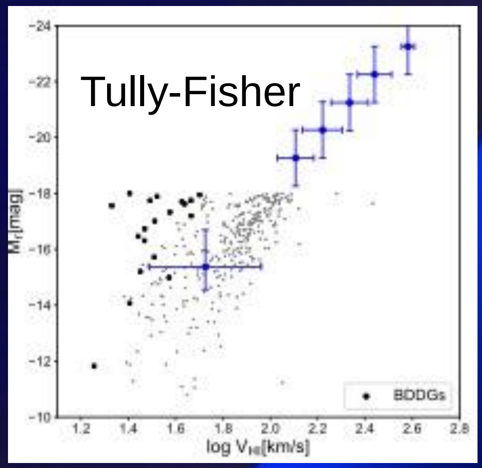


The observable Universe in comoving scale

A different perspective



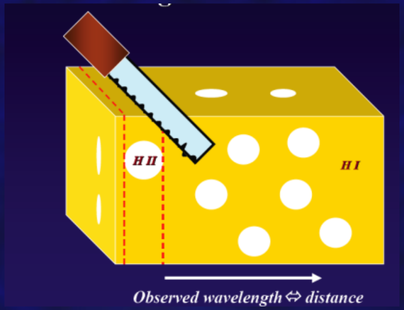




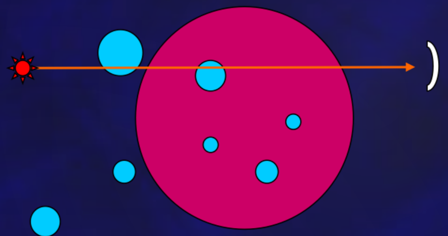
Q. Guo et al.(2019), Nature Astronomy

Modes of 21cm Observation

21cm tomography

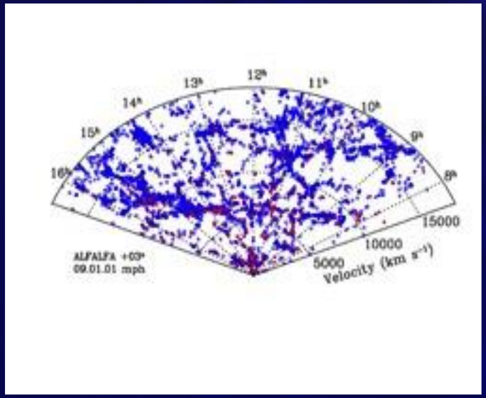


21cm forest

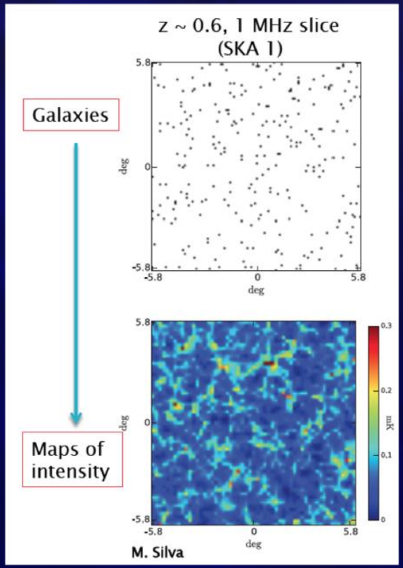


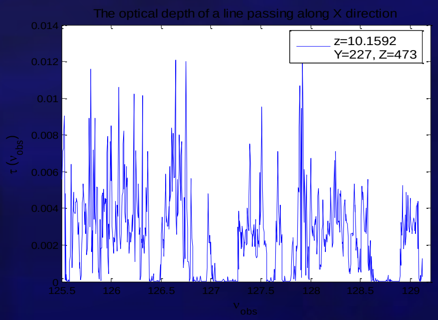
21cm global spectrum

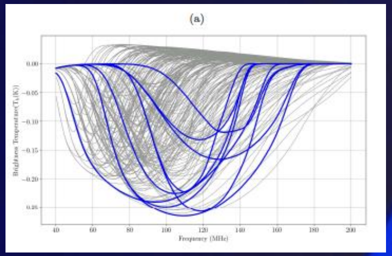
HI galaxies



Intensity Mapping



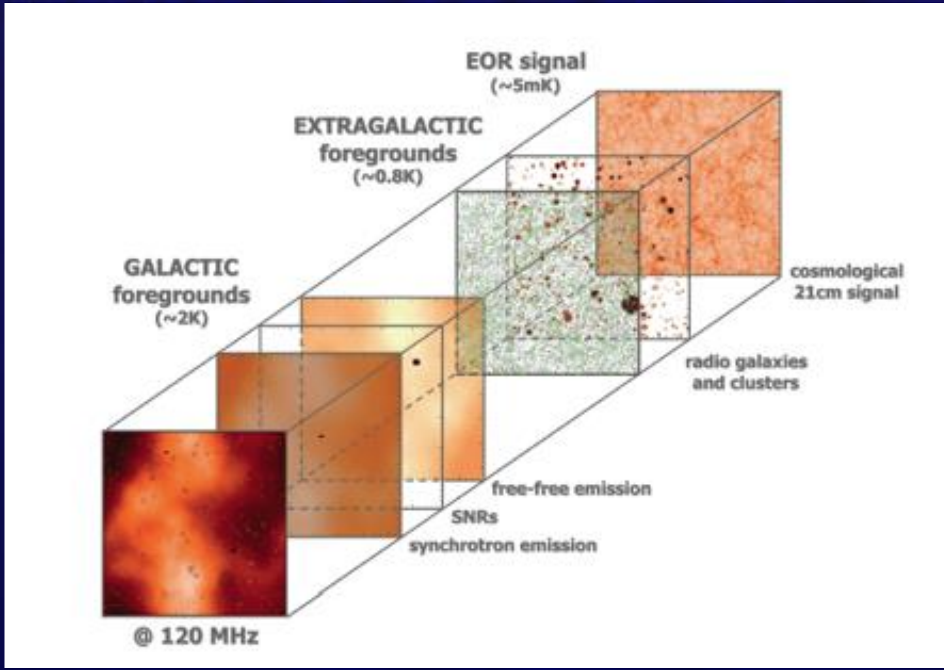




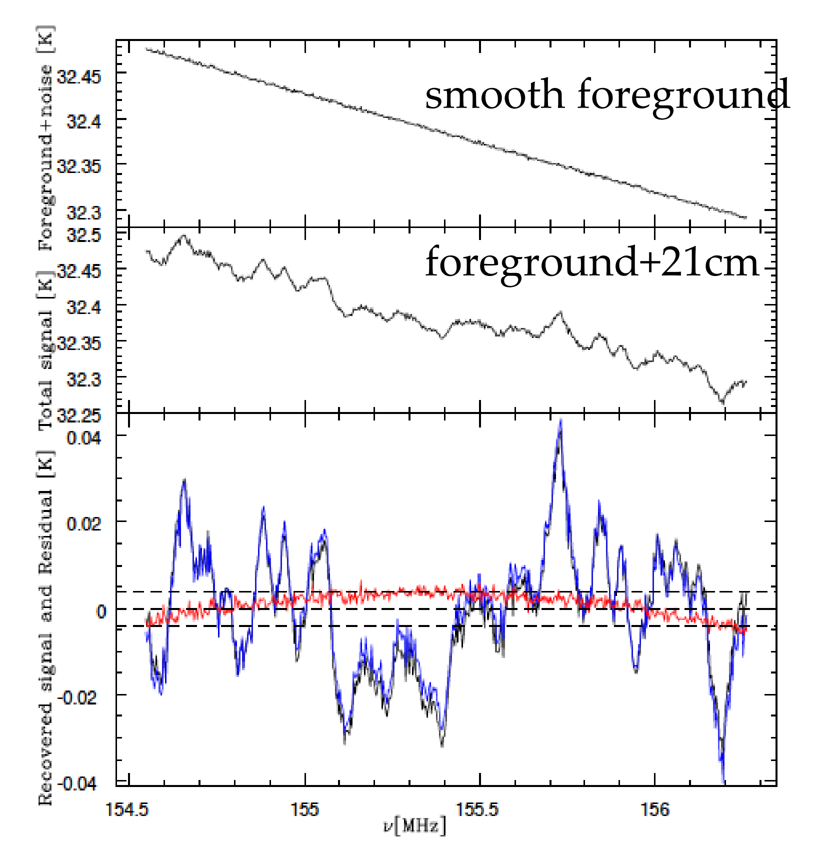
Foreground

raw signal to noise ration (SNR) ~ 10^{-5}

In principle, smooth foreground can be subtracted



V. Jelic et al. (2010)

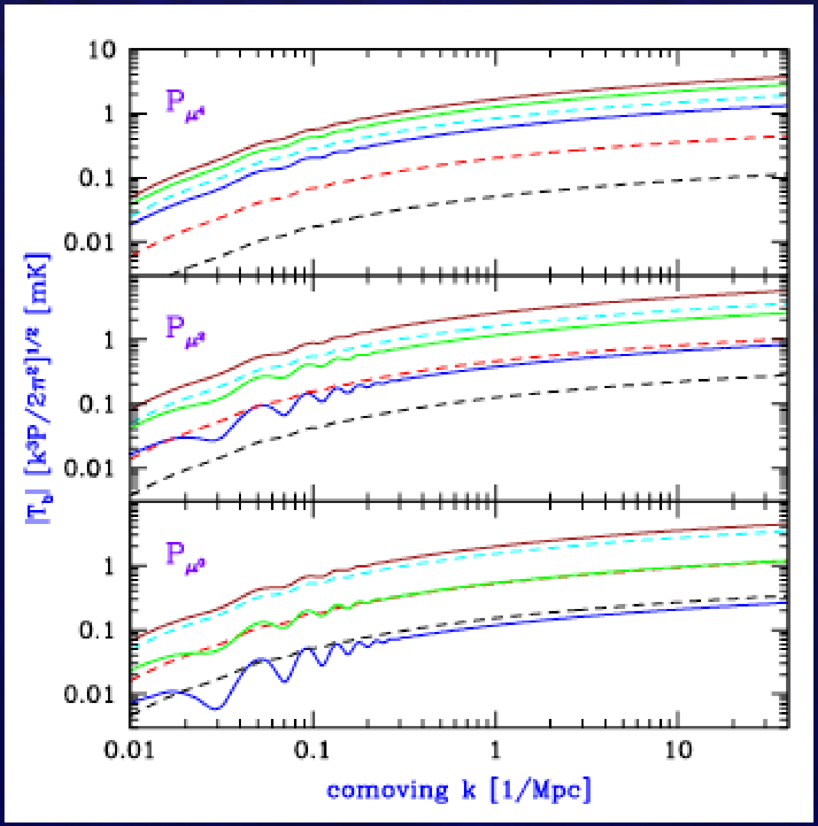


X. Wang et al. (2006)

Cosmic Dark Ages

Loeb & Zaldarriaga 2004

$$N_{21\mathrm{cm}} \sim 3\times10^{16}(l_{\max}/10^6)^3(\Delta\nu/\nu)(z/100)^{-1/2}$$



Barkana & Loeb 2005

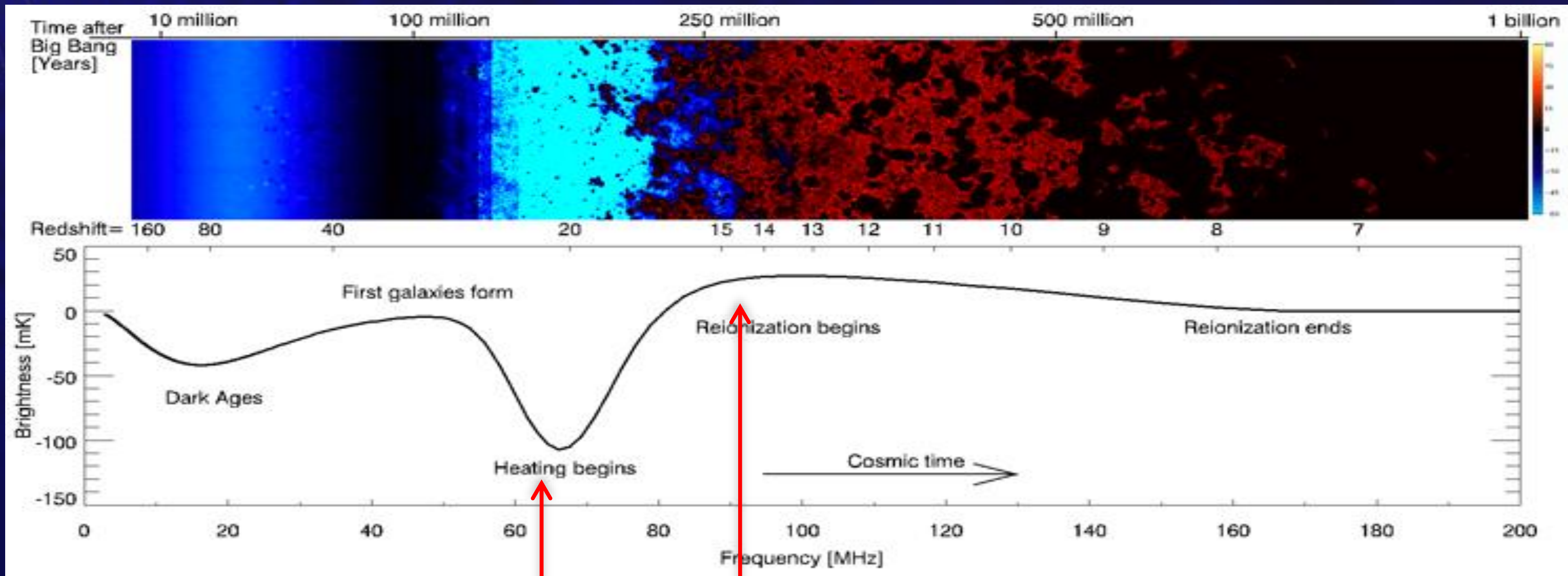
But:

- The signal is redshifted to very low frequencies, ionosphere absorption—may need to observe from the farside of the moon

- Very strong galactic foreground, need extremely large array to achieve enough sensitivity

- First Step: global signal (DSL, DAPPER)

Cosmic Dawn



Reionization signal--Emission

Cosmic Dawn signal—Absorption
(XC& J. Miralda-Escude 2003, 2008)

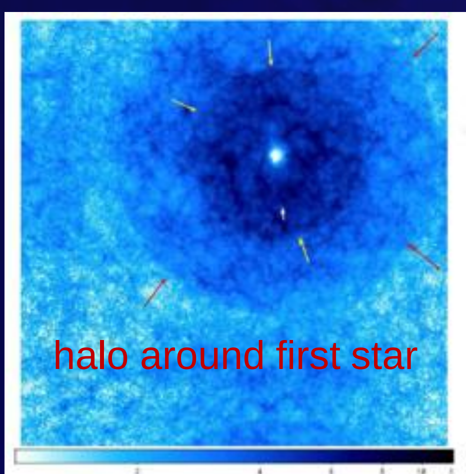
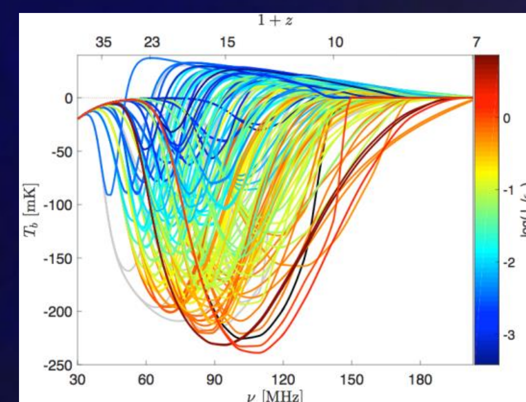
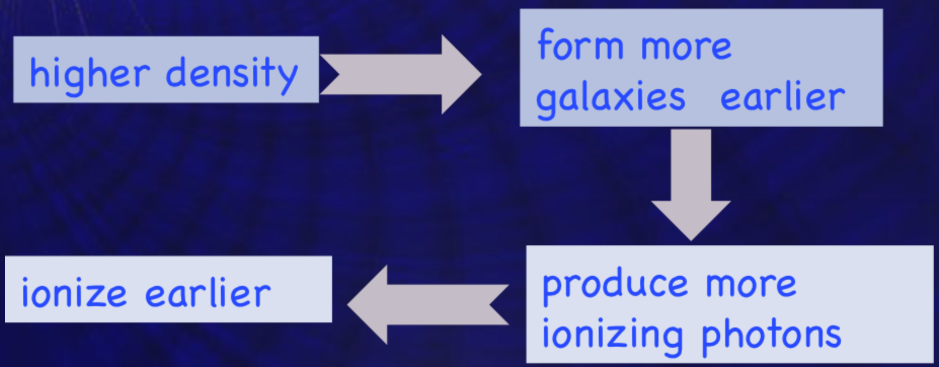


Figure by K. Ahn et al.

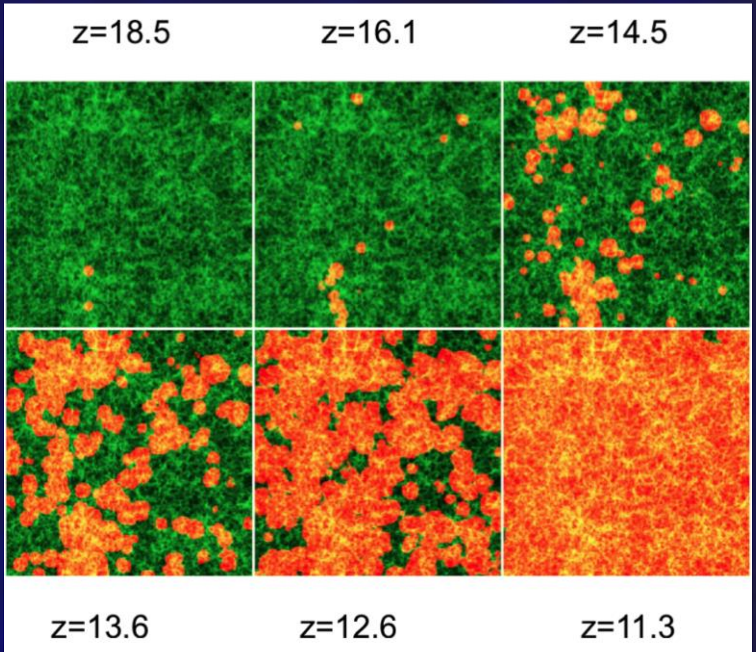


Cohen et al. 2017

Model of Reionization



Iliev et al （2006）

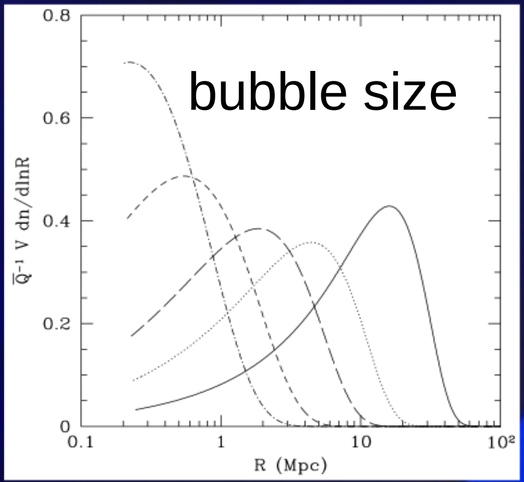


Bubble Model (Furlanetto, Hernquist, Zaldarriaga 2004):

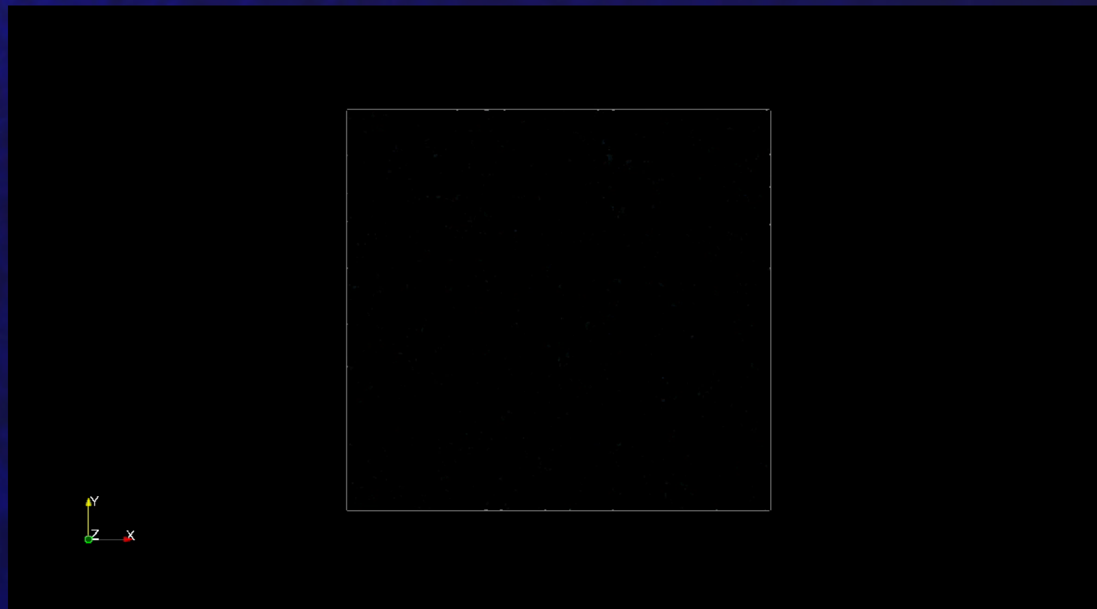
#photon needed = #photon produced

#photon needed = $n_B V (1+n_{rec})$

#photon produced = $\xi n_B V f_{coll}$



Late Stage of EoR



Semi-Numerical Model IslandFAST

- Overlapping bubbles—no longer isolated!
- neutral islands: large low density regions (voids)（Y. Xu et al. 2014, 2017)
- ionization equation: #photons= local produced + backgroud

$$\xi f_{\mathrm{coll}}(\delta_{\mathrm{M}}; M, z) + \frac{\Omega_m}{\Omega_b}\frac{N_{\mathrm{back}} m_{\mathrm{H}}}{M X_{\mathrm{H}}(1+\bar{n}_{\mathrm{rec}})} < 1,$$

Stages of Reionization

Based on Minkowski functionals (Chen et al. 2018)

- Ionized Bubble Stage ($x_{HI} > 0.9$)
- Ionized Fiber Stage ($0.9 > x_{HI} > 0.7$)
- Sponge Stage ($0.7 > x_{HI} > 0.3$)
- Neutral Fiber ($0.3 > x_{HI} > 0.16$)
- Neutral Island Stage ($x_{HI} < 0.16$)

volume

$$V_0(\nu) = \frac{1}{V}\int_V \mathrm{d}^3x\ \Theta[u(\mathbf{x}) - \nu\sigma]$$

area

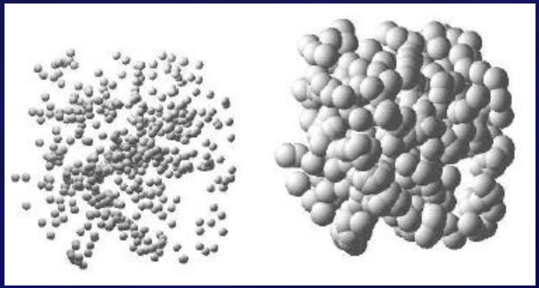
$$V_1(\nu) = \frac{1}{6V}\int_{\partial F_\nu} ds$$

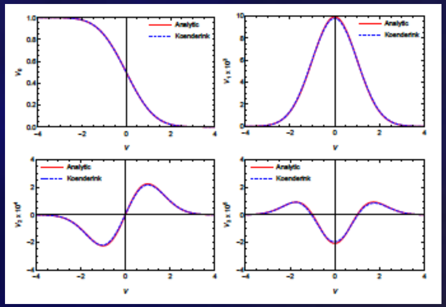
mean curvature

$$V_2(\nu) = \frac{1}{6\pi V}\int_{\partial F_\nu} \mathrm{d}s\ [\kappa_1(\mathbf{x}) + \kappa_2(\mathbf{x})]$$

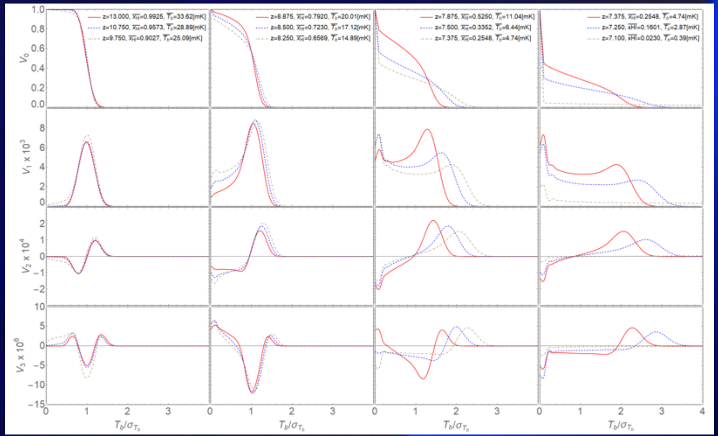
Eular characteristic

$$V_3(\nu) = \frac{1}{4\pi V}\int_{\partial F_\nu} \mathrm{d}s\ \kappa_1(\mathbf{x})\kappa_2(\mathbf{x})$$





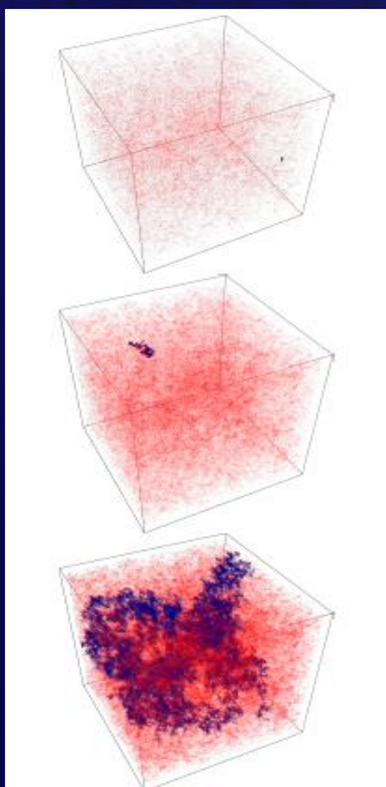
Broadly Consistent with Furlanetto & Oh (2016), Yoshiura et al. (2016), Bag et al. (2018)



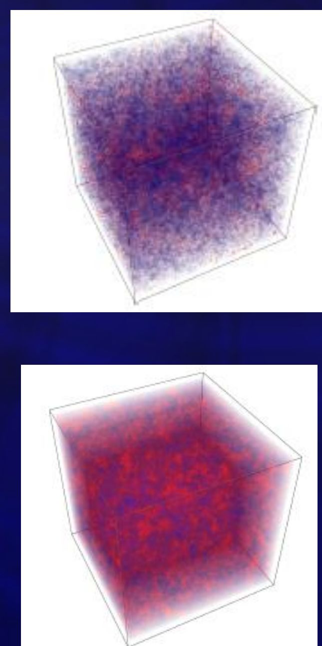
Reionization

blue: largest ionized region
red: other ionized region
transparent: neutral

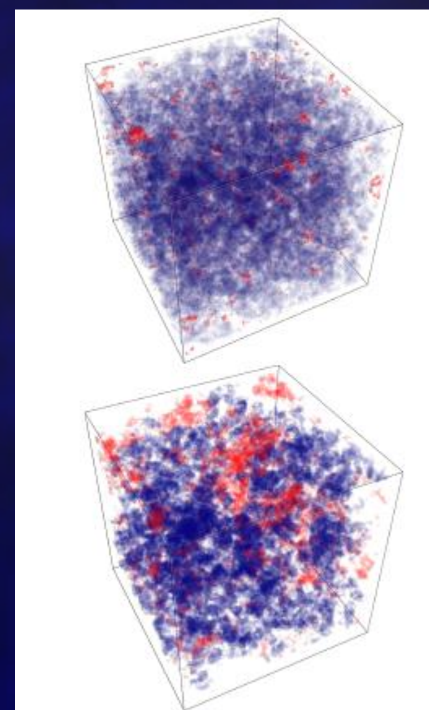
blue: largest neutral region
red: other neutral regions
transparent: ionized



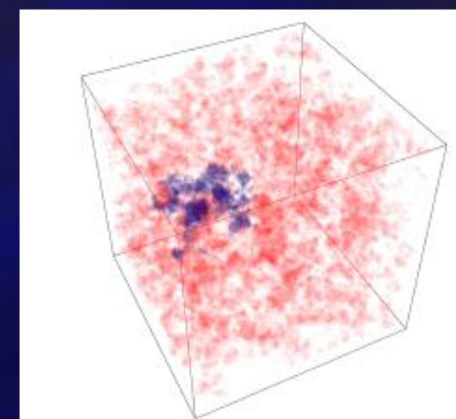
from bubble to fiber



from ionized fiber to sponge



neutral fiber



neutral island

Power spectrum and Bias

neutral fraction cross power

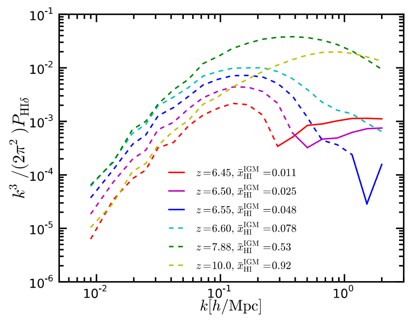


Figure 4. The cross-power spectrum between the neutral fraction and the dark matter density. The solid and the dashed lines represent positive and negative values respectively.

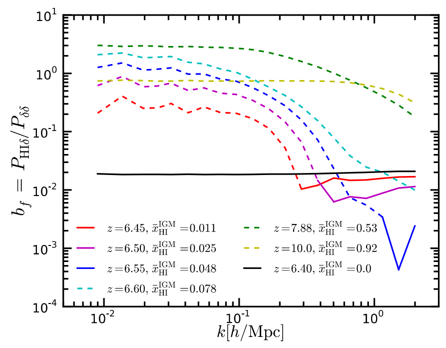


Figure 8. The HI bias at various redshifts.

21cm cross power

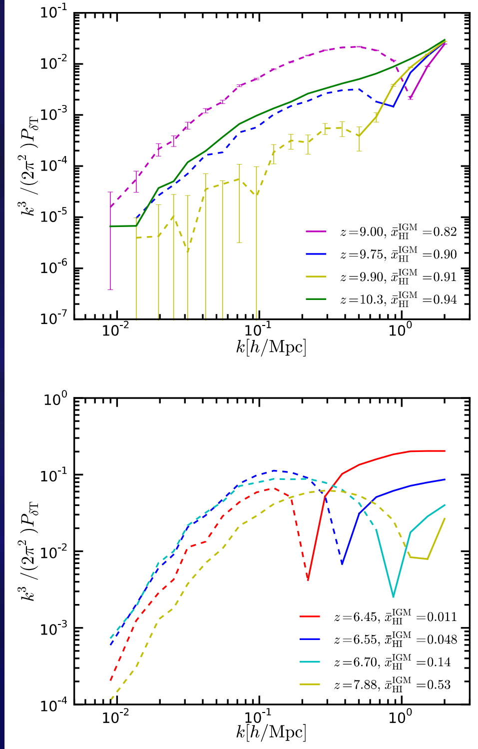


Figure 5. The 21 cm brightness temperature and the dark matter density cross power spectrum. Top panel: early EoR; Bottom panel: late EoR. Solid and dashed lines represent positive and negative values respectively.

The density and neutral fraction anti-correlated on large scales

W. Xu et al. (2019)

The Reality:
Mode Mixing foregrounds

Data = Instrument Response ✪ Sky + Noise

- The Instrument Response is frequency dependent (chromatic beam)
- The Instrument Response is not smooth (sidelobe, standing wave, ...)
- Instrument Response only known up to the precision of calibration (polarization leakage and cross-coupling between array elements, Faraday rotation of the polarization, ...)

Nevertheless, people hope to detect the cosmological 21cm signal!

Foreground Subtraction

Example: GBT (Masui et al. 2013)

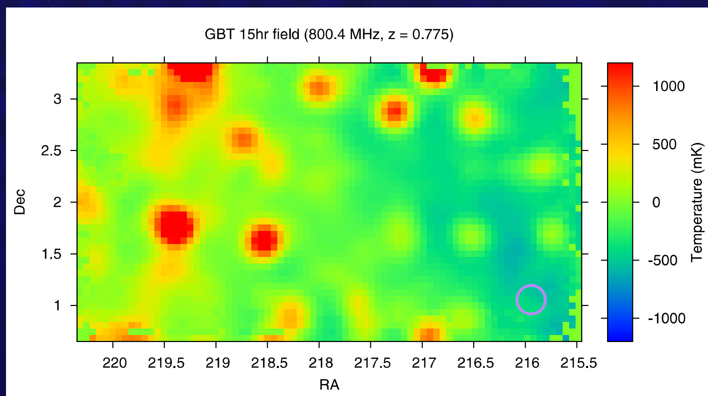
Data covariance matrix:

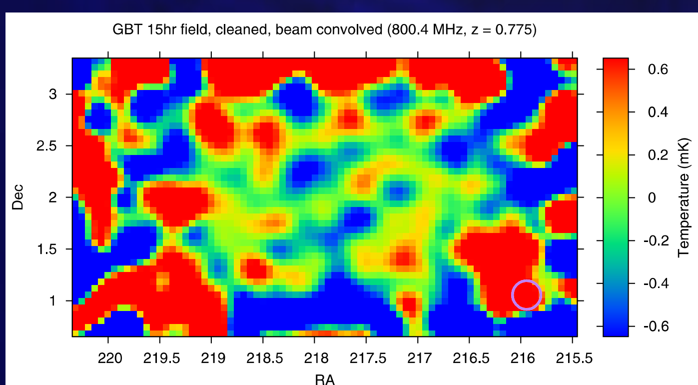
$$C_{\mu\mu'} = < T_x(\mu) T_x(\mu') >_x$$

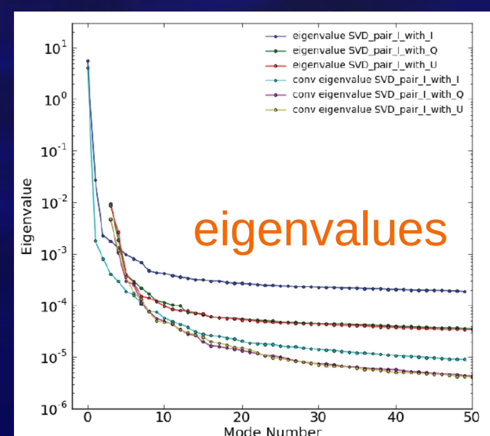
PCA analysis:

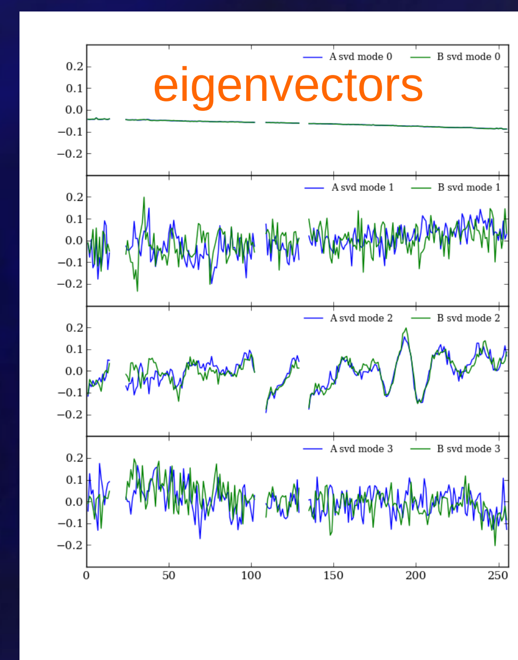
$$C = TT^\dagger$$

$$C v_i = \lambda_i v_i$$







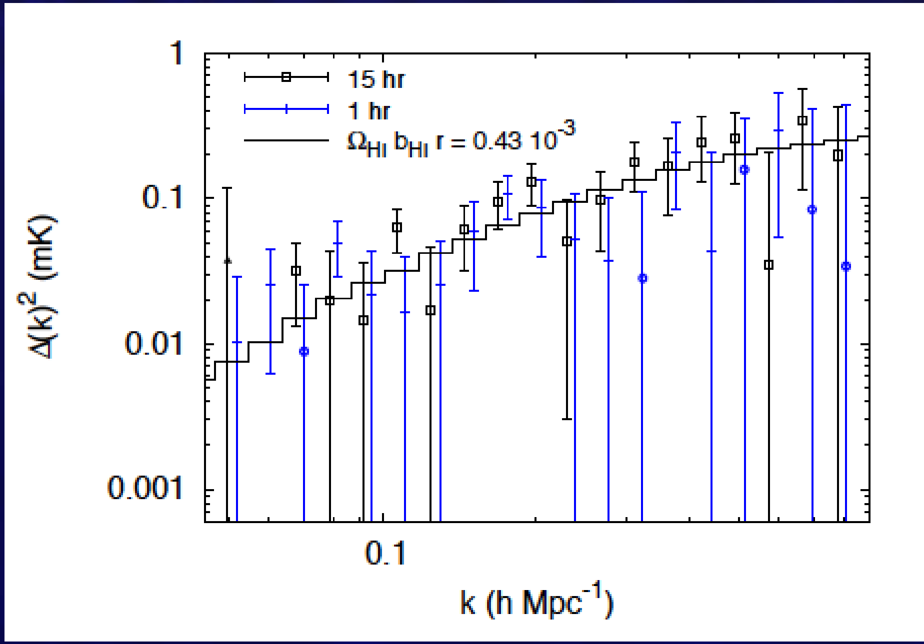


Other foreground subtraction methods developed, e.g. ICA (L. Wolz), RPCA (Zuo et al.)

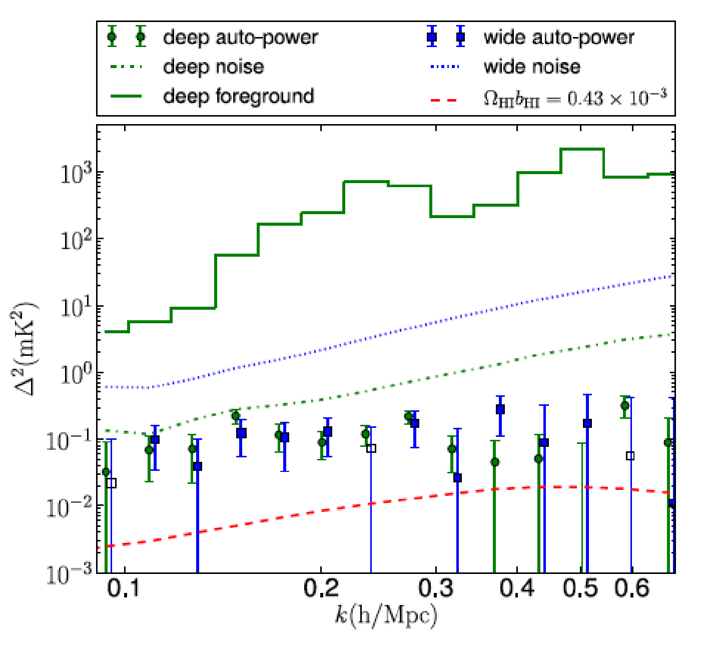
Power Spectra compensation

$$P_{SVD}(k) = \mathcal{T}(k)P(k)$$

$$T(k_i) = \left\langle \frac{[w_A \Pi_{A+s}(T_A + T_s) - W_A \Pi_A T_A]^T Q_i T_s}{(w_A T_s)^T Q_i T_a} \right\rangle^2$$

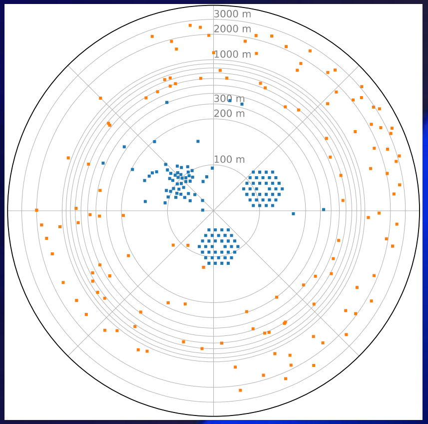


cross correlation with WiggleZ (Masui et al 2013)

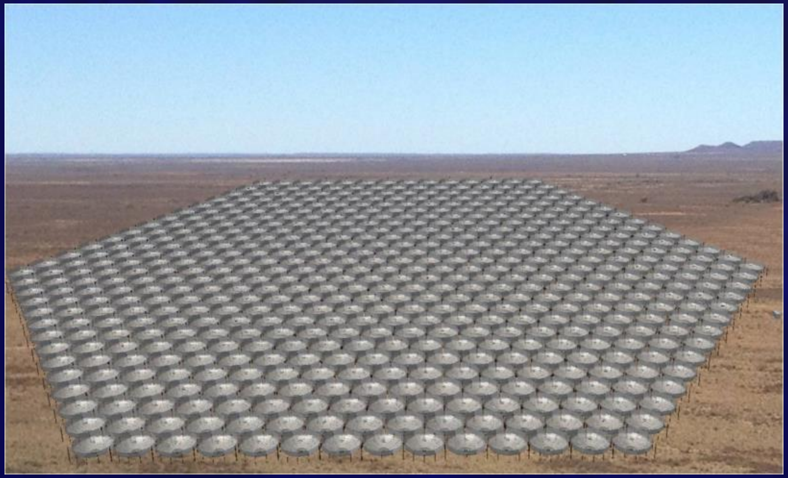


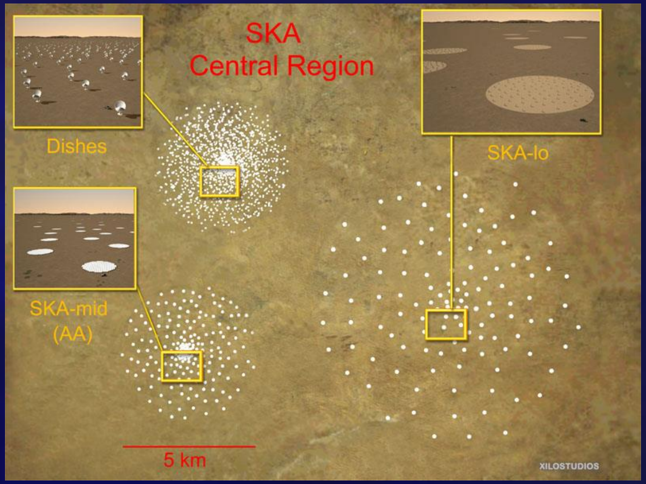
auto correlation (Switzer et al. 2013)

EoR tomography Experiments



EoR 21cm experiments

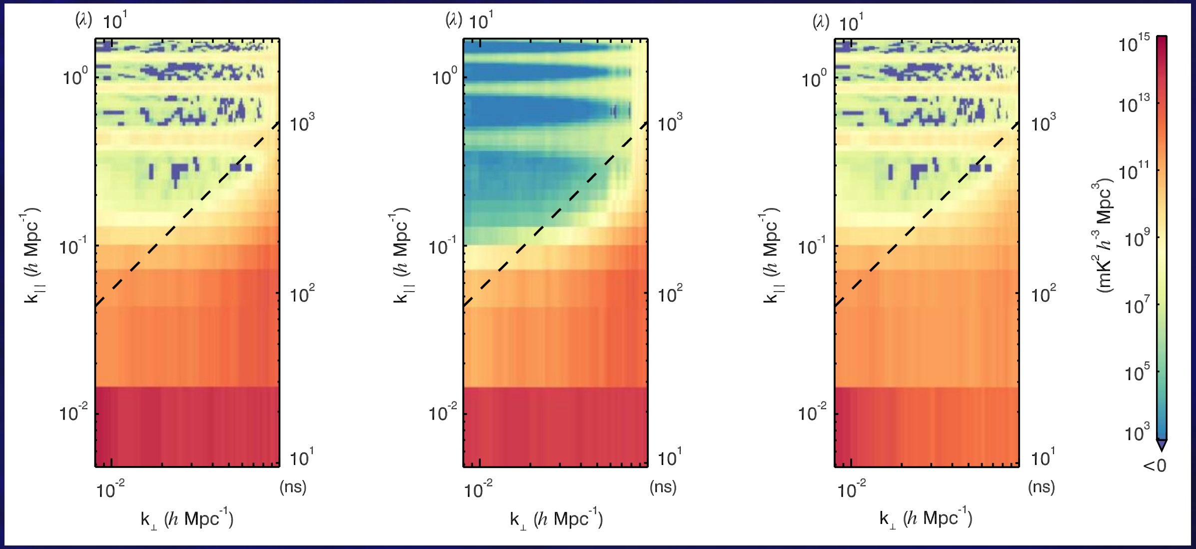




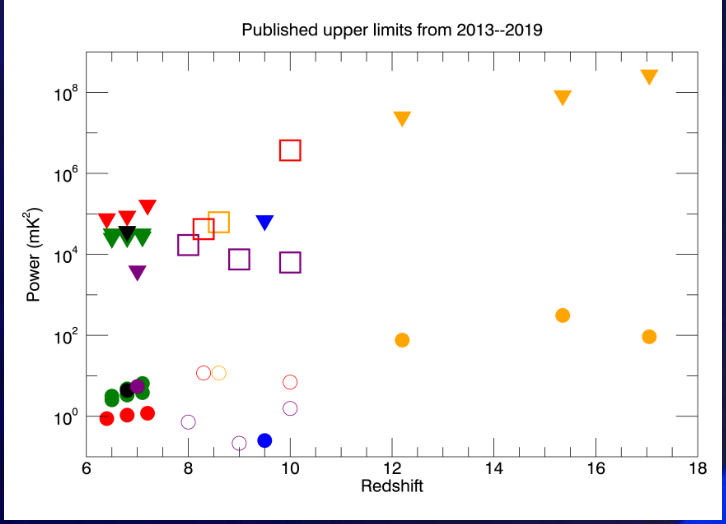
HERA: 350 x 14m dish, measure the 3D 21cm power spectrum. Regular grid, redundant baseline calibration

SKA-low: 512 x 256 dipole, randomized uv coverage, imaging EoR region

EoR power spectrum

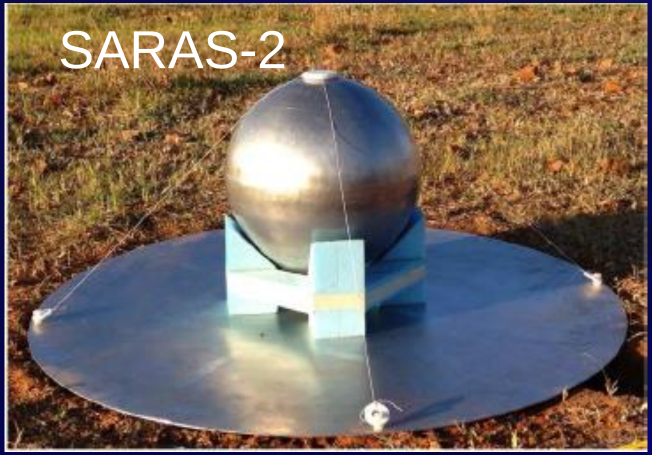


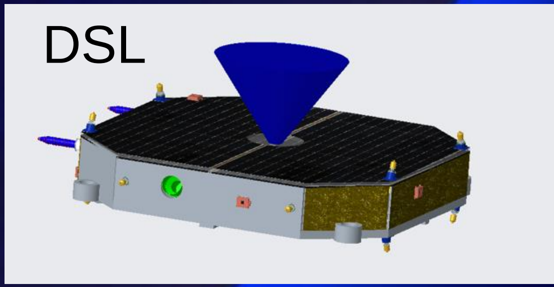
N. Barry et al. arxiv:1909.00561



Beardsley et al. arxiv:1910.02895

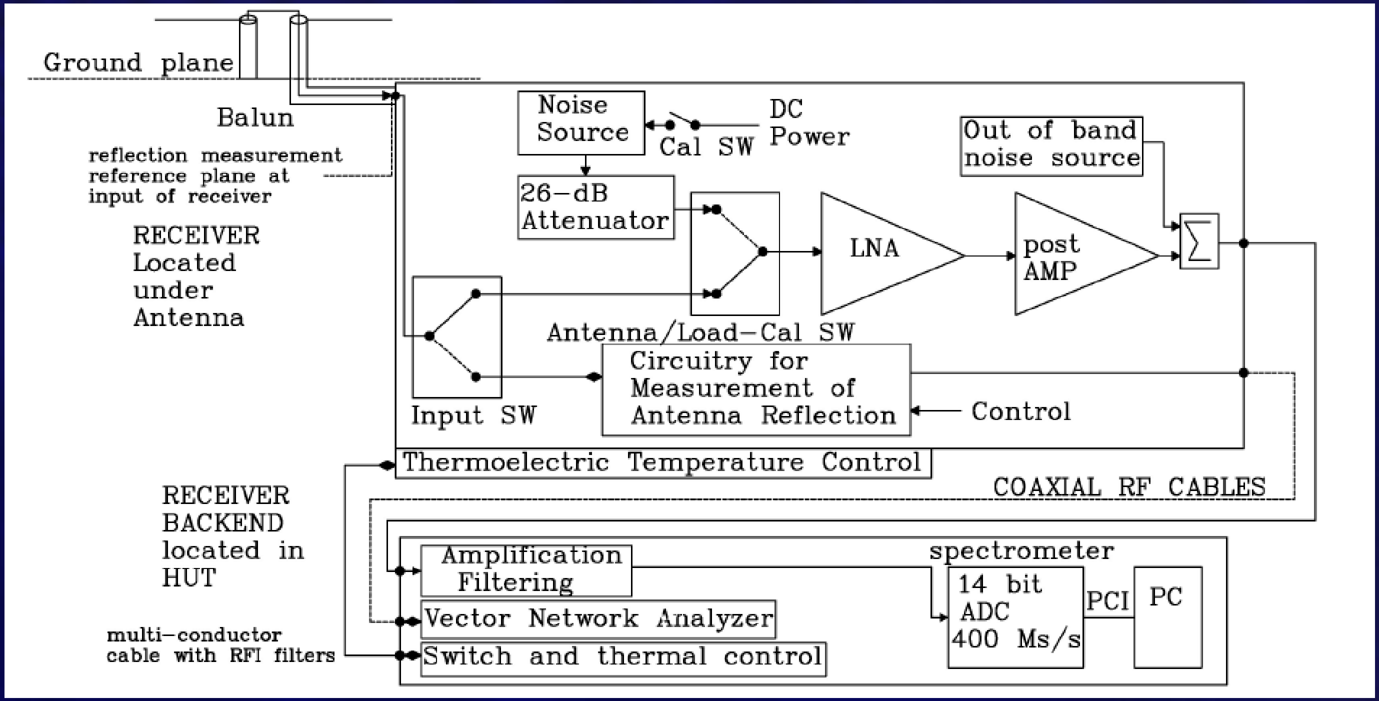
Global Spectrum Experiments



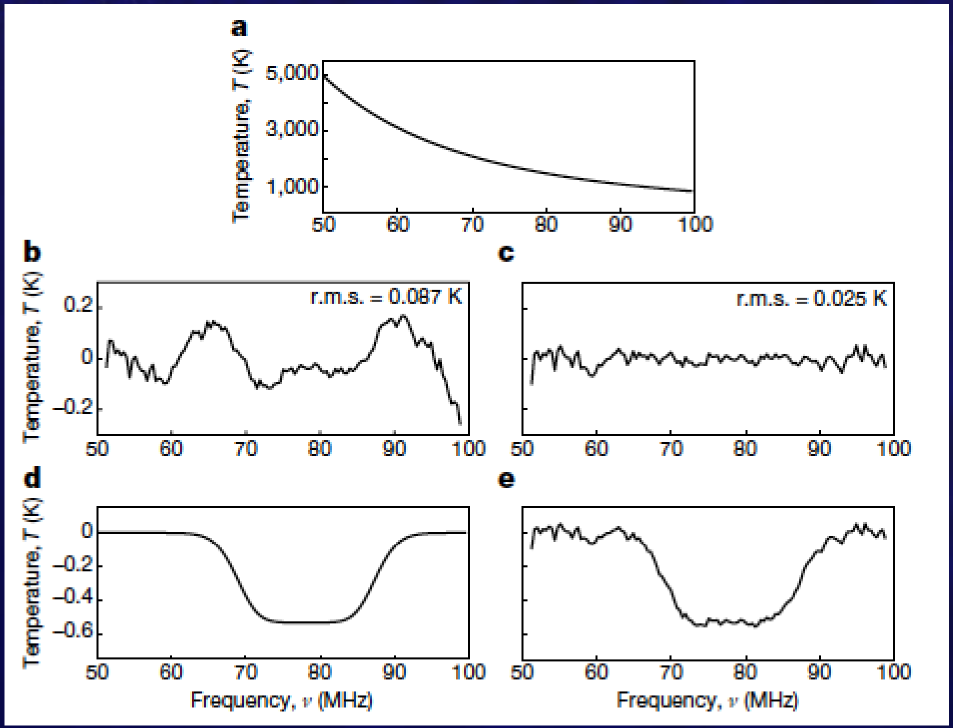


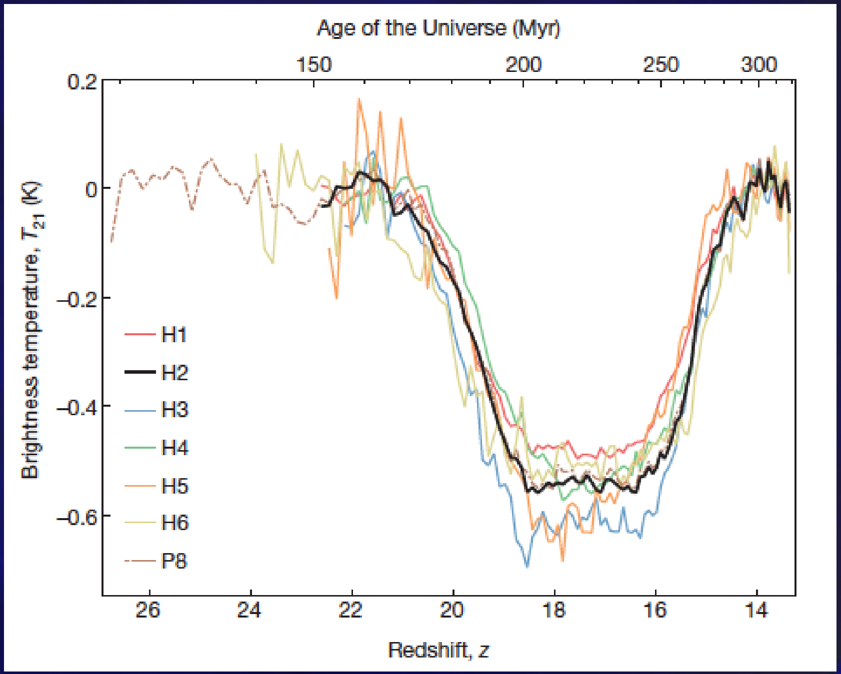
How to achieve Precision Calibration

- Internal Calibration
- sky calibration: galaxy up down



EDGES-low result





Interpretation of the Result

The absorption observed by EDGES is much stronger than typical model, even stronger than maximum case!

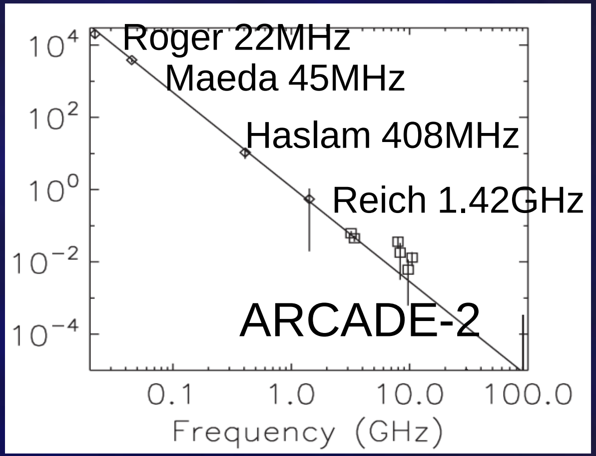
$$T_{21}(z) \approx 0.023\ \mathrm{K} \times x_{\mathrm{HI}}(z) \left[\left(\frac{0.15}{\Omega_{\mathrm{m}}} \right) \left(\frac{1+z}{10} \right) \right]^{\frac{1}{2}} \left(\frac{\Omega_{\mathrm{b}} h}{0.02} \right) \left[1 - \frac{T_{\mathrm{R}}(z)}{T_{\mathrm{S}}(z)} \right]$$

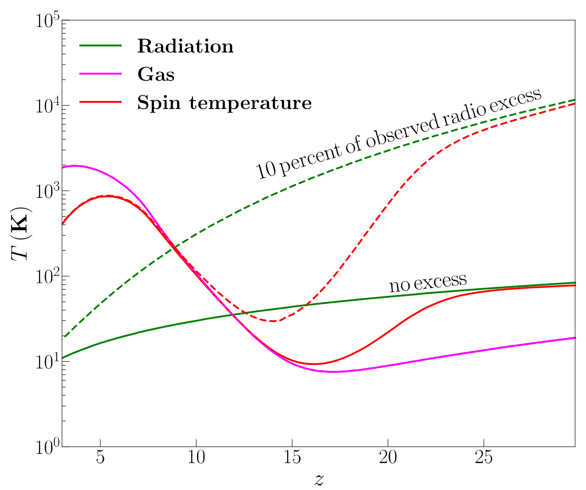
- foreground contamination (Hills et al. 2018)
- unknown systematics: e.g. underground water reflection, ionosphere
- colder baryons (cooled by interacting dark matter, $(T_S < 3.2\ \mathrm{K})$)
- extra-radio background $(T_R > 104\ \mathrm{K})$

Excess Radio Background

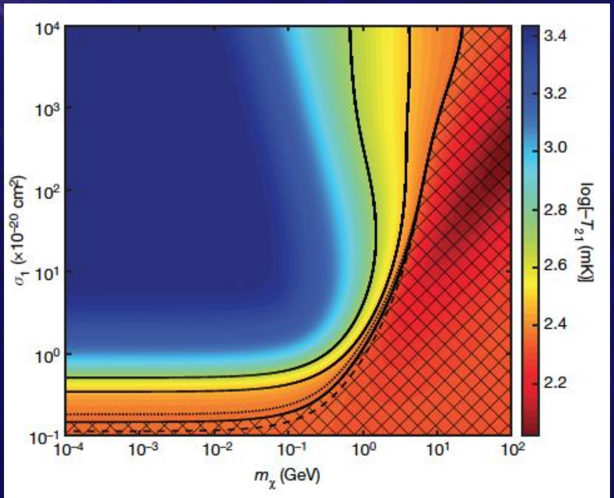
$$\delta T_b \propto \left(1 - \frac{T_{\rm CMB} + T_{\rm rad}}{T_s}\right)$$

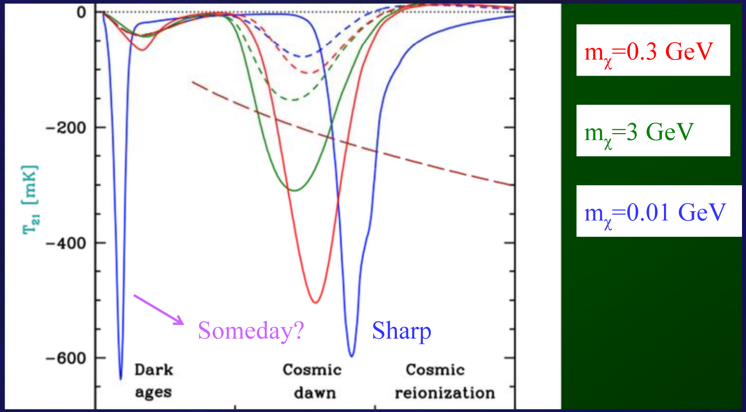
- Maybe in the cosmic dawn, in addition to CMB, there is a radio background generated by early sources AGN, pop star, ... (Ewall-Wice et al. 2018)
- Must be very radio loud (Mirocha & Furlanetto 2018) but at high-z, inverse-Compton stronger, the main radio mechanism-synchrotron likely to be comparatively weaker (Sharma 2018)
- Constrained by reionization redshift, radio and X-ray source count, ...
- If global signal enhanced, fluctuation signal is also strong





Dark Matter Cooling



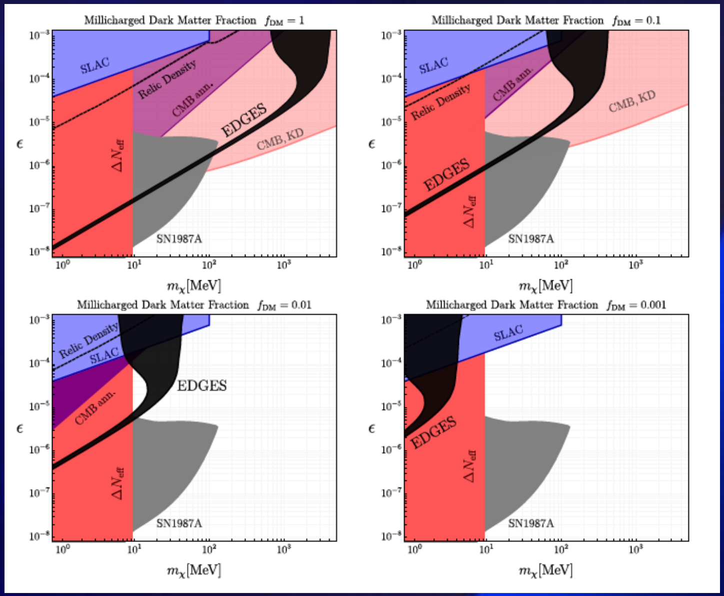


Barkana 2018

- DM is cooler than baryon as it decoupled earlier, but need baryon-DM interaction, temperature (energy) dependent, e.g. Coloumb interaction

$$\sigma(v) = \sigma_c \left(\frac{v}{c}\right)^{-4} = \sigma_1 \left(\frac{v}{1\,\mathrm{km\,s^{-1}}}\right)^{-4}$$

- Severely constrained by various experiments

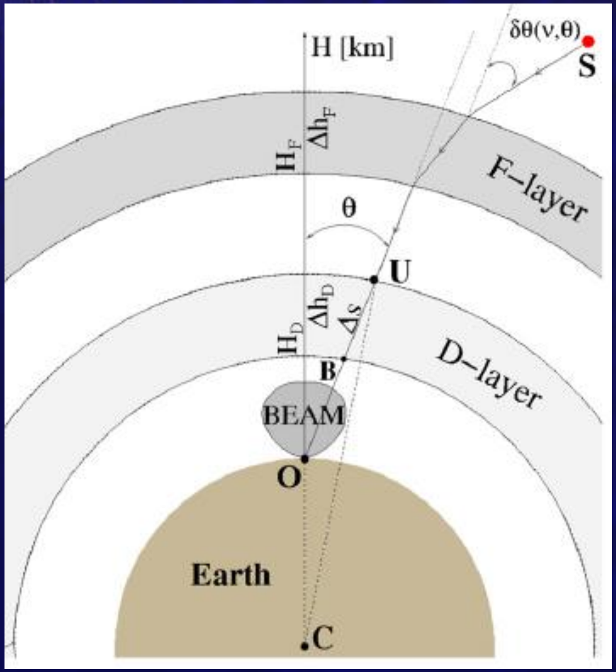


Berlin et al. 2018

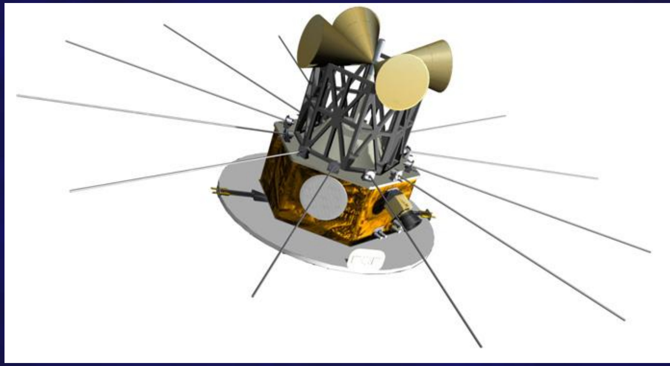
Other Ideas

- Baryonic Universe + MOND (S. McGaugh)
- Early baryon decoupling (so it is colder) by an early dark energy (Hill & Haxter)
- Modify early Hubble parameter by Interacting dark energy (A. Costa et al.)
- Dark photon mixing (M. Pospelov et al.)
- axion Bose-Einstein condensation cooling (Houston et al. 2018)
- Dark matter decay to radio (Fraser et al.)
- Dark matter annihilation to radio (Yang)
- Dark force (Li & Cai)

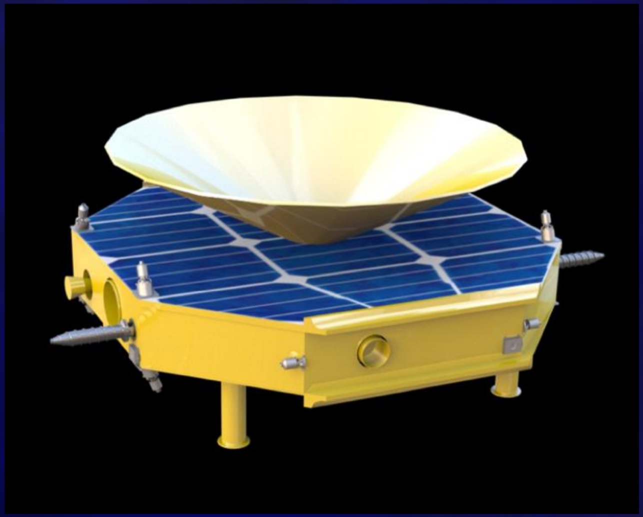
Space Experiment



ionosphere refraction and absorption also affects global spectrum



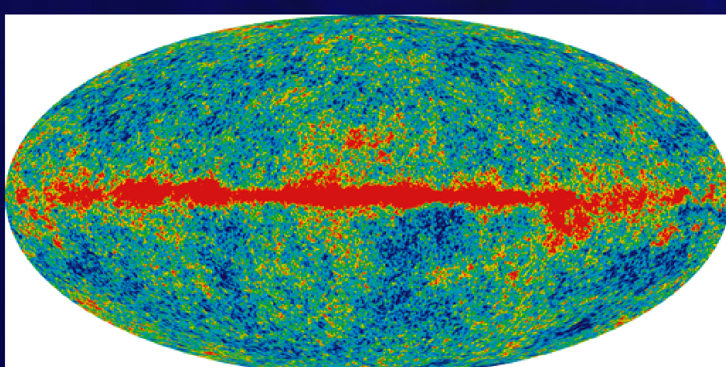
DARE



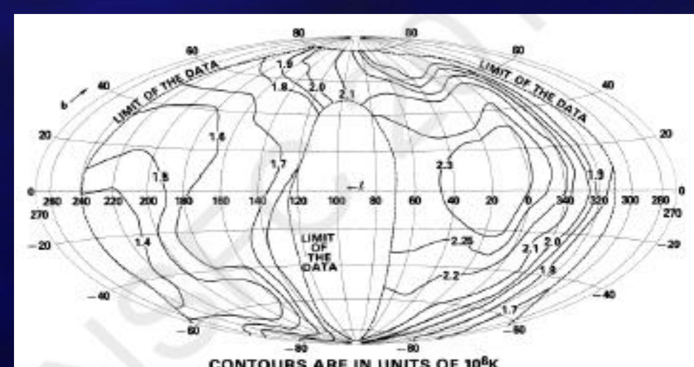
DSL HFS

Space-based low frequency radio observation

- Below 10MHz, due to ionosphere absorption, ground observation is nearly impossible.



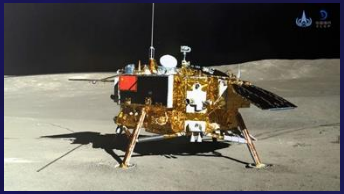
Planck map



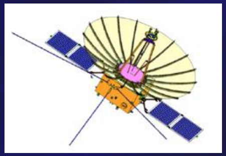
RAE-2 sky map (1979)

Experiments during CE-4 mission

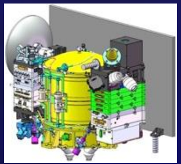
- CE-4 Lander



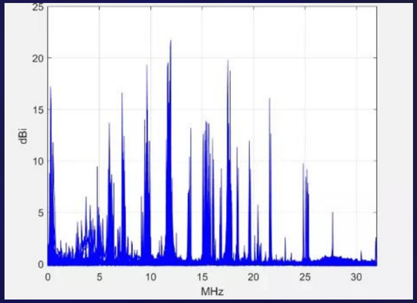
- Netherland-China Low frequency Experiment (Relay Satellite)



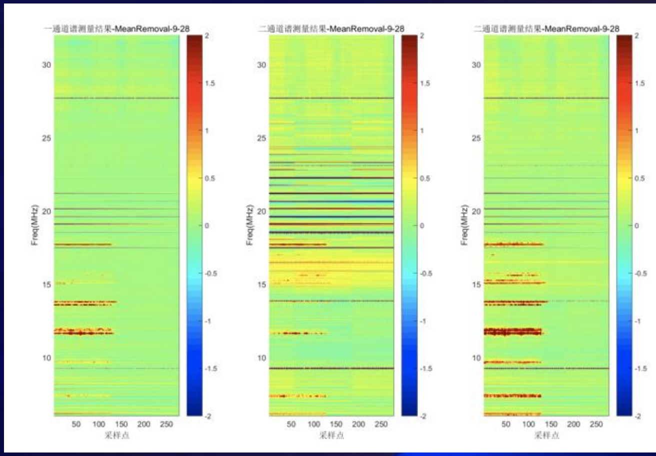
- Longjiang orbiting satellites (piggy-back on relay satellite launch)--unfortunately, Longjiang-1 malfunctioned



EMI

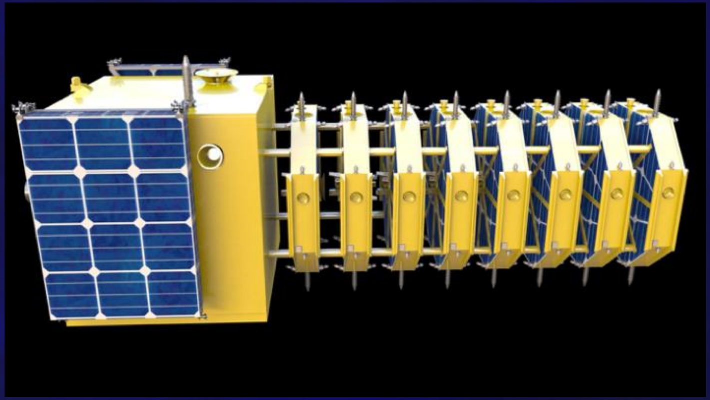


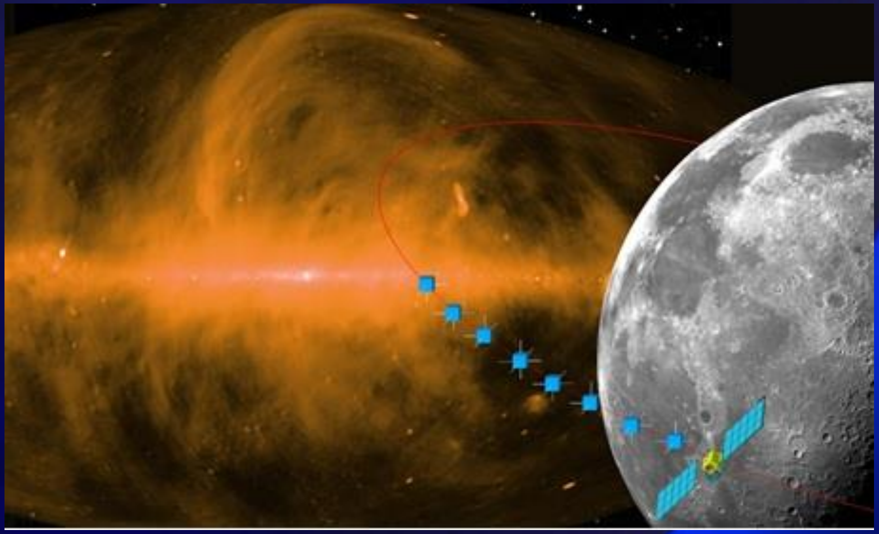
- EMI limited sensitivity, and also work time is very short due to limited power, but still can see moon shield radiation from Earth



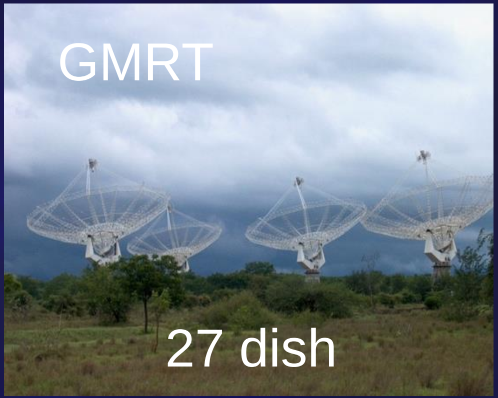
Discovering Sky at Longest (DSL) wavelength

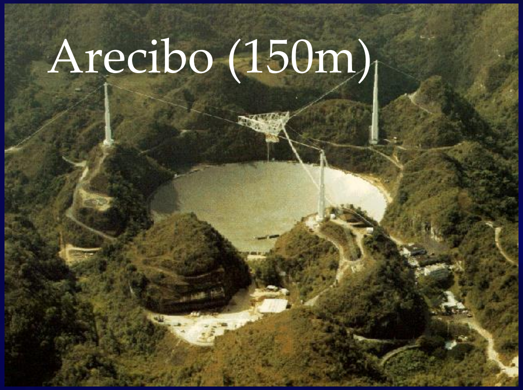
- A linear array (5-8) of satellites moving around the moon, take observation at the backside of the moon, then transmit data back at the front side of the moon.
- A mother satellite measure the position of the daughter satellites
- Low frequency aims for imaging of foregrounds, high frequency aims to detect cosmic dawn signal by precise global spectrum measurement





Current mid-redshift Radio Telescopes



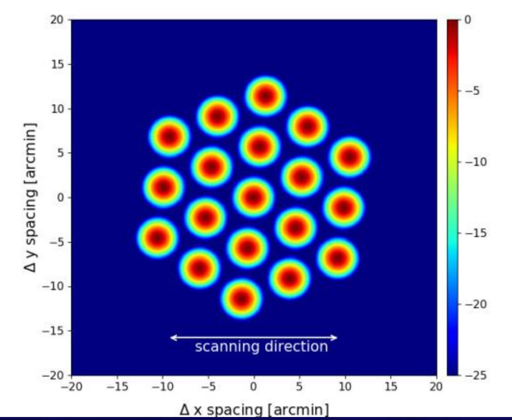


FAST survey

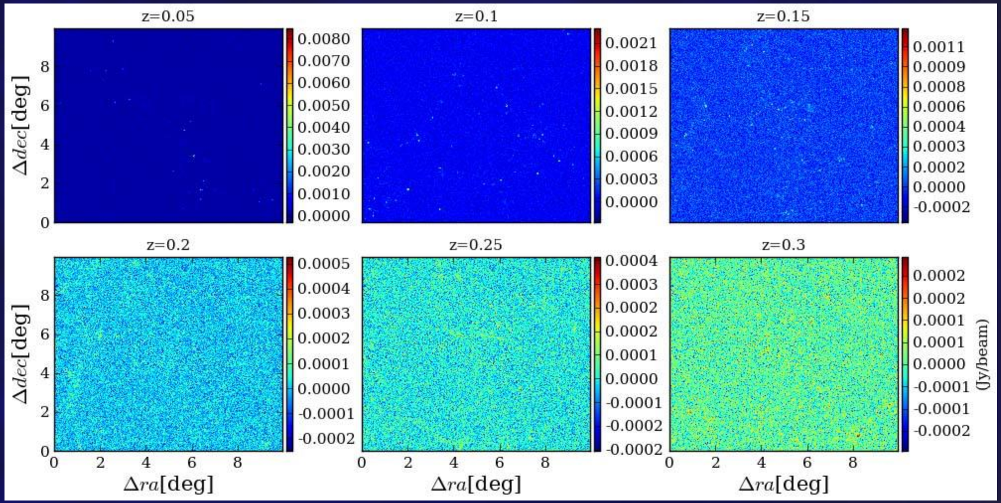
Wenkai Hu et al., Forecast for FAST: from Galaxies Survey
Mapping", arxiv:1909.10946

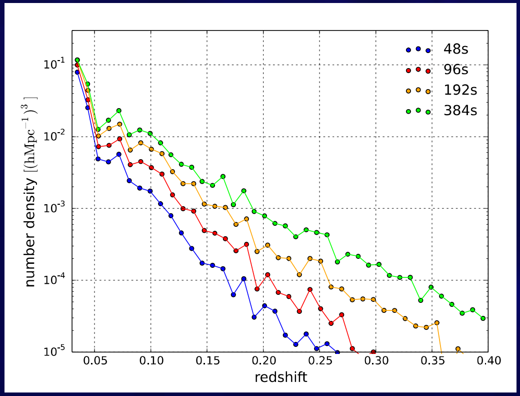
receiver	band(GHz)	Beams	$T_{\rm rec}$(K)	$t_{\rm sur}$(days)
L-band	1.05-1.45	19	20	220
Wide-band	0.27-1.62	1	60	1211
UHF PAF (future)	0.5-1.0	81	30	135

$$\theta = 1.22 \times \frac{21\,\mathrm{cm}(1+z)}{300\,\mathrm{m}} = 2.94(1+z)\,\mathrm{arcmin}$$

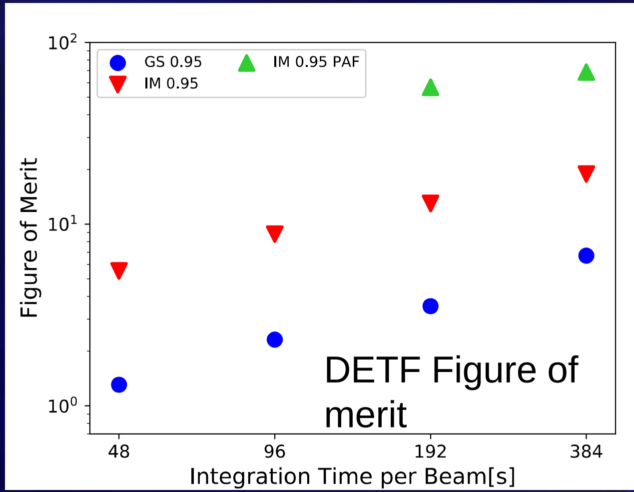


L-band beams



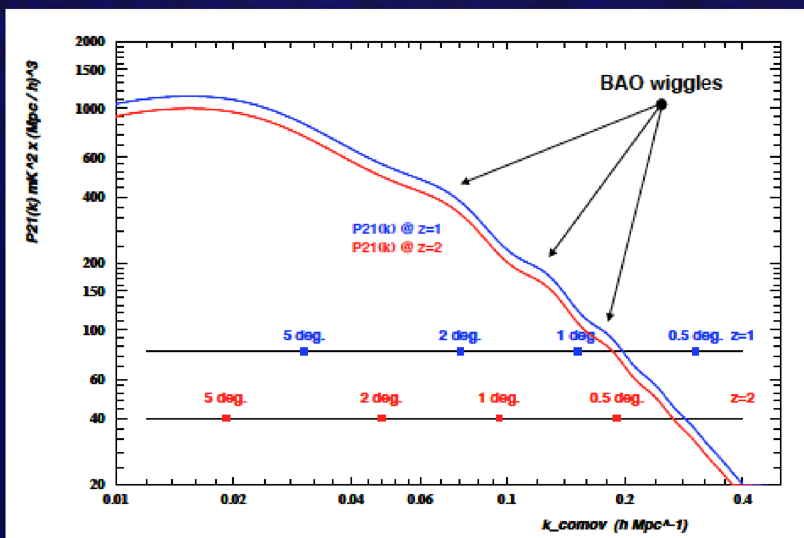


number density of detected galaxies

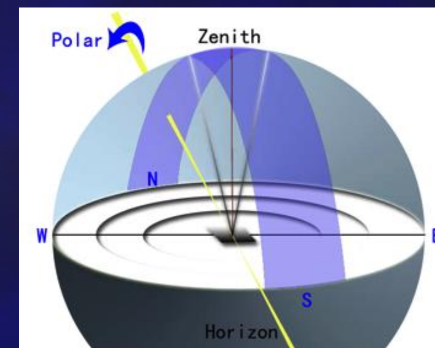


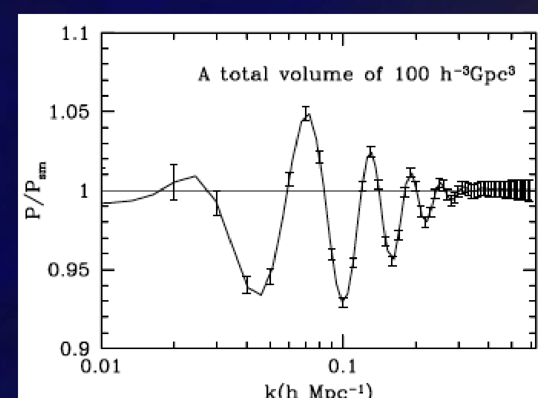
Dedicated Experiments

- Stable, large field of view（also good FRB searcher)
- Array Size: ~ 100 m for BAO (T. Chang et al. 2008, Seo et al. 2009, Ansari et al. 2012)



$$\frac{S}{N} = \sqrt{\frac{4\pi k^2 dk V_{\rm survey}}{2(2\pi)^3}} \frac{P_{\rm HI}}{P_{\rm HI} + \left[\frac{(g\bar{T}_{\rm sky} + \bar{T}_a)}{gT_{\rm sig}\sqrt{t_{\rm int}\Delta f}}\right]^2 V_R + \frac{1}{\bar{n}}},$$





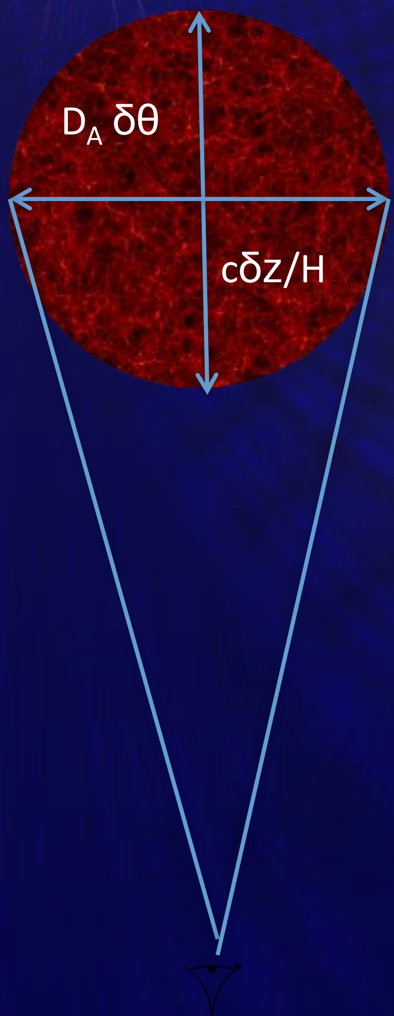
The Tianlai (heavenly sound) Experiment

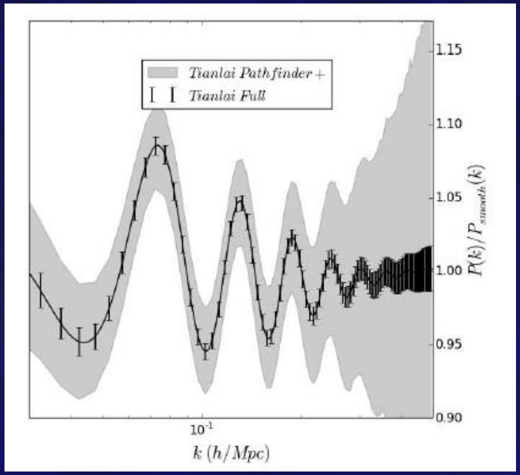
- Cylinder pathfinder : 3x15m x 40m, 96 feeds
- Dish Pathfinder: 16 x 6m

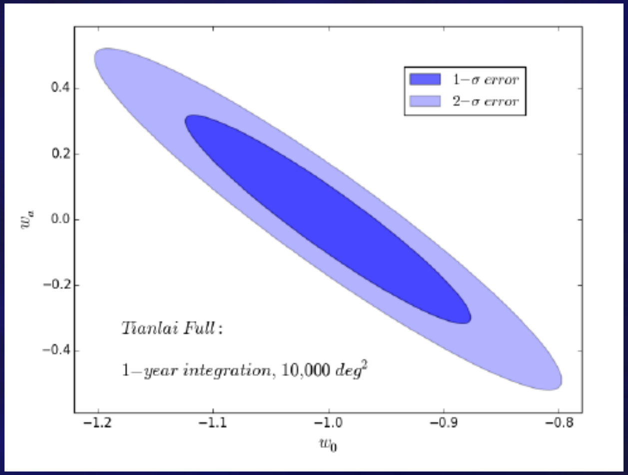
frequency: 700-800MHz, can be tuned in 600~1420MHz

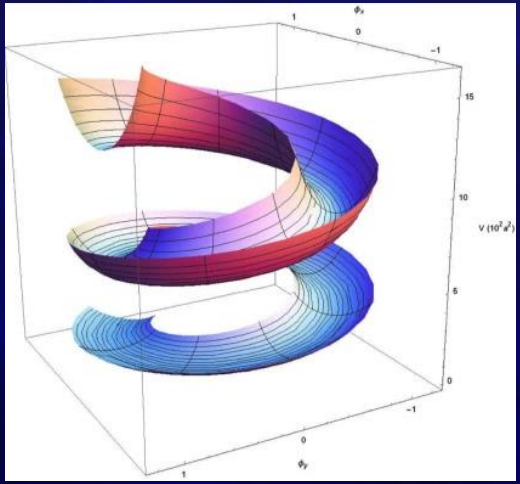
probe of Large Scale Structure (BAO,PNG, inflation features)

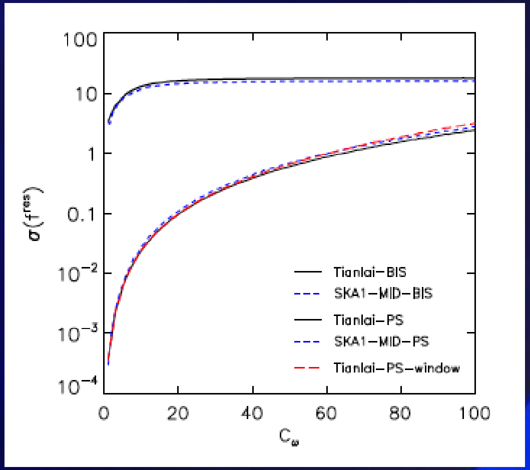
Xu, Wang & Chen (2015)





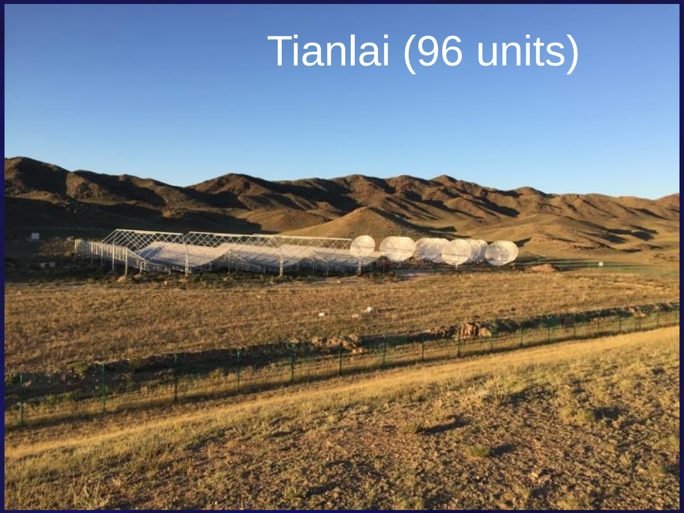


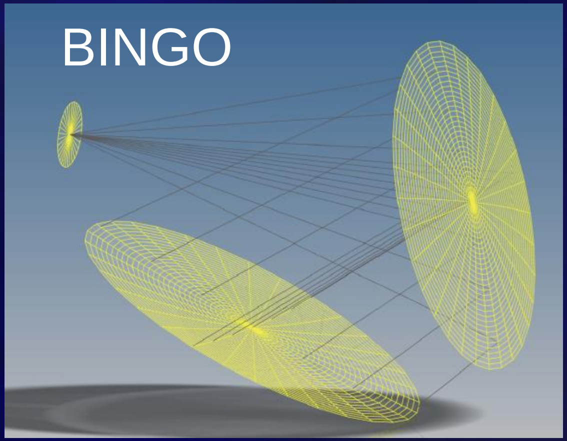




Xu, Hamann, Chen(2016)

21cm Intensity Mapping Experiments



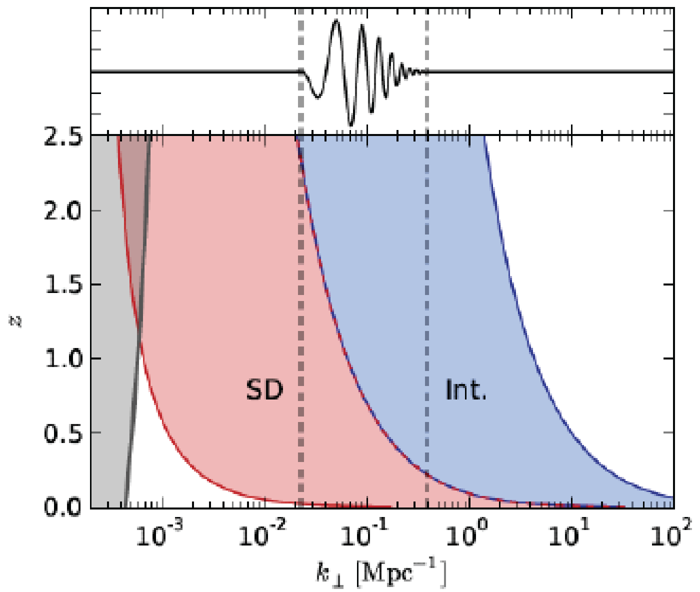


Near Future: SKA-mid

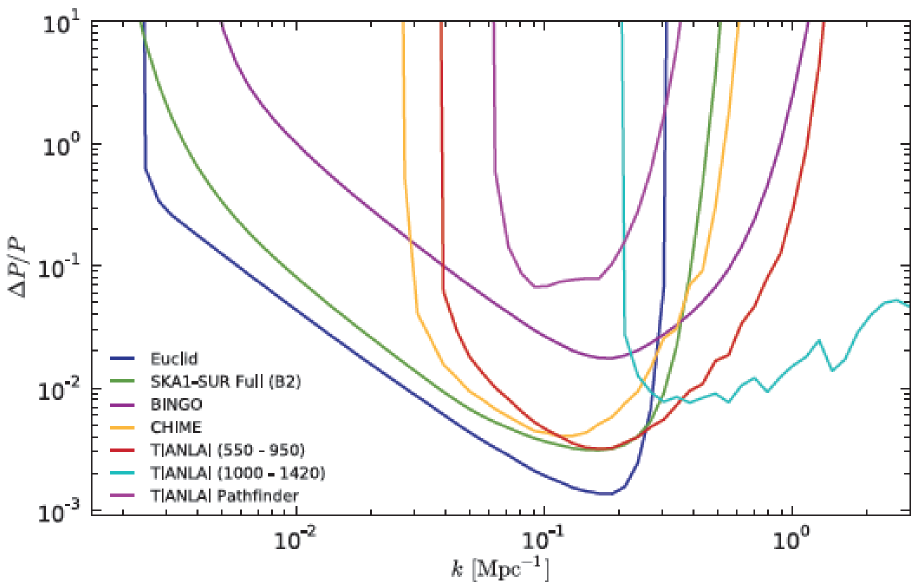
SKA-1: 197 dish (15m) + 64 MeerKAT dish

SKA-2: ～ 3000 dish

Intensity Mapping BAO measurements



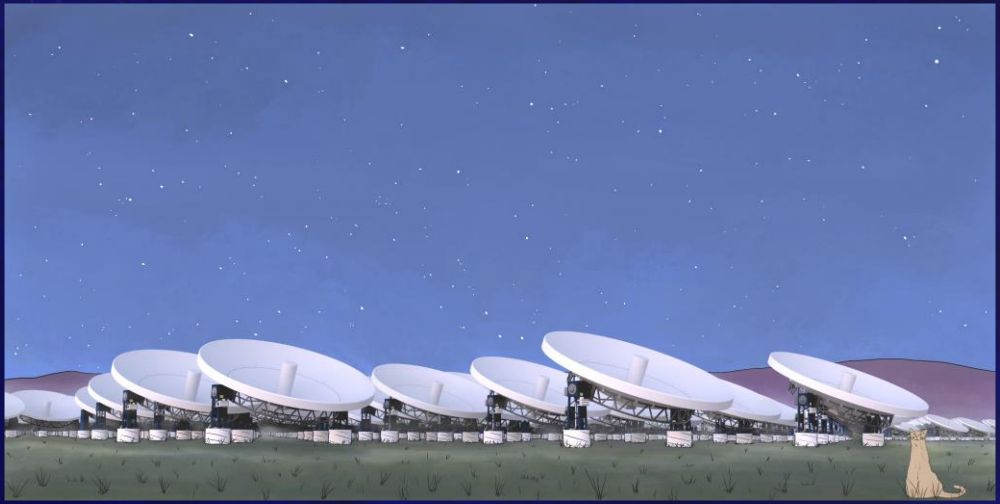
BAO scales probed by SKA1 – dish versus interferometer

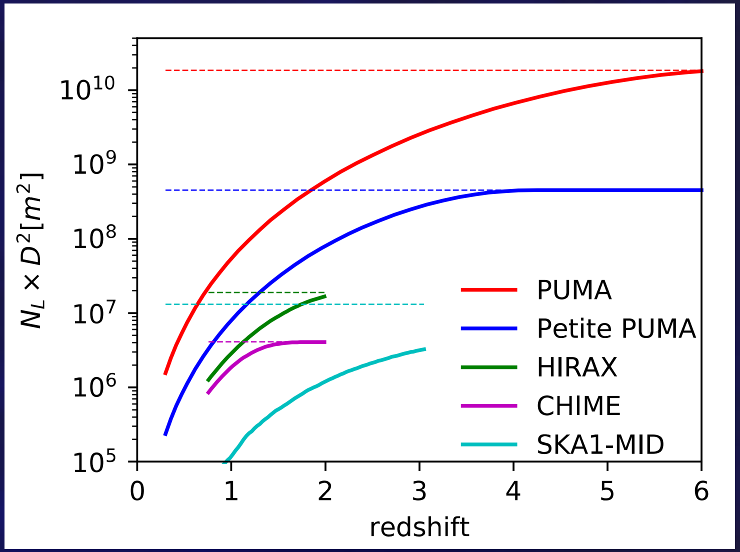


Credit: Phil Bull

SKA Cosmology Workgroup （http://skacosmology.pbworks.com)

Future Ideas: PUMA





200～1100MHz，6m dish, 10^4 elements

Slosar et al., arxiv:1907.12559

Outlook

- 21cm experiments are easy (to start) and hard (to detect!)—lots of experiment efforts going on
- Varies approaches: global spectrum, single dish, regular and irregular interferometer arrays
- New and more powerful data analysis method: AI?
- The 21cm auto-correlation is still to be detected, but progresses are being made
- The 21cm cosmology is coming!

Thanks and Enjoy!

Backup slides

Problems with Lunar Array

Traditional imaging algorithm can not work!

- short dipole (l<<λ) antenna have very wide field of view (almost whole sky), traditional synthesis algorithm only for small field of view (flat sky, small w-term)

- A mirrow symmetry w.r.t. orbital plane, can be broken by 3D baselines (produced by orbital plane precession)

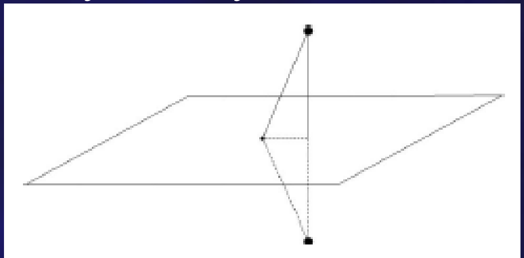
- Different baselines have different part of sky blocked by Moon

map-making by invertion

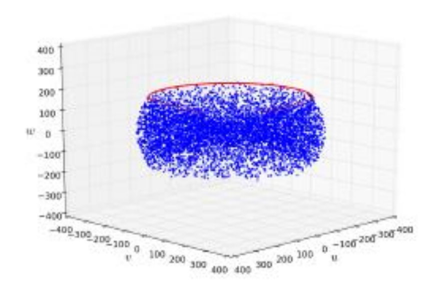
$$\mathbf{V} = \mathbf{B}\,\mathbf{T} + \mathbf{n}.$$

$$\hat{\mathbf{T}} = (\mathbf{B}^{\dagger}\mathbf{N}^{-1}\mathbf{B})^{-1}\mathbf{B}^{\dagger}\mathbf{N}^{-1}\mathbf{V} \equiv \mathbf{B}^{-1}\mathbf{V}.$$

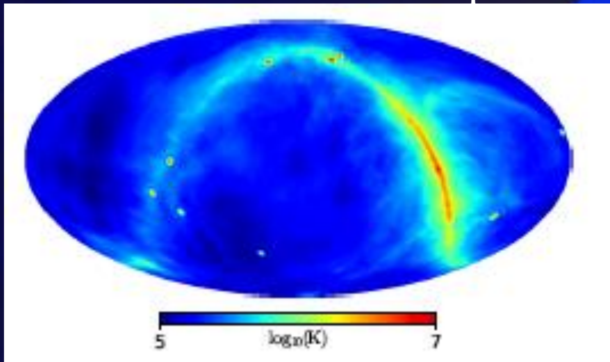
mirrow symmetry



3D baselines



simulated reconstruction map



Huang et al., arXiv:1805.08259

galaxy detection vs intensity mapping

Cheng et al (2018): criterion

L_{SN} : luminosity scale for voxel shot noise
σ_L : rms noise per voxel
l_* : galaxy characteristic luminosity.

Table 3. Four limiting regime defined by the relative value of the luminosity scale where the voxels are highly susceptible to shot noise, L_{SN}, the rms noise per voxel, σ_L and the characteristic luminosity for a certain luminosity function, $l_\star$}.

number	regime	optimal strategy
1	$L_{SN} < \sigma_L < l_\star$	galaxy detection
2	$\sigma_L < L_{SN} < l_\star$	galaxy detection/intensity mapping[a]
3	$L_{SN} < l_\star < \sigma_L$	intensity mapping
4	$l_\star < L_{SN}$	intensity mapping

[a] Here the optimal strategy is an intermediate between the intensity mapping and galaxy detection observables.

$$\sigma^2_{SN}(l) = V_{vox}\phi_* \int_0^l dl' l'^{\alpha+2} e^{-l'}.$$