21cm Cosmology

Global Signal

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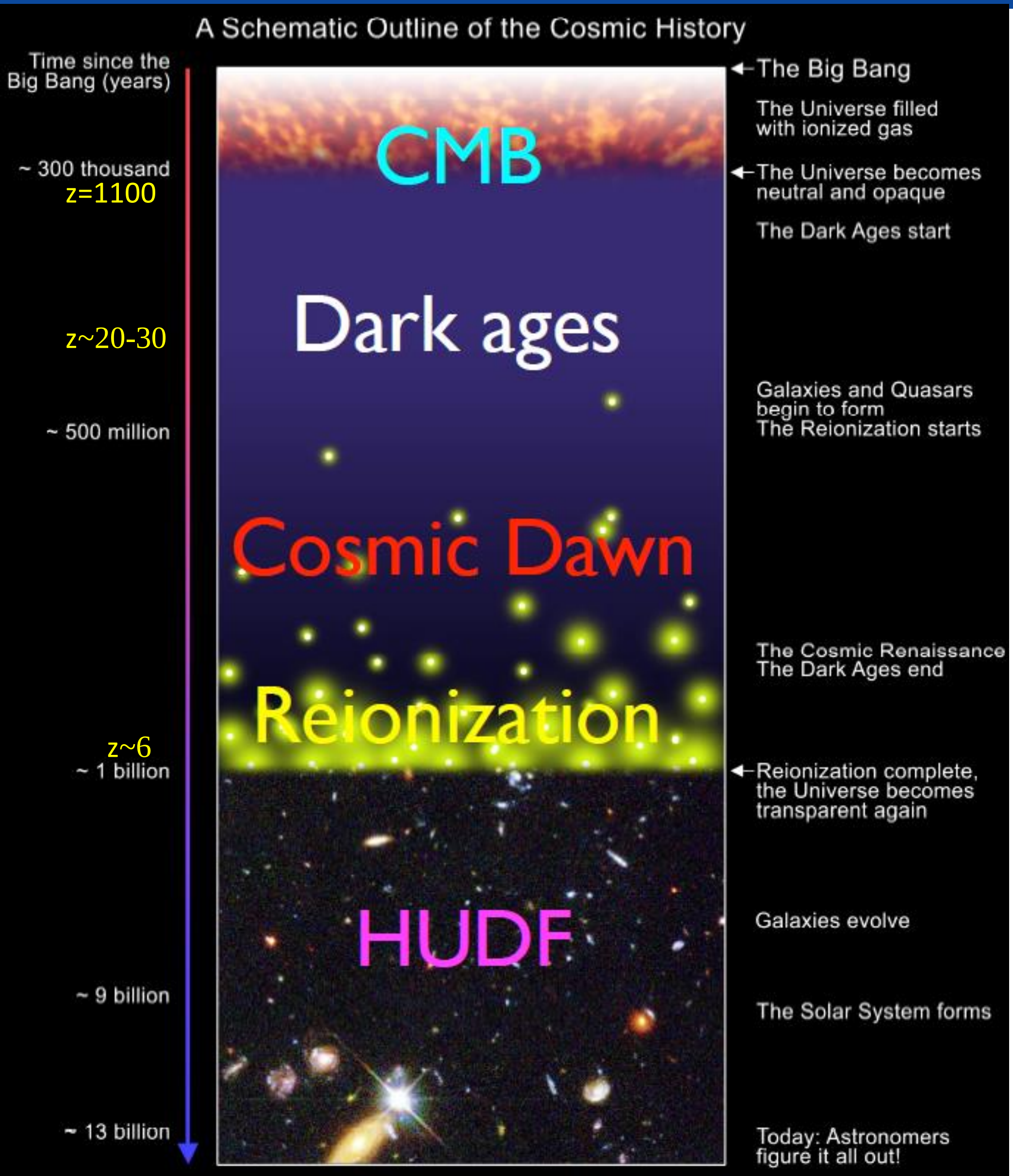
The First Half-Billion Years

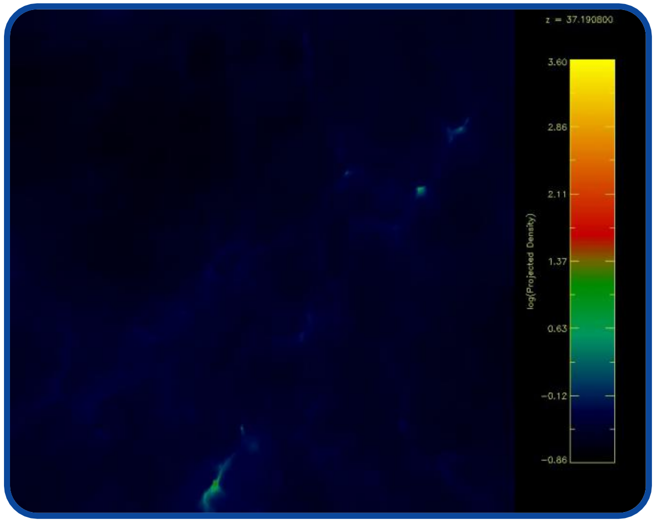


A Schematic Outline of the Cosmic History

S.G. Djorgovski et al. & Digital Media Center, Caltech

The First Stars

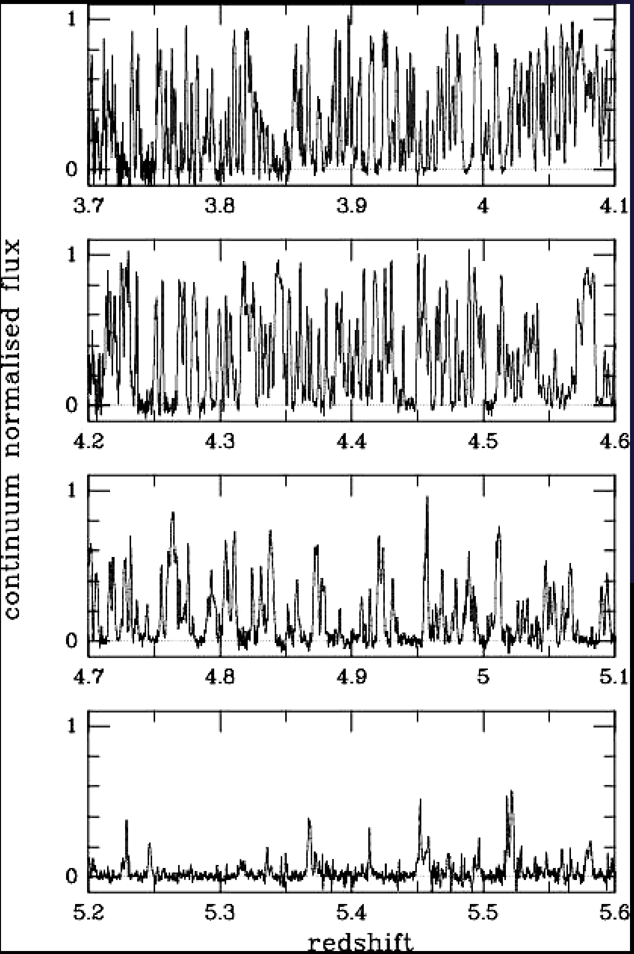
John Wise, Georgia Tech



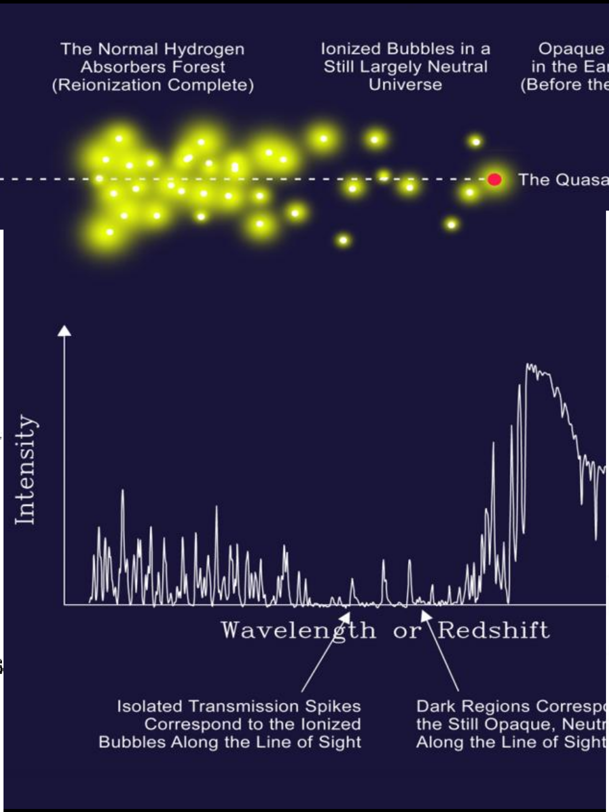
Dare Science Questions

- When did the First Stars ignite? What were these First Stars?
- When did the first accreting Black Holes turn on? What was the characteristic mass?
- When did Reionization begin?
- Any signs of exotic physics (e.g. Dark Matter decay) from global signal?

Constraint I: Gunn-Peterson Effect



Djorgovski (2003)

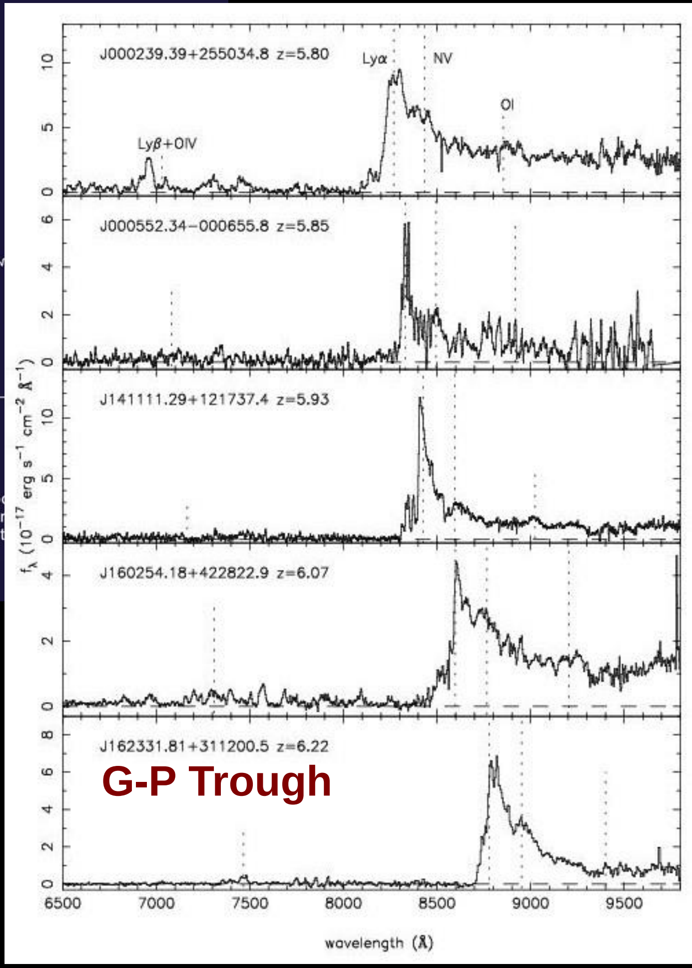


Z < 5

Z > 5

$\mathbf{z_{reion} > 7}$

ULAS J1120+0641 at z=7.085
(Mortlock et al. 2011)



Fan et al. (2004)

Contraint II: The CMB

Temperature fluctuations due to density inhomogeneities at the surface of last scattering (z ~ 1000)

Thomson scattering of the photons by the ionized medium during reionization (z~10)

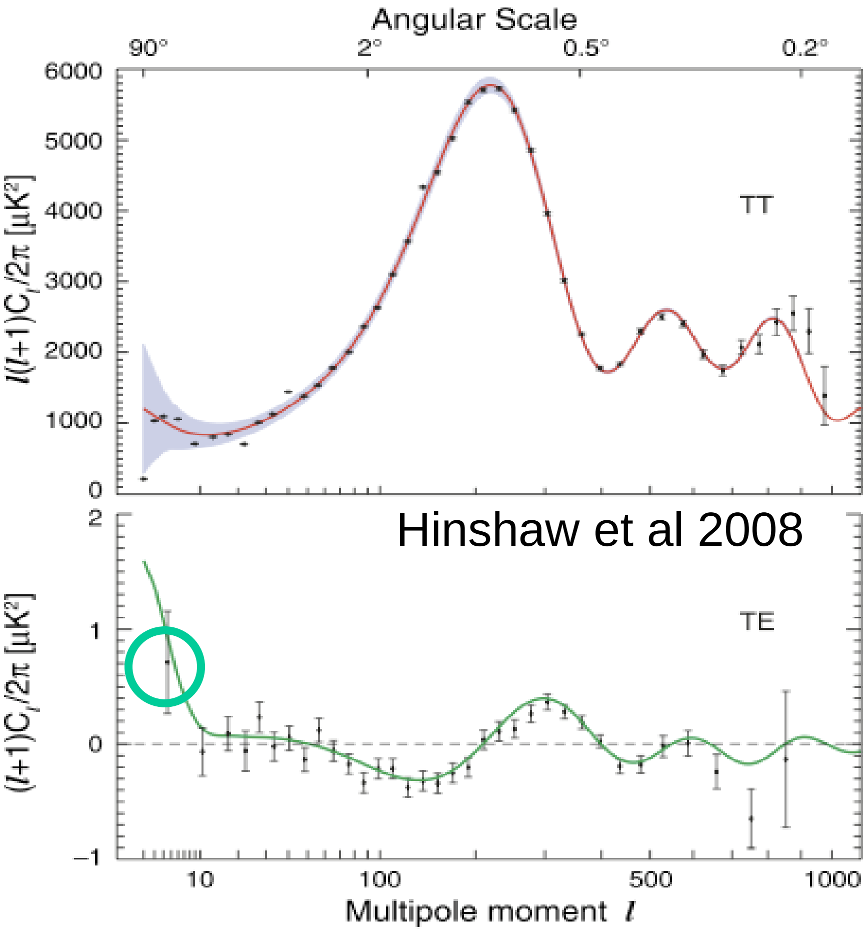
From large-scale temperature-polarization cross power spectrum, we get the T.S. Optical depth :-

$\tau_e = 0.087 \pm 0.014$ → 0.066+/- 0.016 (Planck '15)

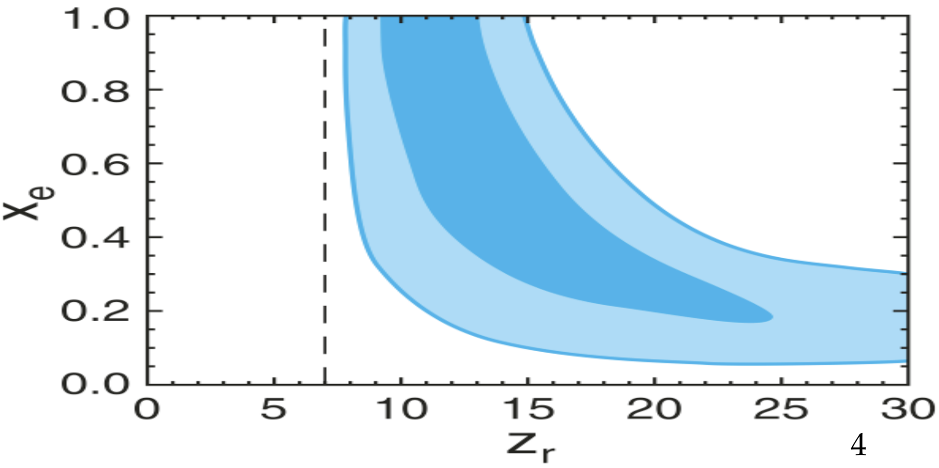
↓

$z_{reion} < 10.4 \pm 2$ → 8.8 +/- 1.4 (Planck'15)

WMAP 7 results



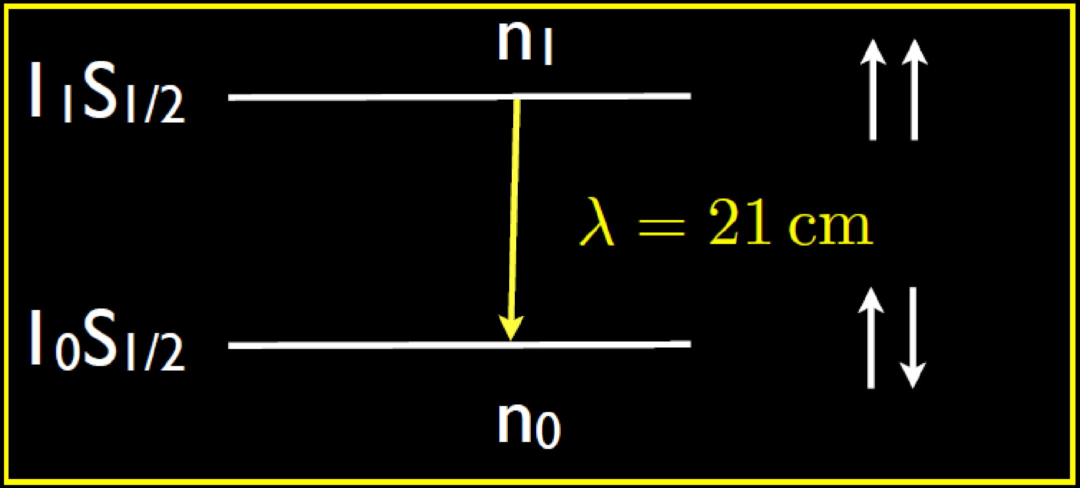
Hinshaw et al 2008



The 21-cm Hyperfine Line of Neutral Hydrogen

$$\nu_{21cm} = 1,420,405,751.768 \pm 0.001\,\mathrm{Hz}$$

Hyperfine transition of neutral hydrogen



Spin temperature describes relative occupation of levels

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

Useful numbers:

$200\,\mathrm{MHz} \rightarrow z = 6$

$100\,\mathrm{MHz} \rightarrow z = 13$

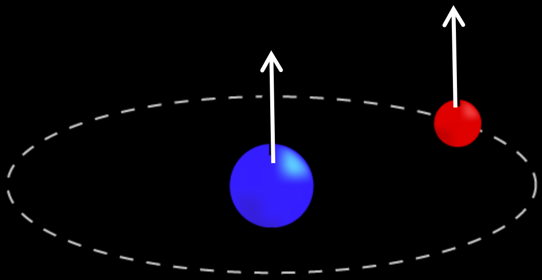
$70\,\mathrm{MHz} \rightarrow z \approx 20$

$40\,\mathrm{MHz} \longrightarrow z \approx 35$

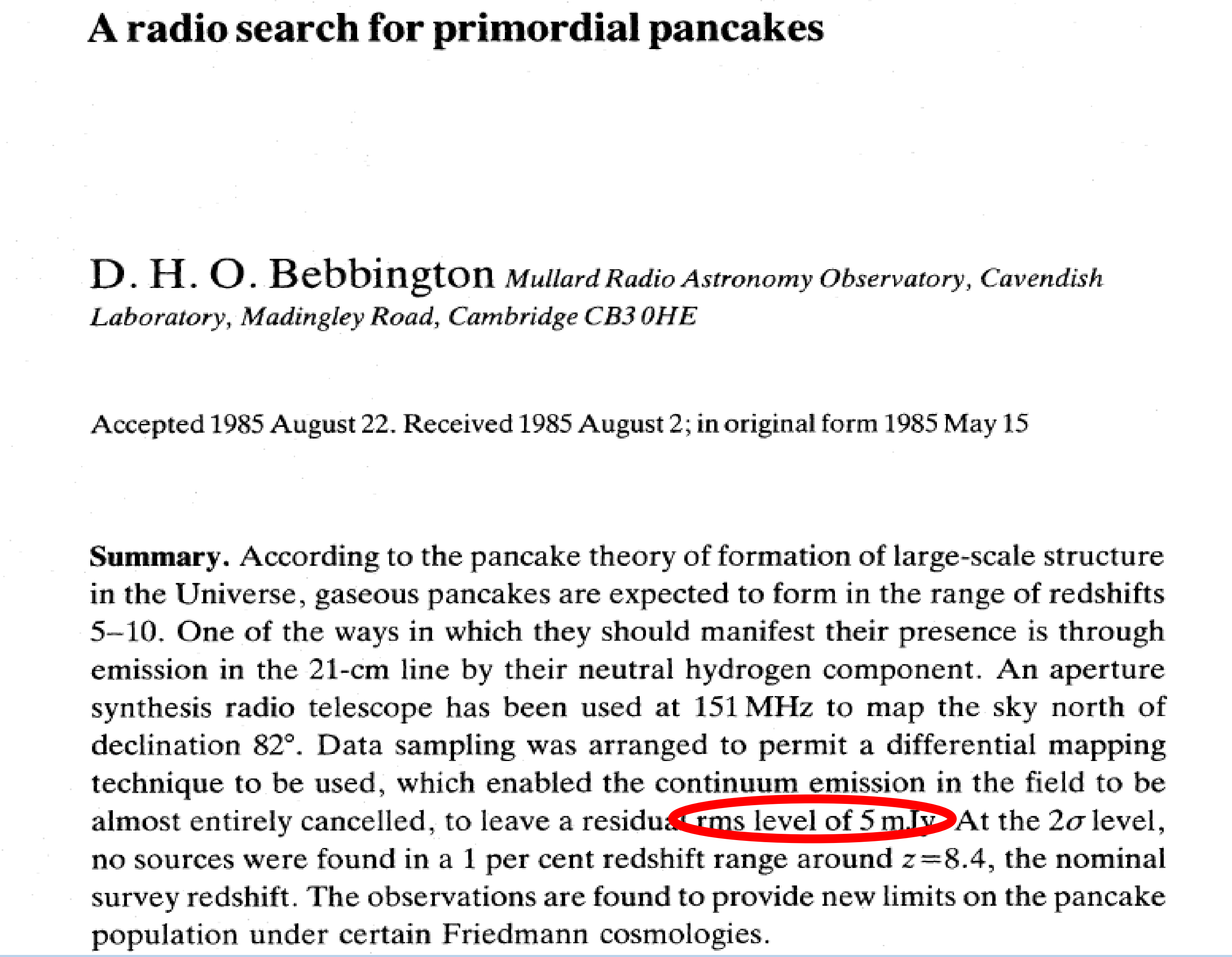
$t_{\mathrm{Age}}(z = 6) \approx 1\,\mathrm{Gyr}$

$t_{\mathrm{Age}}(z = 10) \approx 500\,\mathrm{Myr}$

$t_{\mathrm{Age}}(z = 20) \approx 150\,\mathrm{Myr}$



First Attempt



A radio search for primordial pancakes

D. H. O. Bebbington *Mullard Radio Astronomy Observatory, Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE*

Accepted 1985 August 22. Received 1985 August 2; in original form 1985 May 15

Summary. According to the pancake theory of formation of large-scale structure in the Universe, gaseous pancakes are expected to form in the range of redshifts 5–10. One of the ways in which they should manifest their presence is through emission in the 21-cm line by their neutral hydrogen component. An aperture synthesis radio telescope has been used at 151 MHz to map the sky north of declination 82°. Data sampling was arranged to permit a differential mapping technique to be used, which enabled the continuum emission in the field to be almost entirely cancelled, to leave a residual rms level of 5 mJy. At the 2σ level, no sources were found in a 1 per cent redshift range around $z=8.4$, the nominal survey redshift. The observations are found to provide new limits on the pancake population under certain Friedmann cosmologies.

Signal I: Cosmic Stromgren spheres @z > 6 QSOs

Cosmic Stromgrene Sphere is different from Galactic HII region.

CSS is large in size and not static.

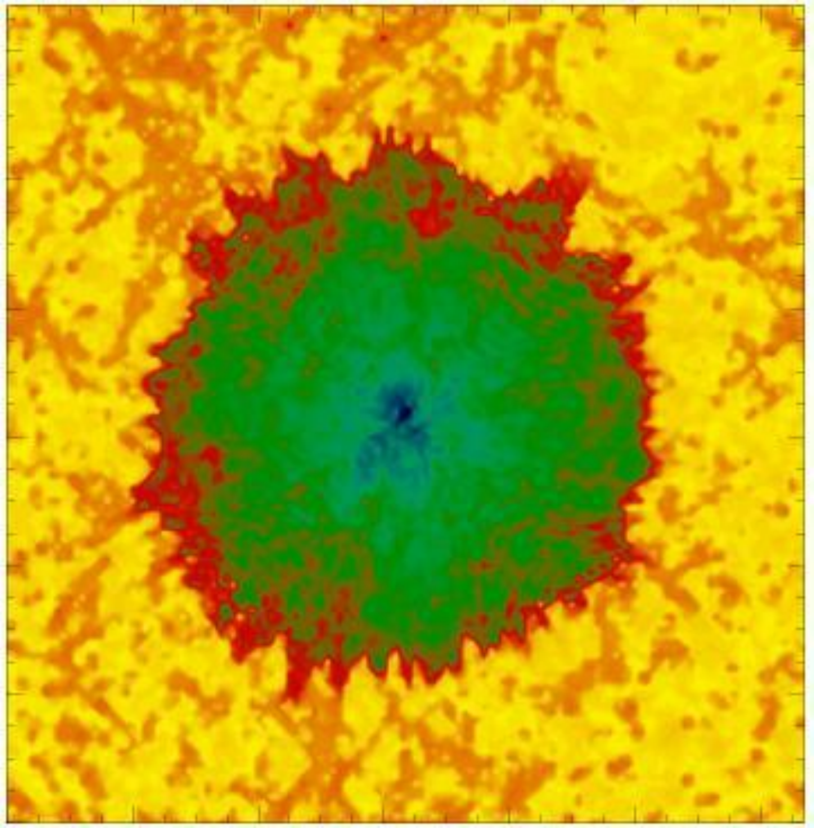
Brightness Temperature ~ 20 mK

Size of a HII region ~ 4 Mpc

Angular size ~ 15 arcmin.
@ 200 MHz (z~ 6.5)

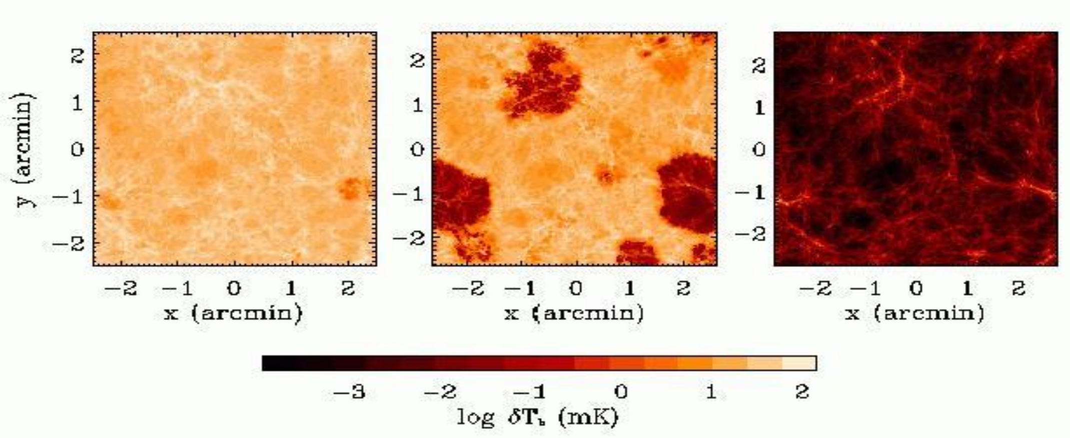
Bandwidth ~ 2 MHz

Density of CSS ~ 1-2
per 15 deg FOV
per 16 MHz



Mcquinn (2007)

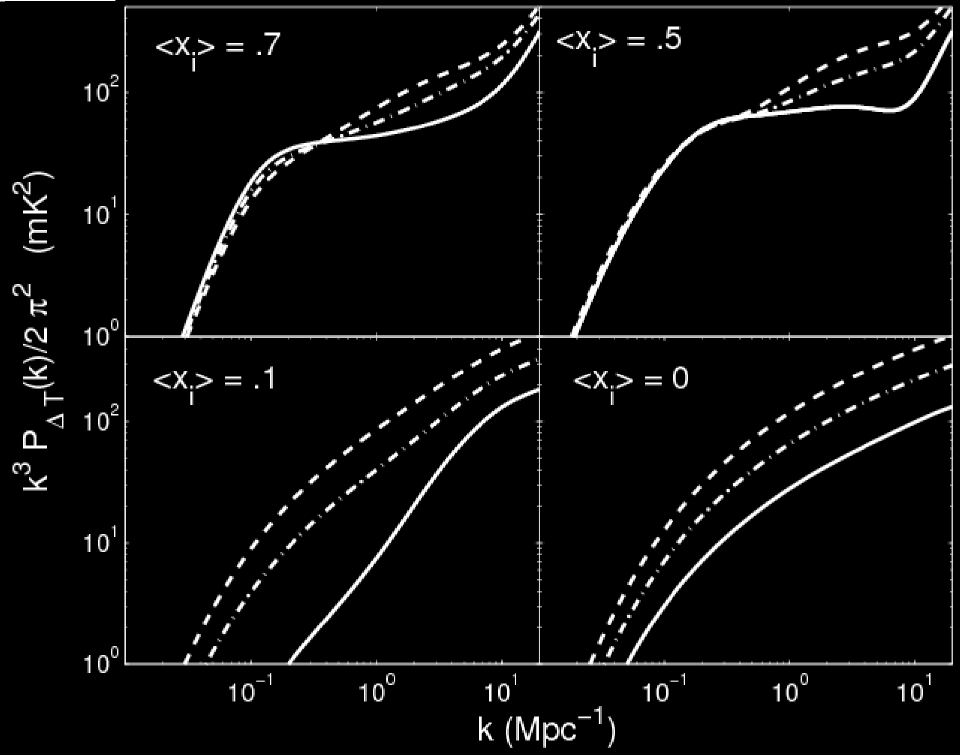
Signal II: 1D Spherically Averaged Power spectrum

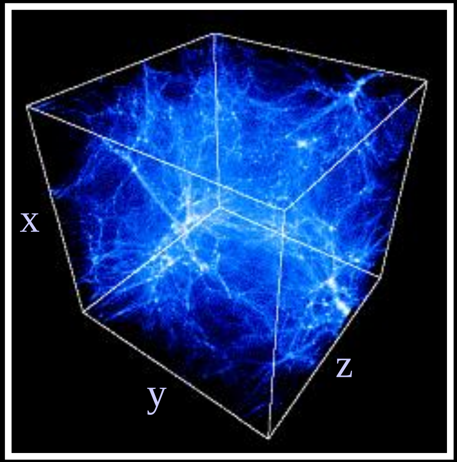


3D tomography of IGM- best way to probe EoR

Not possible with first generation EoR Telescopes

McQuinn, Zahn, Hernquist, & Furlanetto (2006)

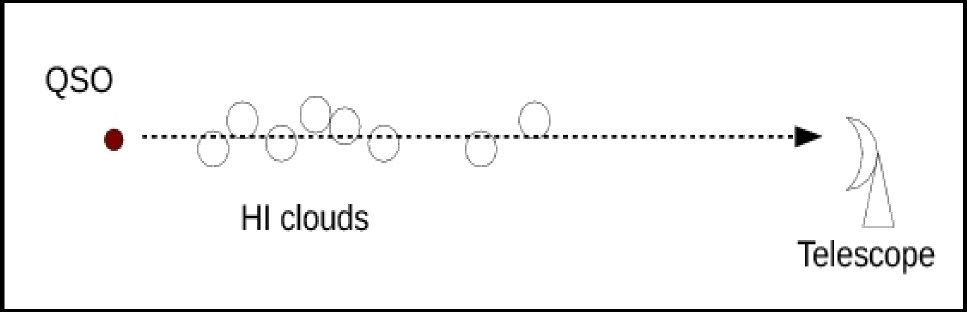


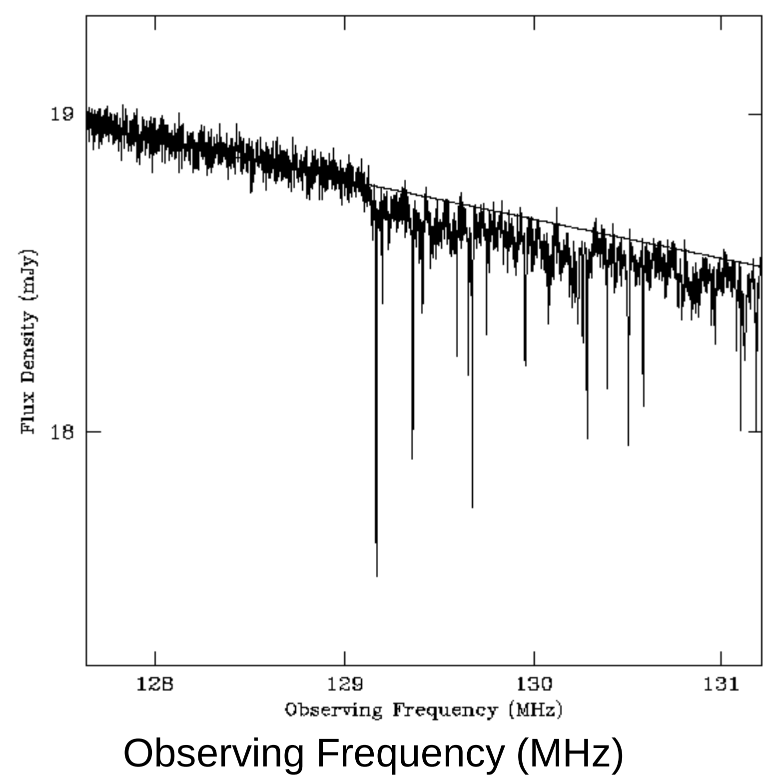


F.T.

Power spectra to gain S/N

Signal III: HI 21 cm Forest





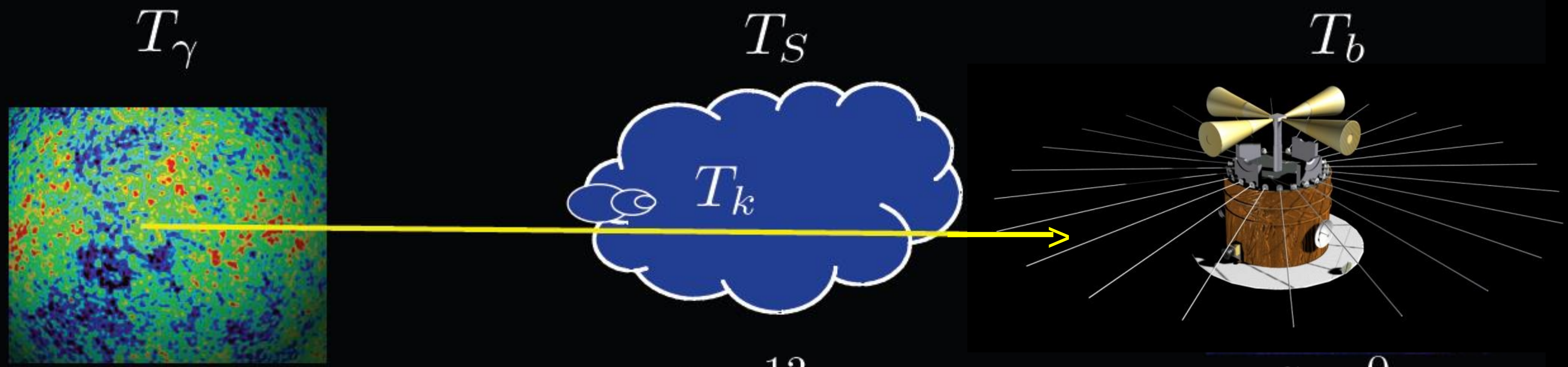
Flux Density

Observing Frequency (MHz)

Carilli et al. (2002)

- “Easiest” to detect – single line of sight
- Only probe of small scale structure
- Requires strong radio sources beyond
- Epoch of reionization
- Can be done with existing telescopes like GMRT or WSRT
- Constrain the IGM temperature and
- neutral HI content.

The 21-cm Line in Cosmology



$z = 13$
$\nu = 1.4\,\mathrm{GHz}$

$z = 0$
$\nu = 100\,\mathrm{MHz}$

CMB acts as back light

Neutral gas imprints signal

Redshifted signal detected

neutral fraction

baryon density

spin temperature

peculiar velocities

brightness temperature
(P=k$T_b\Delta\nu$)

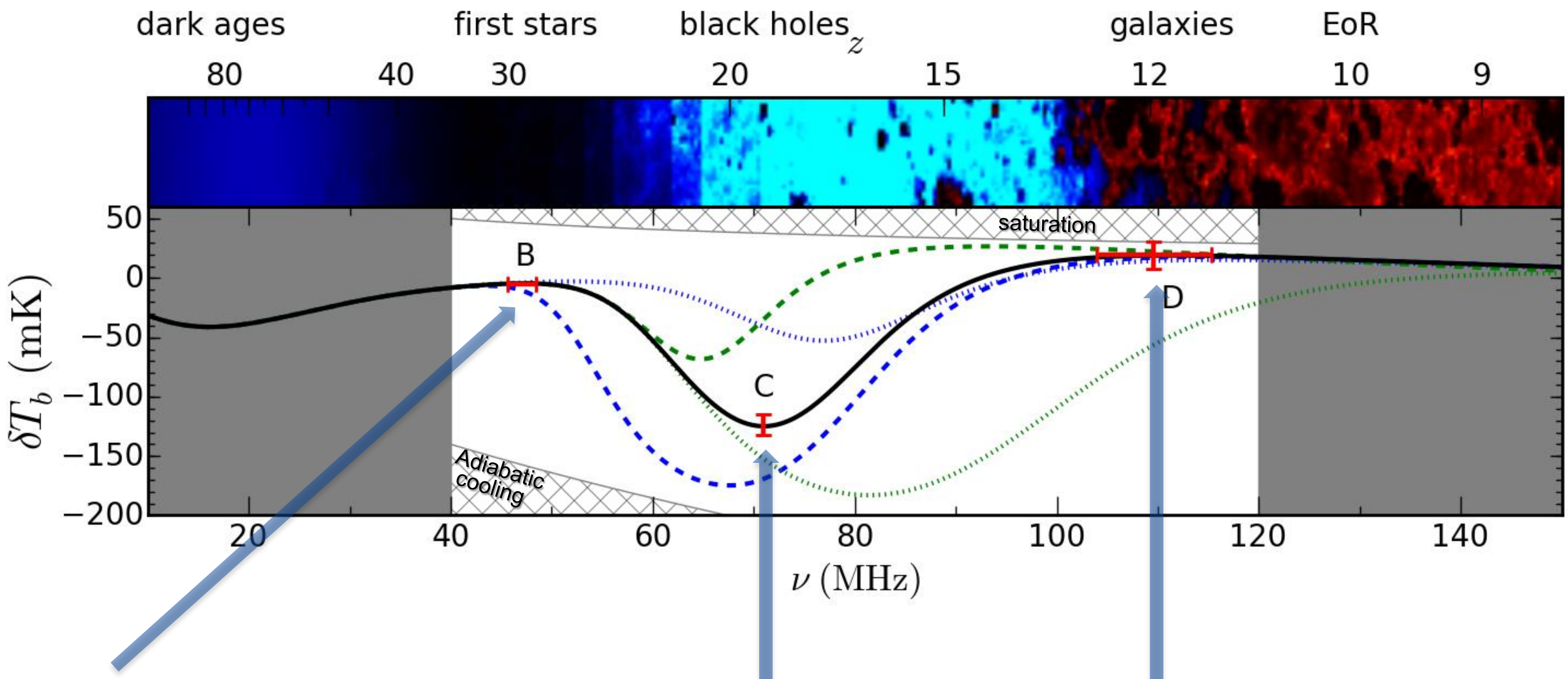
$$T_b = 27 x_{\mathrm{HI}} (1+\delta_b) \left(\frac{T_S - T_\gamma}{T_S}\right) \left(\frac{1+z}{10}\right)^{1/2} \left[\frac{\partial_r v_r}{(1+z)H(z)}\right]^{-1} \mathrm{mK}$$

spin temperature set by different mechanisms:

Radiative transitions (CMB)
Collisions
Wouthysen-Field effect

Courtesy of J. Pritchard

The 21-cm Global Signal Reveals the Birth & Characteristics of the First Stars & Galaxies



B: ignition of first stars

- When did the First Stars ignite? What were these First Stars?
- What surprises emerged from the Dark Ages?

C: heating by first black holes

- When did the first accreting black holes turn on? What was the characteristic mass?

D: the onset of reionization

- When did Reionization begin?

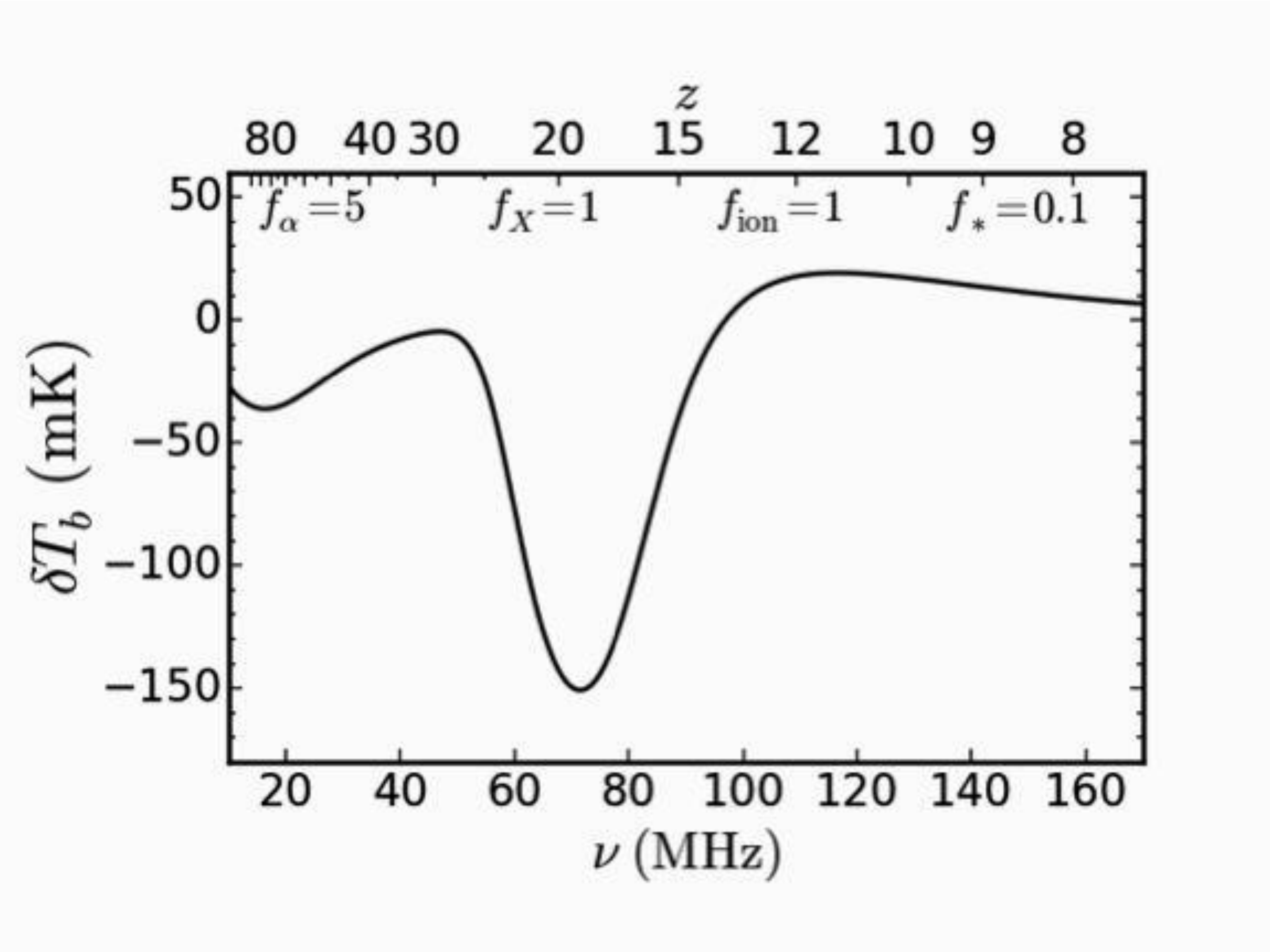
--- ··· uncertainties in 1^{st} star models

--- ··· uncertainties in 1^{st} black hole models

DARK AGES RADIO EXPLORER

Adapted from Pritchard & Loeb, 2010, *Phys. Rev. D,* 82, 023006
and Mirocha, Harker, & Burns, 2015, ApJ, 813, 11.

Range of Model Parameters for 1st Stars & Galaxies



Courtesy of Jordan Mirocha

ARES (Accelerated Reionization Era Simulations**) code**
https://bitbucket.org/mirochaj/ares

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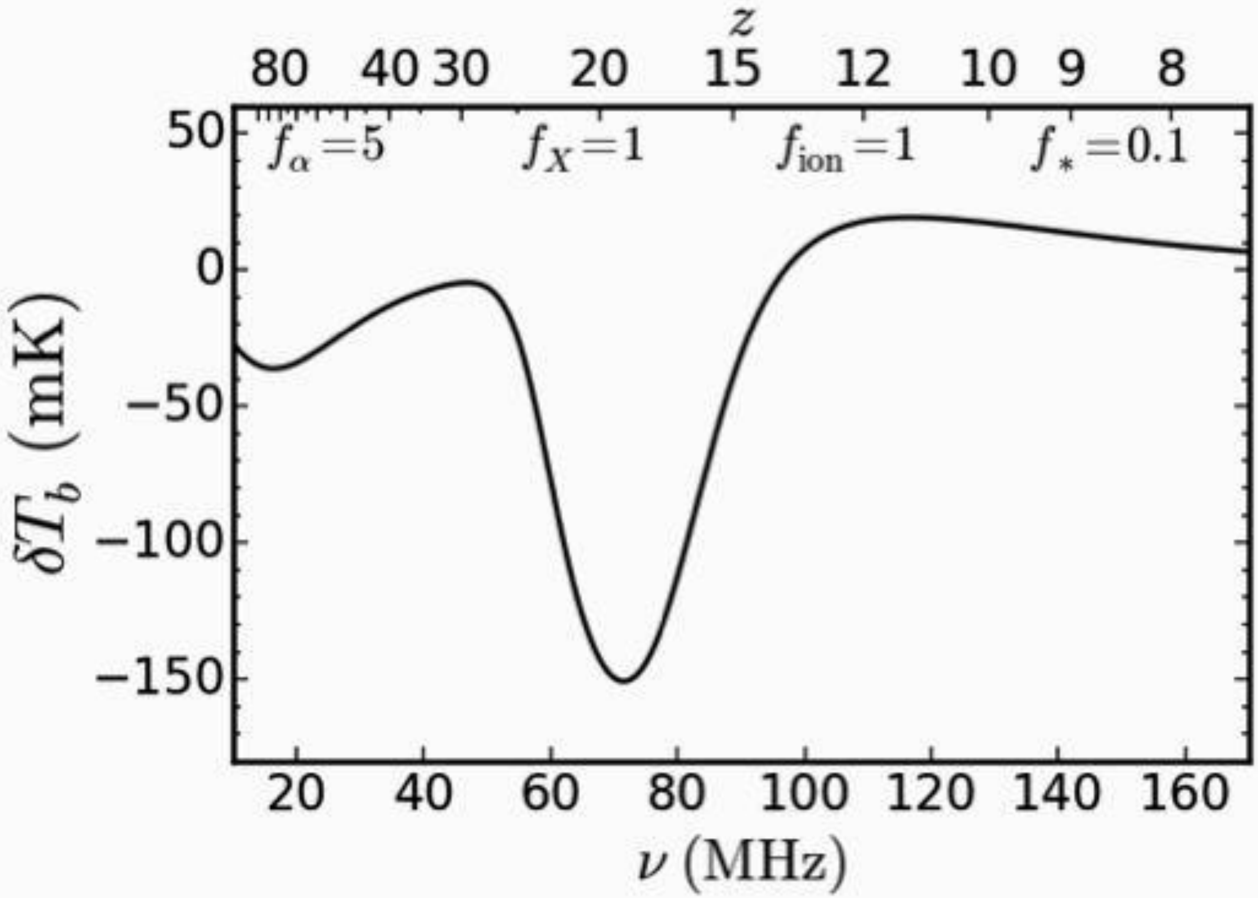

Courtesy of Jordan Mirocha

ARES (Accelerated Reionization Era Simulations) code

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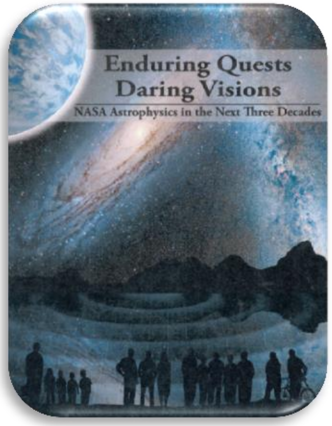
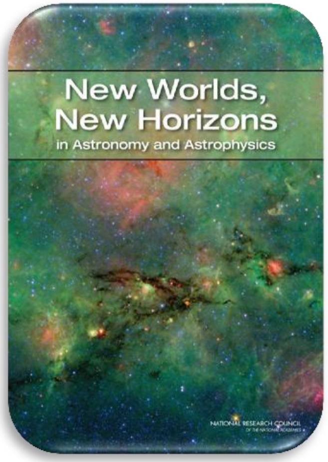
Astrophysics Decadal Survey & Astrophysics Roadmap identify Cosmic Dawn as a top Science Objective

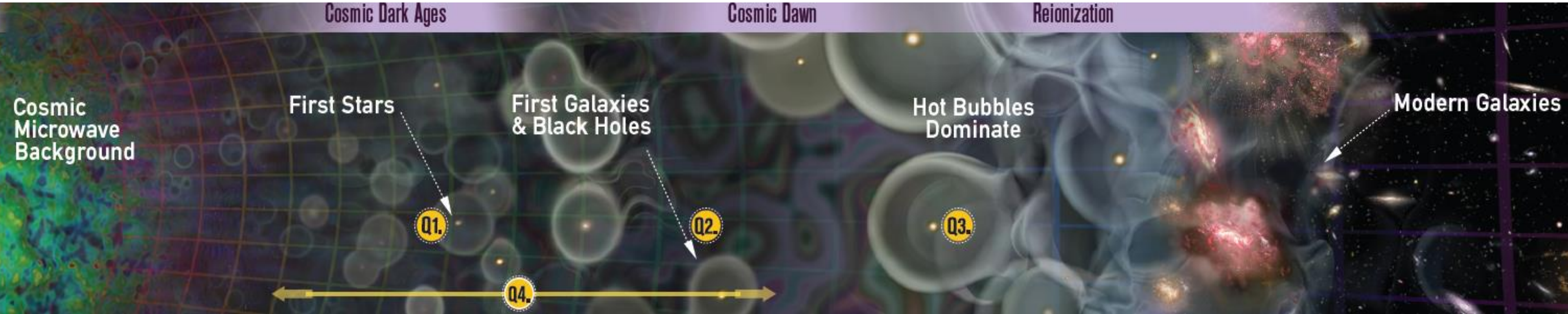
- "A great mystery now confronts us: When and how did the first galaxies form out of cold clumps of hydrogen gas and start to shine—when was our cosmic dawn?" *New Worlds, New Horizons (NRC 2010)*



- How Does our Universe Work? Small Mission: "Mapping the Universe's hydrogen clouds using 21-cm radio wavelengths via a lunar orbiter observing from the farside of the Moon" *NASA Astrophysics Division Roadmap (2013)*



"What were the first objects to light up the Universe and when did they do it?" We can uniquely address this mystery with DARE in orbit above the lunar farside.



Observational Approaches for Detection of Global 21-cm Monopole

Single Antenna Radiometers

- EDGES (Bowman & Rogers)
- SARAS (Patra et al.)
- LEDA (Greenhill, Bernardi et al.)
- SCI-HI (Lopez-Cruz, Peterson, Voytek et al.)
- BIGHORNS (Sokolowski et al.)
- DARE (Burns et al.)

Challenges include systematics arising from stability issues, accurate calibration, polarization leakage, foregrounds.

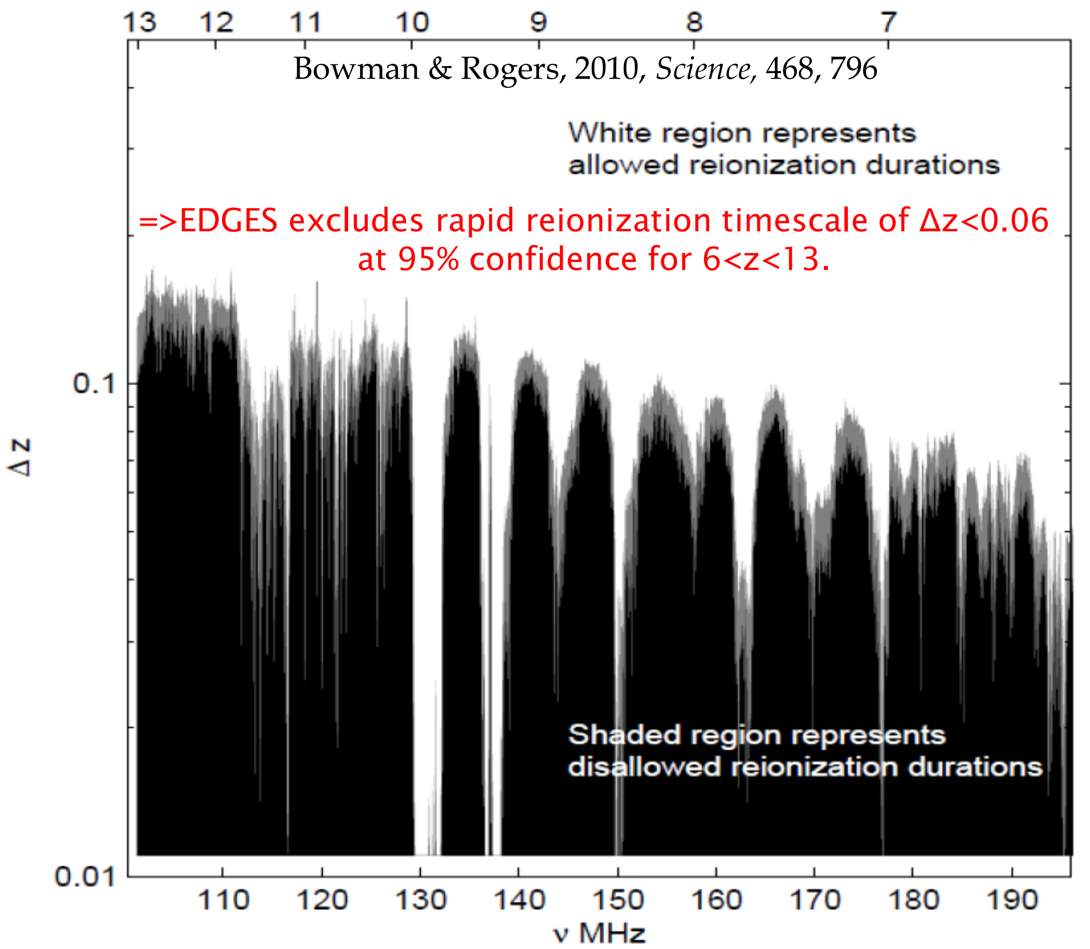
Small, Compact Interferometric Arrays

- Vedantham et al.
- Mahesh et al.
- Presley, Parsons & Liu
- Subrahmanyan, Singh et al.

Challenges include cross-talk among antenna elements, mode-coupling of foreground continuum sources into spectral confusion, sensitivity.

Current/Upcoming Global Signal Experiments

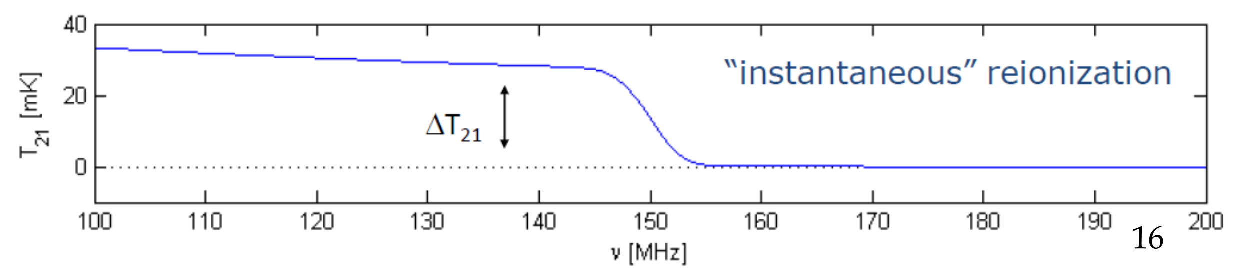
Experiment	Site	ν range (MHz)
EDGES	WA	100-200
DARE	Moon	40-120
LEDA	NM	30-80
DAWN	NM	30-80
BigHorns	WA	50-200
SARAS	India	87.5-175


Bowman & Rogers, 2010, *Science*, 468, 796

White region represents allowed reionization durations

=>EDGES excludes rapid reionization timescale of $\Delta z<0.06$ at 95% confidence for $6<z<13$.

Shaded region represents disallowed reionization durations


"instantaneous" reionization

Ground-Based Heritage

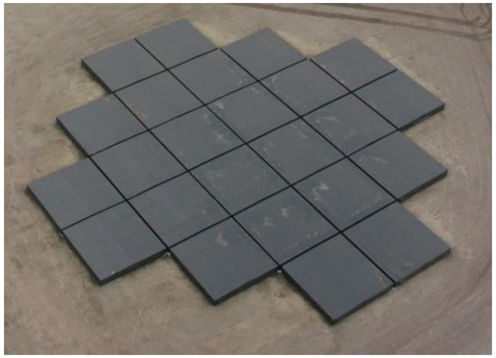
Ground-based telescopes generally operate at >100 MHz & *probe only the end of the Epoch of Reionization (EoR)*

Single Antenna, Total Power: EoR Global Signal

Experiment to Detect the Global EoR Step = EDGES (Bowman & Rogers)

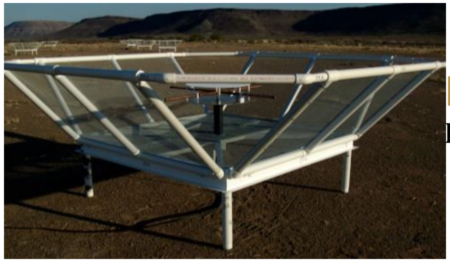
- Total power receiver; 3 position Dicke-switch to calibrate spectrum.
- New antenna topologies.
- New wide-band receiver.
- Set first limits on Reionization step function.

Interferometric Arrays: Measure Power Spectrum of EoR



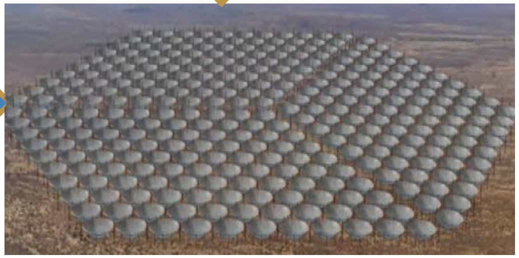
LOFAR - Europe

MWA – Western Australia



PAPER – South Africa

Evolving into



HERA – 320 element array

=>In contrast, DARE will measure Global Cosmic Dawn monopole down to 40 MHz, a measurement requiring a lunar-orbiting telescope.

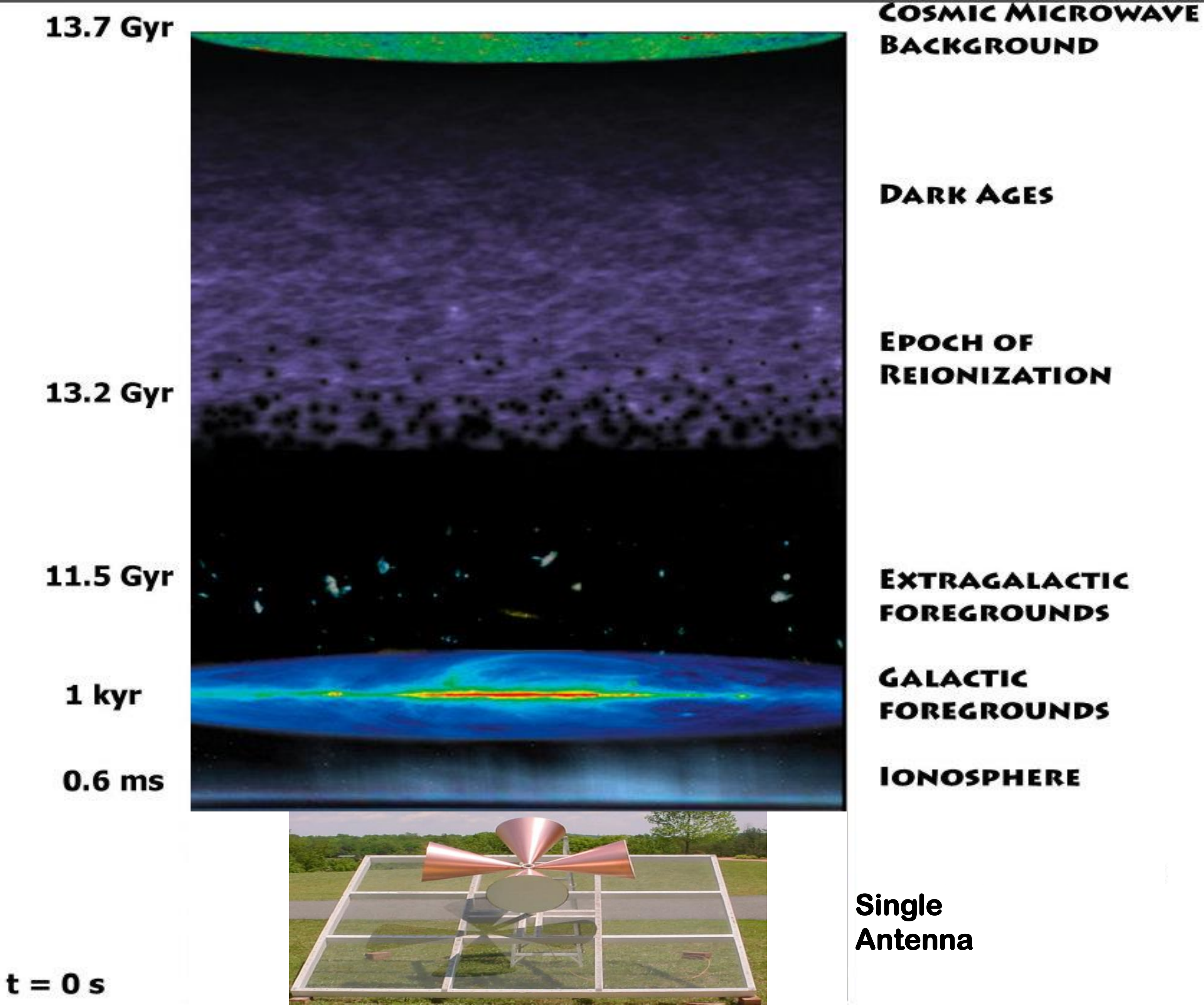


Diagram has been modified from a LOFAR presentation by S. Zaroubi (http://www.lsw.uni-heidelberg.de/users/christlieb/teaching/WS0910/100126_Zaroubi_LOFAR.pdf)

Foregrounds: Major Challenge

- **Earth's Ionosphere** (e.g., Vedantham et al. 2014; Datta et al. 2016; Rogers et al. 2015; Sokolowski et al. 2015)
  - Refraction, absorption, & emission
  - Spatial & temporal variations related to forcing action by solar UV & X-rays => 1/f or flicker noise acts as another systematic or bias.
  - Effects scale as ν^{-2} so they get much worse quickly below ~100 MHz.

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- **Radio Frequency Interference (RFI)**
  - RFI particularly problematic for FM band (88-110 MHz).
  - Reflection off the Moon, space debris, aircraft, & ionized meteor trails are an issue everywhere on Earth (e.g., Tingay et al. 2013; Vedantham et al. 2013).
  - Even in LEO (10^8 K) or lunar nearside (10^6 K), RFI brightness T_B is high.

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- **Galactic/Extragalactic**
  - Mainly synchrotron with expected smooth spectrum (~3rd order log polynomial, $\log T_{\mathrm{fg}} = \sum_{i=0}^{N_{\mathrm{poly}}} a_i \log\left(\frac{\nu}{\nu_0}\right)^i$, although it is corrupted by antenna beam; e.g., Bernardi et al. 2015).
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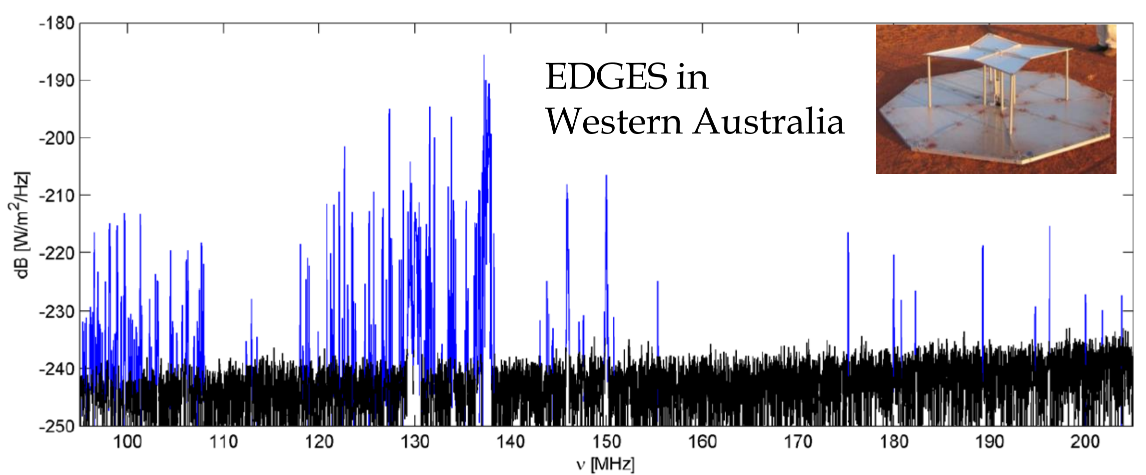
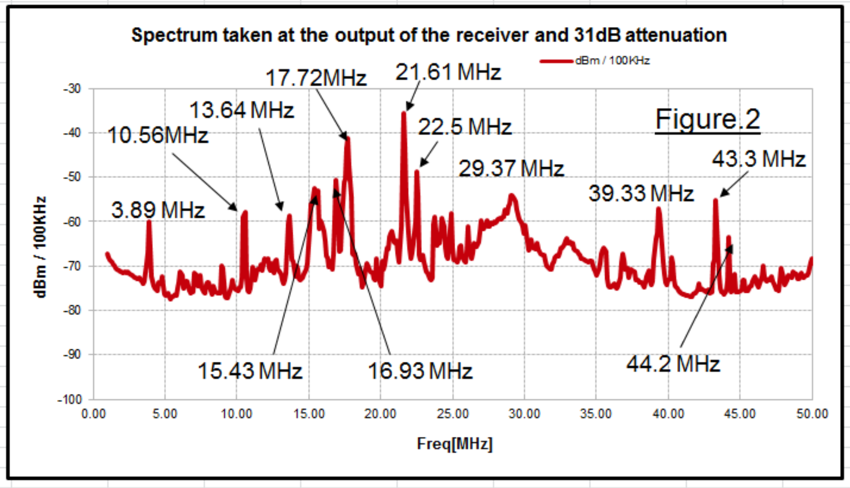
- **Other Foregrounds -** lunar thermal emission & reflections; Jupiter; Recombination lines.

These observations are best done from the lunar farside which is free of Radio Frequency Interference & the Earth’s Ionosphere => DARE will be placed in lunar orbit to access the radio-quiet zone above the lunar farside.

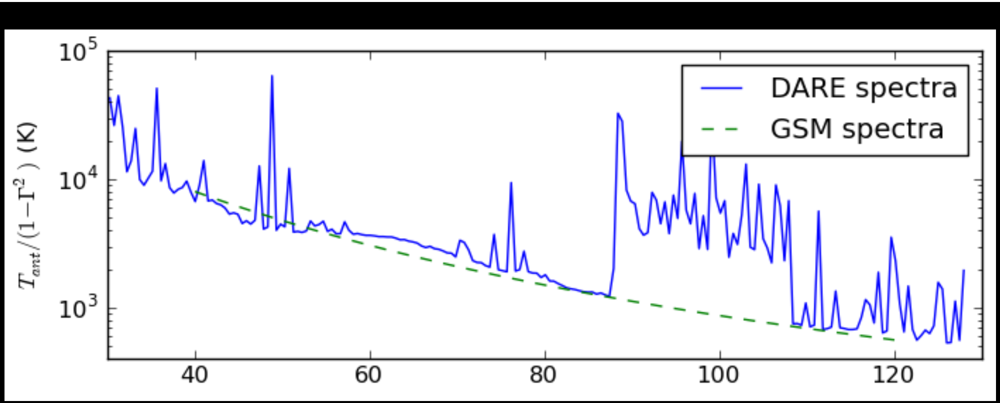


Blue spikes in spectrum is caused by interference from the Orbcomm Satellite.

Also, reflection of FM band from the Moon (Mckinley et al. w/ MWA).



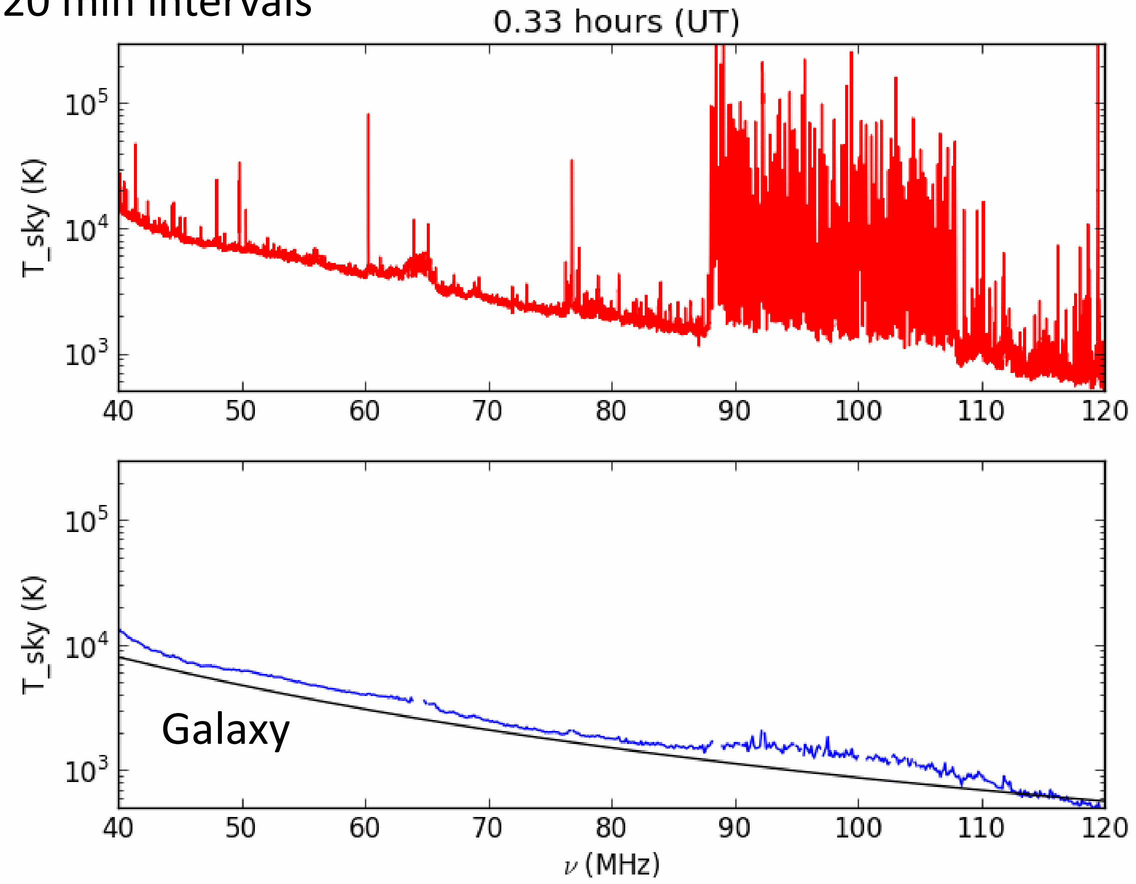
Data collected by DARE engineering prototype in Western Australia. Interference spikes are probably due to naval radar.

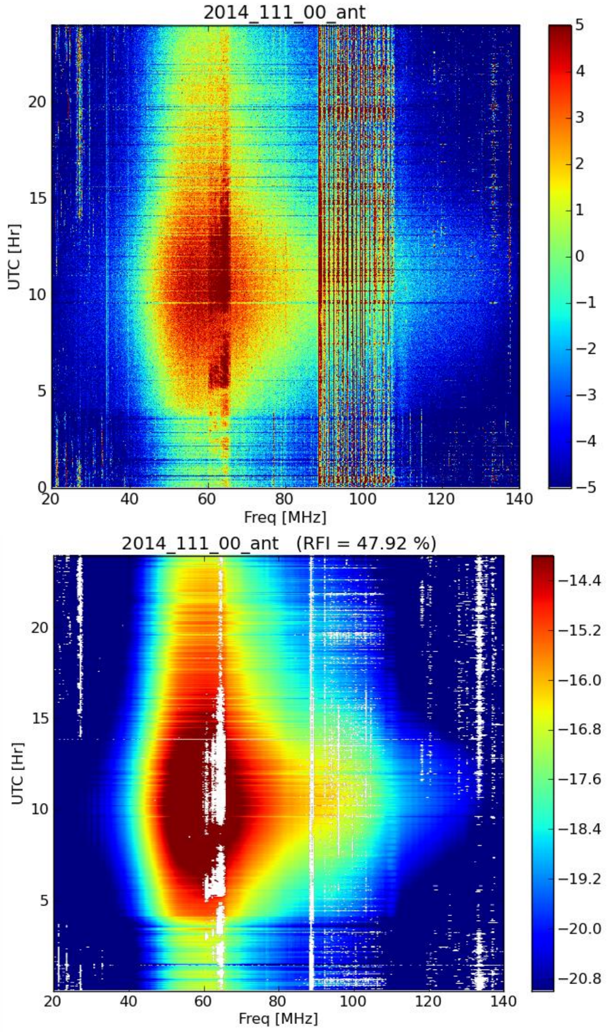


Data collected by DARE engineering prototype in Green Bank, WV. FM band (88-108 MHz) wipes out major portion of low frequency spectrum. Below 60 MHz, effects due to ionosphere become apparent.

RFI Excision and Calibration

Observations on April 21, 2014; plots averaged over 20 min intervals

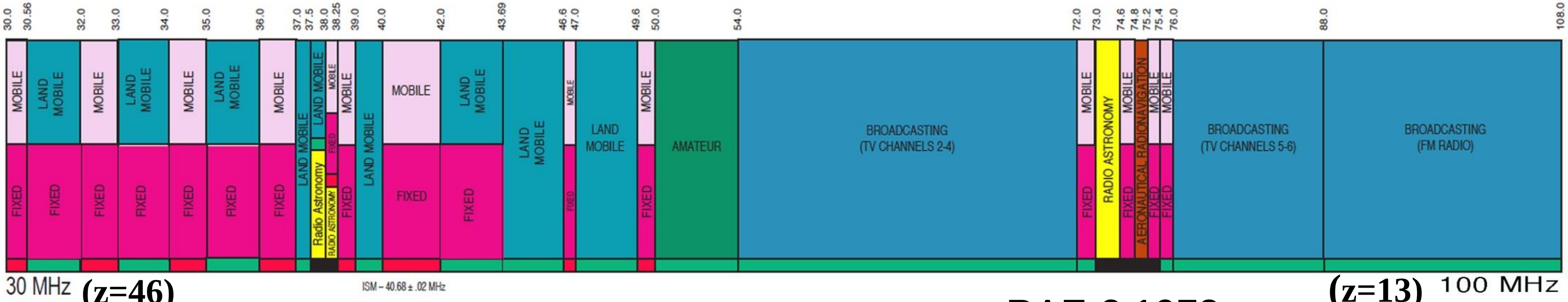




Top Panel: Initial calibrated data without RFI excision (in red).
Bottom Panel: Initial calibrated data with RFI excision (in blue).

About 50% of the data are flagged due to RFI.

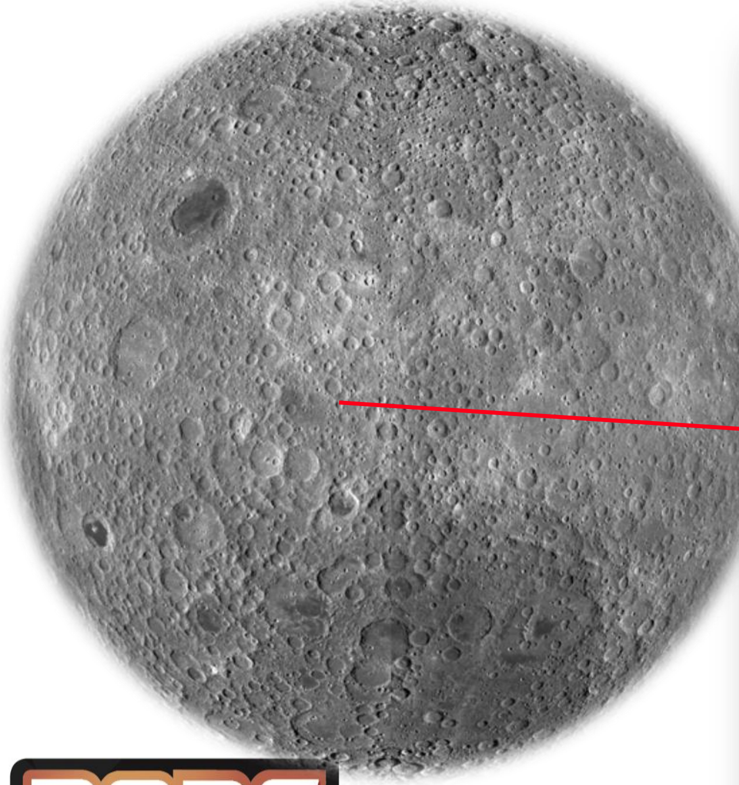
Lunar Farside: No RFI or Ionosphere!

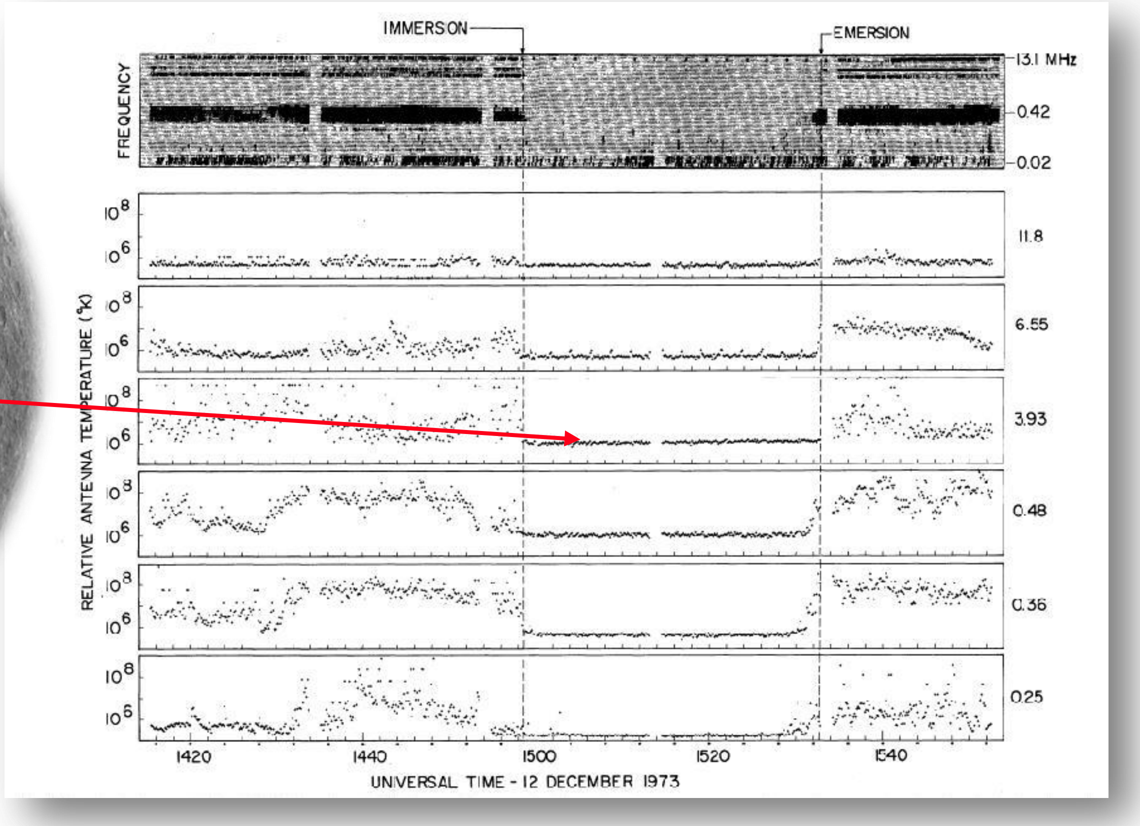


(z=46)

(z=13)

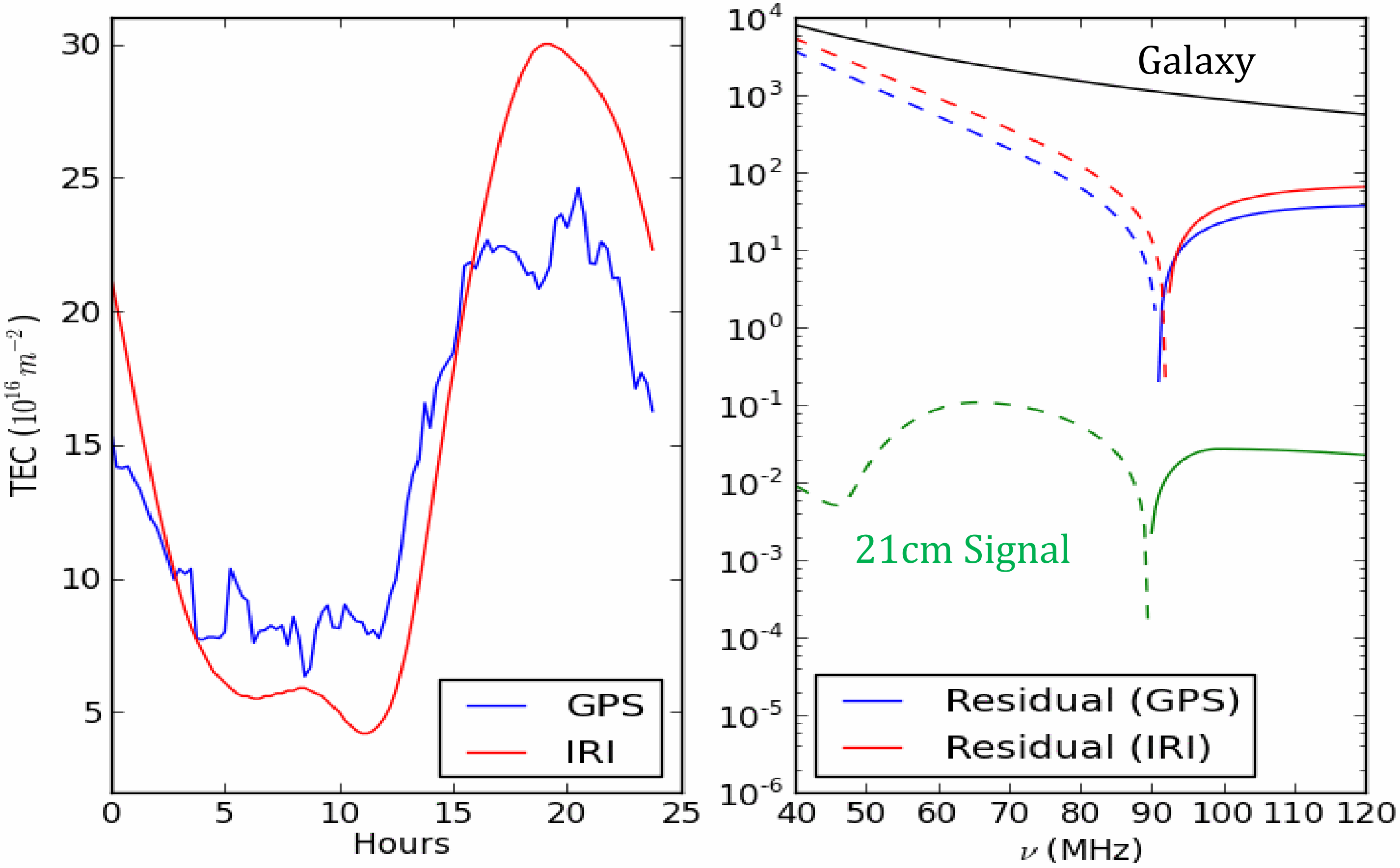
RAE-2 1973





DARE
DARK AGES RADIO EXPLORER

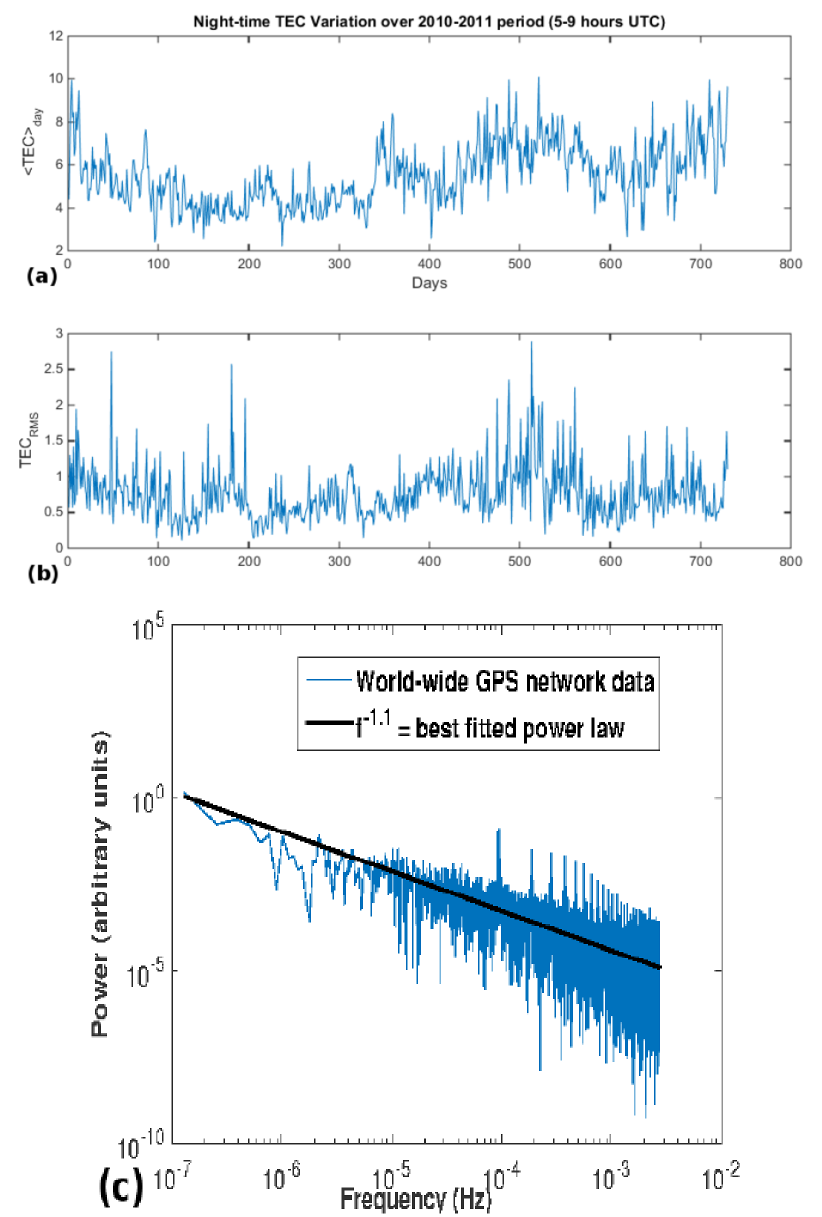
Case for Space: Combined Effects of Refraction and Absorption/Emission from the Ionosphere



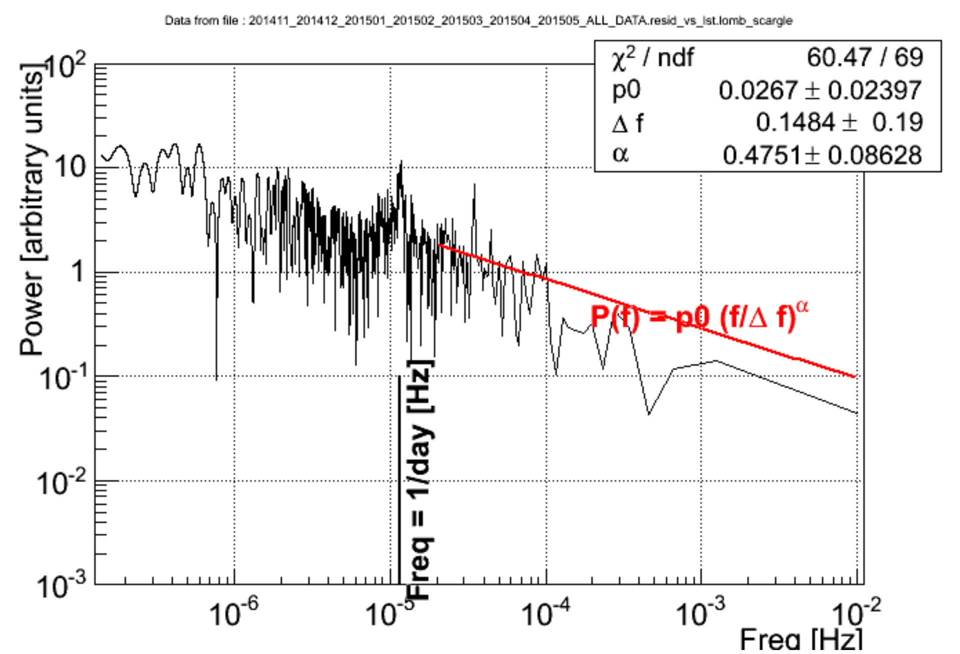
GPS data Green Bank (WV) location IRI- International Reference Ionosphere Model

Datta *et al.* 2015

Does flicker noise matter at all if ionosphere does not introduce frequency structure ?



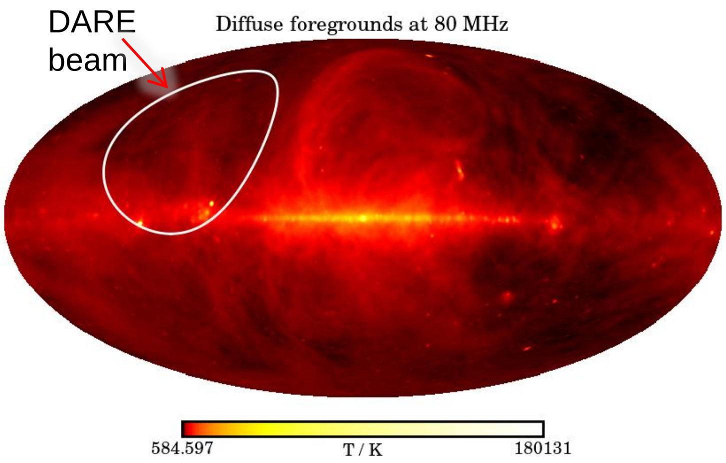
Abhi Datta et al,



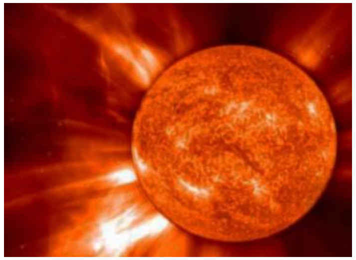
Flicker noise power spectrum of fluctuations observed in BIGHORNS. Night time data – unclear if roll-off is real or artefact of the analysis.

Extraterrestrial Foregrounds

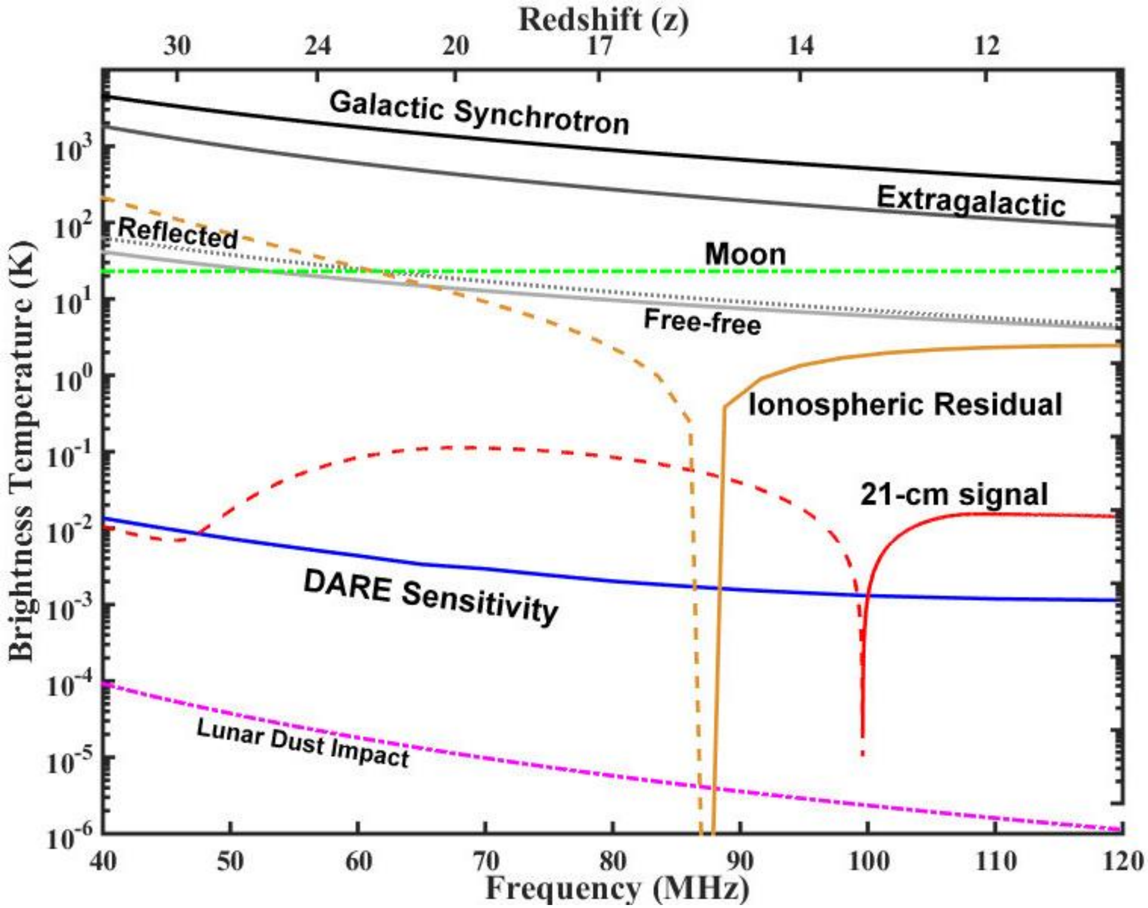
1) Milky Way synchrotron emission + “sea” of extragalactic sources.



2) Solar system objects: Sun, Jupiter, Moon.

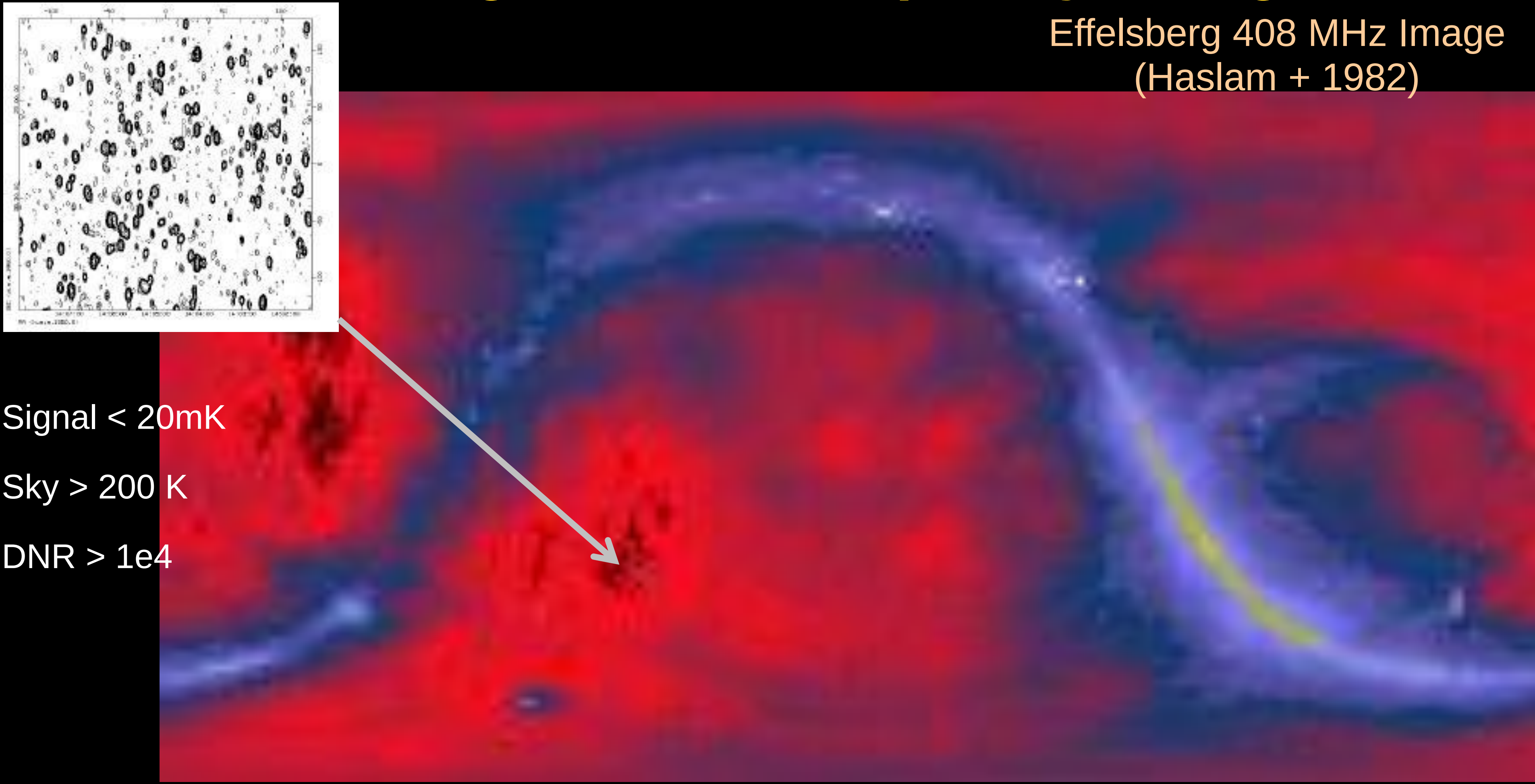


Spectra of Foregrounds



=>Must employ advanced statistical techniques to simultaneously fit signal, foregrounds, & instrument parameters

Challenges: Low–Frequency Foregrounds



Effelsberg 408 MHz Image
(Haslam + 1982)

Signal < 20mK

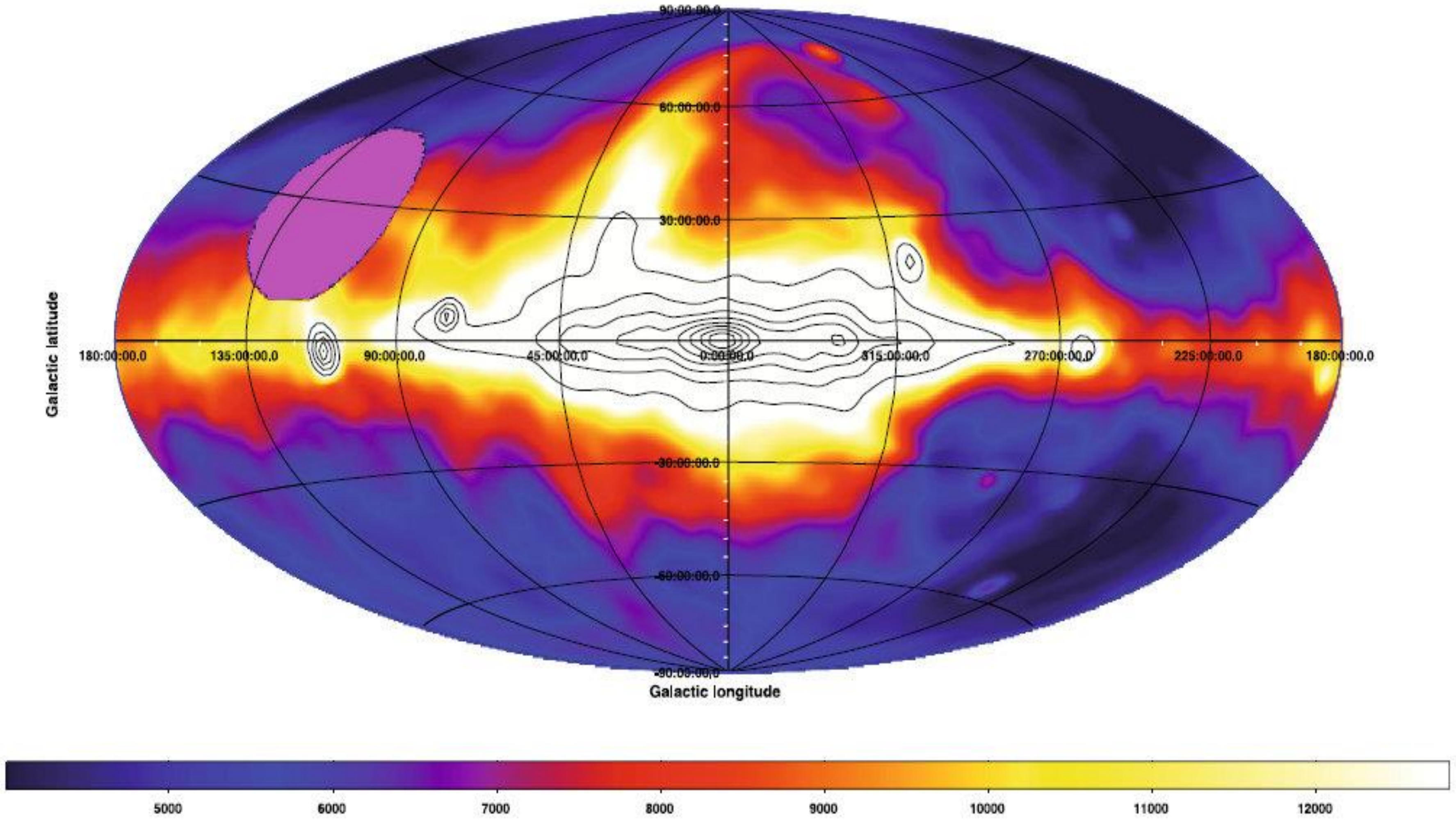
Sky > 200 K

DNR > 1e4

- Coldest regions: T ~ 180 (ν/180 MHz)^-2.6 K

- 90% = Galactic foreground (~200-1000K, 99% Synchrtron, 1% Free-free),
10% = Egal. radio sources (~50K) , Galactic RRLs (< 1K), Sun

Low–Frequency Foregrounds at 45 MHz



Maipu and MUradar

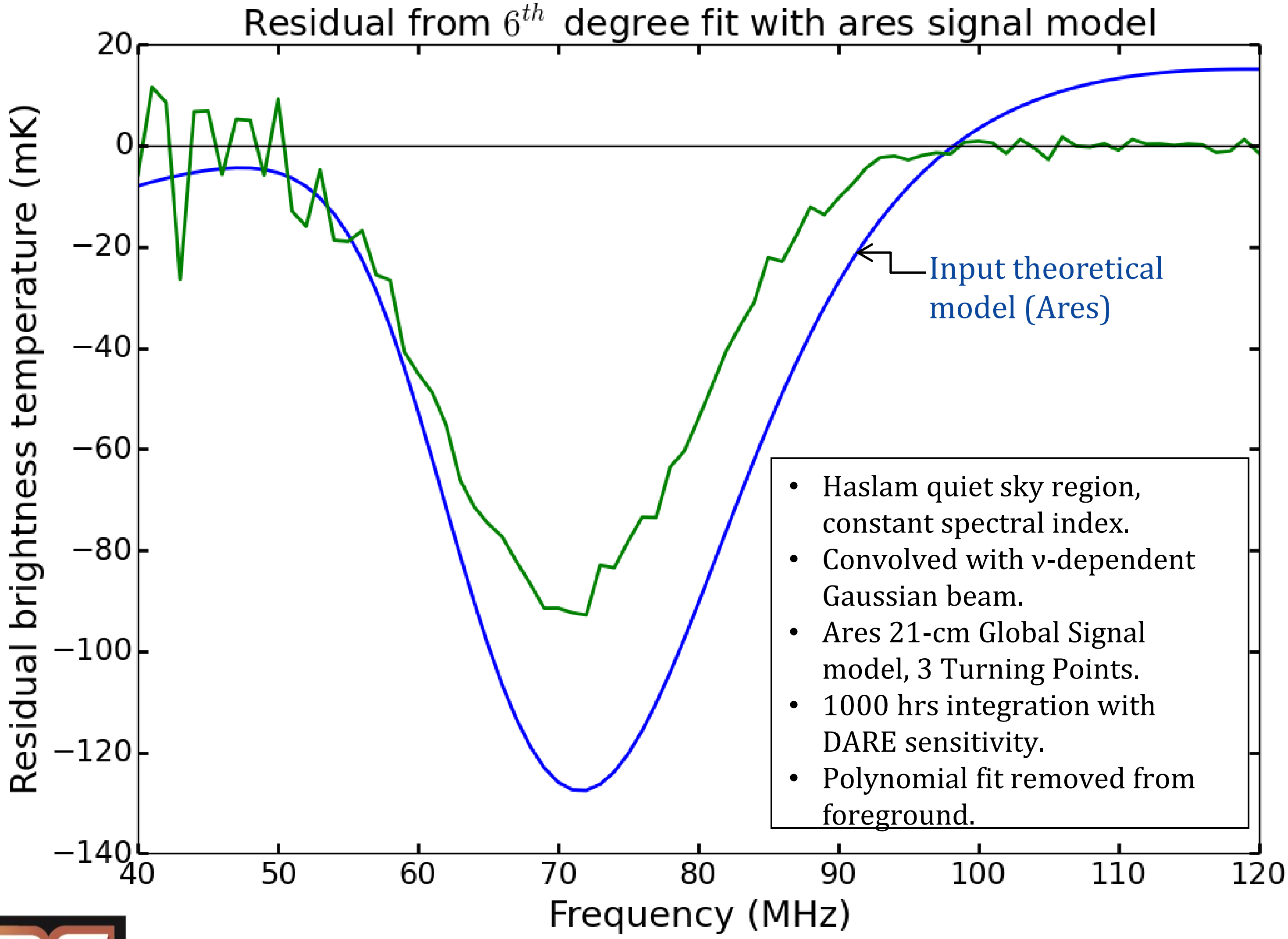
Guzman et al. 2011

Foreground Removal Methods

Hierarchically removing foreground from data based on previous knowledge of the nature of the foreground	**Simultaneously fitting for both Foreground and Signal Parameters**
Bowman et al. 2008, 2010.	Harker et al. 2012
Rogers et al. 2008, 2012.	Harker 2015
Voytek et al. 2013	Harker et al. 2015
Bernardi et al. 2013	Mirocha et al. 2015

Either schemes rely on the accurate knowledge of the nature of the foreground- Otherwise the signal recovery becomes a **challenge**!

Detecting the strongest spectral feature in the presence of the Galactic foreground



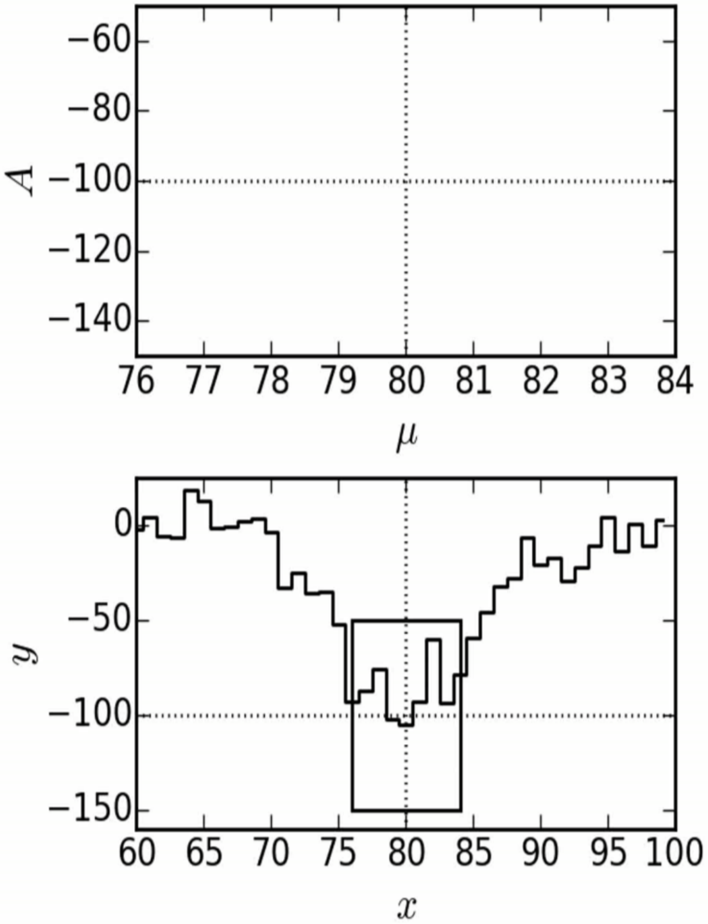
Input theoretical model (Ares)

- Haslam quiet sky region, constant spectral index.
- Convolved with ν-dependent Gaussian beam.
- Ares 21-cm Global Signal model, 3 Turning Points.
- 1000 hrs integration with DARE sensitivity.
- Polynomial fit removed from foreground.

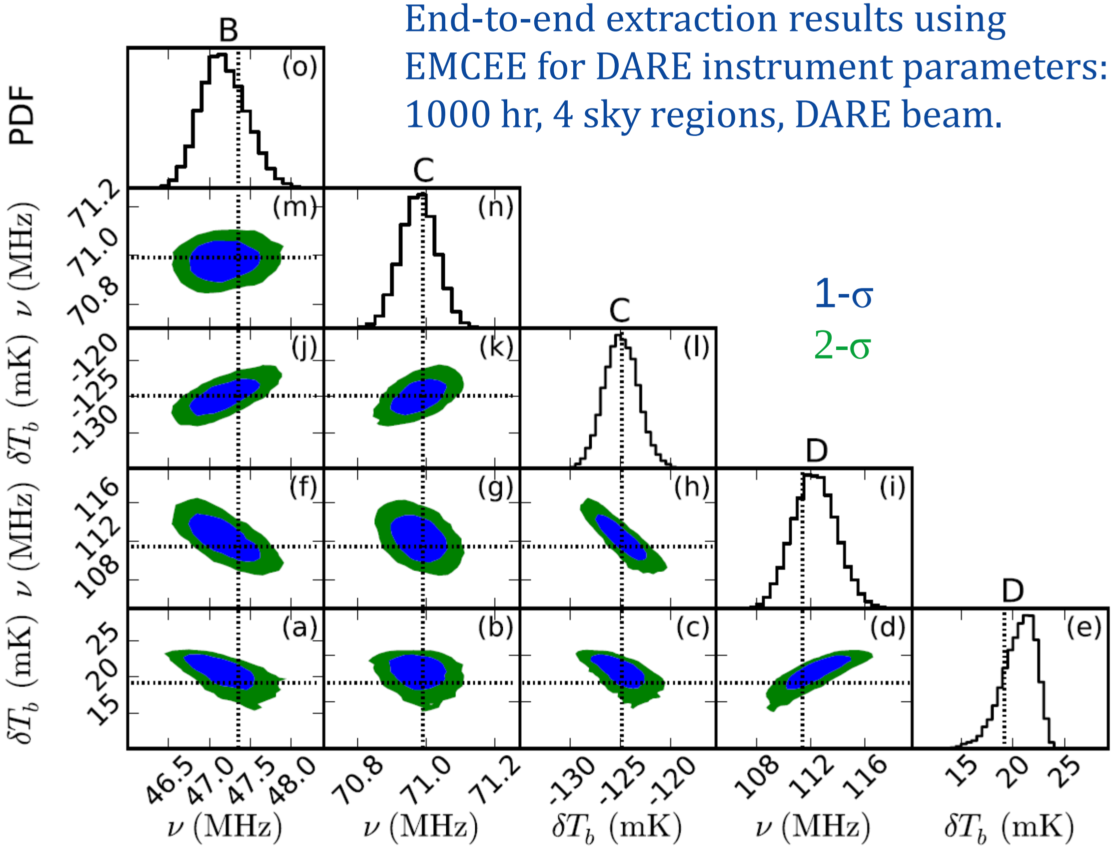
- Instrument Requirement: Minimize Chromatic beam effects

Keith Tauscher & J. Burns

Signal Extraction using MCMC



End-to-end extraction results using EMCEE for DARE instrument parameters: 1000 hr, 4 sky regions, DARE beam.

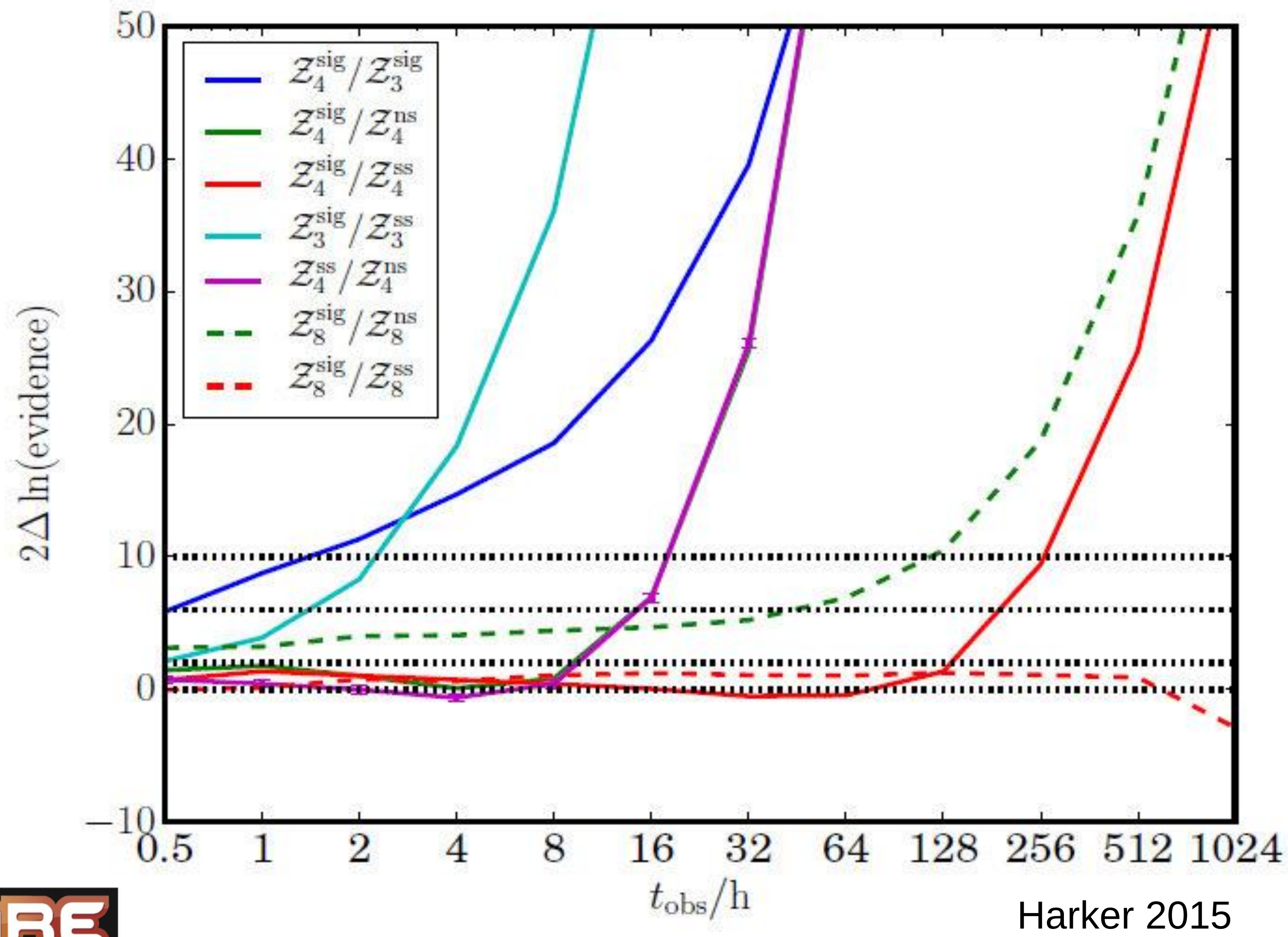


This technique captures degeneracies & covariances between parameters, including those related to signal, foregrounds, & the instrument.

DARE
DARK AGES RADIO EXPLORER

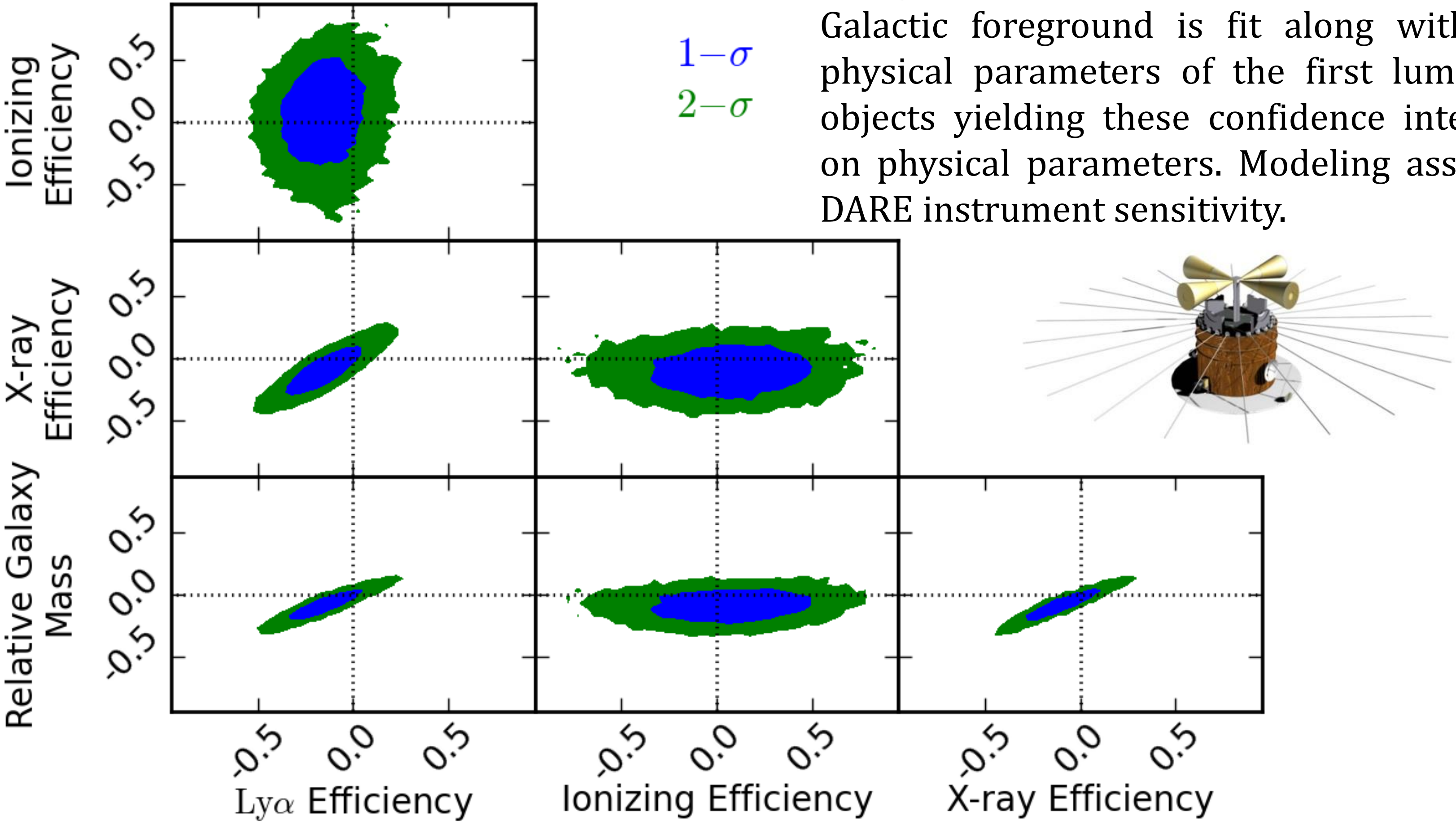
For details see Harker et al. (2012), MNRAS, 419, 1070; and Harker et al. (2016), MNRAS, 455, 3829.

Warning against removing higher order polynomials!



Harker 2015

Characterizing the First Stars & Galaxies



Using an MCMC statistical framework, the Galactic foreground is fit along with the physical parameters of the first luminous objects yielding these confidence intervals on physical parameters. Modeling assumes DARE instrument sensitivity.

Global Experiments have the potential to bound the properties (e.g., mass, spectra) of the first generation of stars, black holes, & galaxies for the first time (0.1-0.2 dex).

DARE
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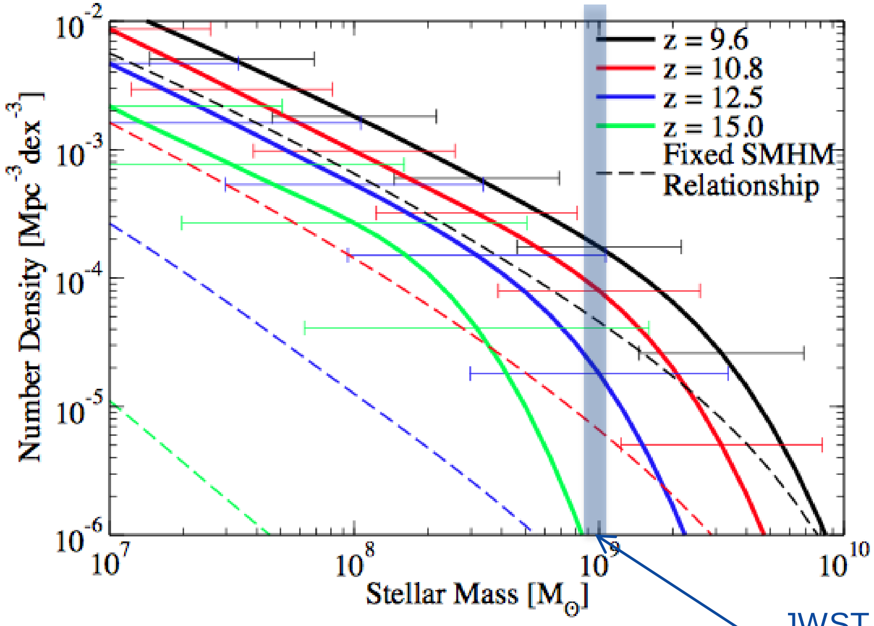
Mirocha et al. 2015

Synergies: Major Instruments

- **Planck recently released their full dataset**
  - Limit on reionization, nothing about pre-reionization
- **Hydrogen Epoch of Reionization Array (HERA, PAPER, MWA, LOFAR, etc.)**
  - HERA is a next-generation ground-based 21-cm interferometer (Parsons et al.).
  - Should nail down middle/late parts of reionization history
  - *May* poke into pre-reionization era
- **LEDA, LWA, others may go after very high-redshift signal (but ionosphere…)**
- **James Webb Space Telescope**
  - DARE will have comparable timescale
  - Images (bright) galaxies out to possibly z~15
- **Athena**
  - X-ray probe of black holes/AGNs to z~10.



JWST Deep Field

Behroozi & Silk (2014)

DARE

DARK AGES RADIO EXPLORER