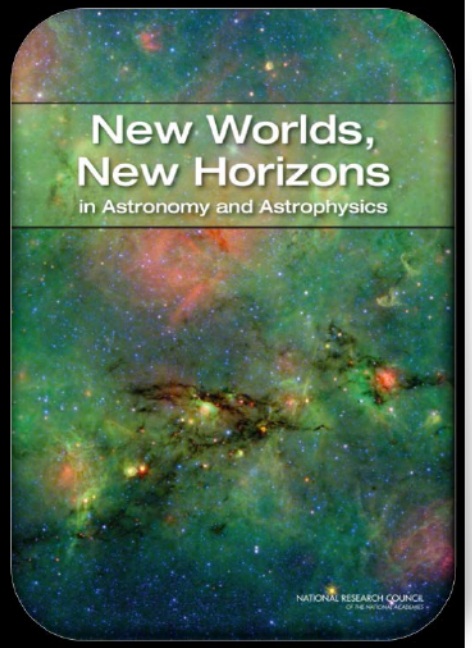
Probing The Dark Ages and Cosmic Dawn
A Roadmap for NASA Astrophysics

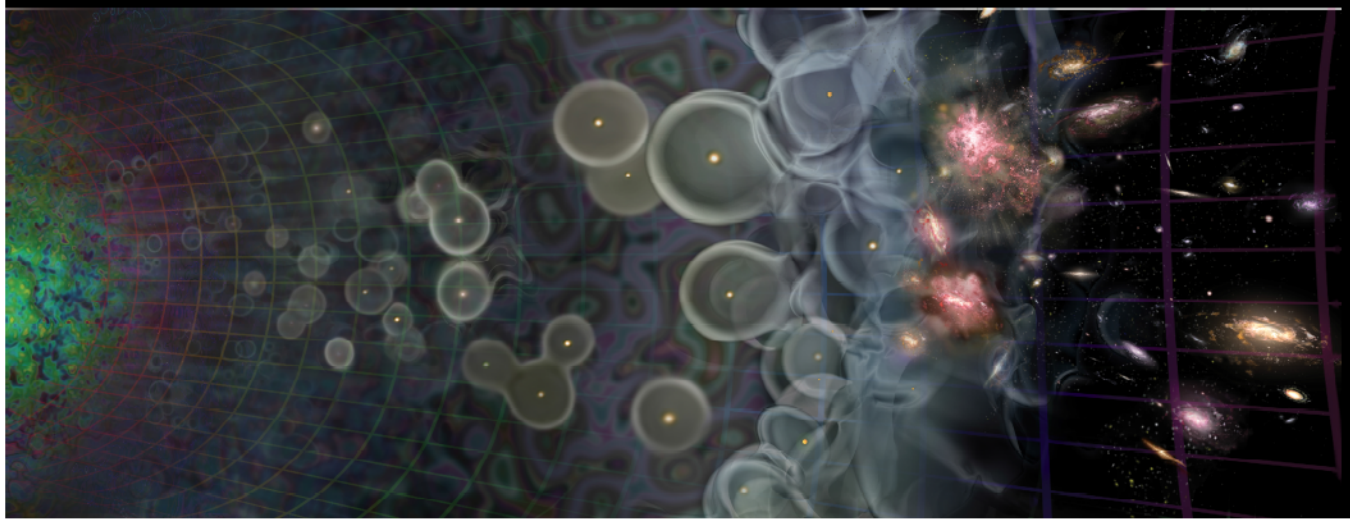
Joseph Lazio
(Jet Propulsion Laboratory, California Institute of Technology; Joseph.Lazio@jpl.nasa.gov)
&
Judd D. Bowman (Arizona State Univ.), Jack O. Burns (Univ. Colorado at Boulder), W. M. Farrell (NASA/GSFC), Steven R. Furlanetto (UCLA), D. L. Jones (Jet Propulsion Laboratory, California Institute of Technology), J. C. Kasper (Harvard-Smithsonian Center for Astrophysics), R. J. MacDowall (NASA/GSFC), K. P. Stewart (Naval Research Laboratory), K. Weiler (Computational Physics, Inc.)

Cosmic Dawn is a top *NWNH* science objective

LUNAR UNIVERSITY NETWORK for ASTROPHYSICS RESEARCH

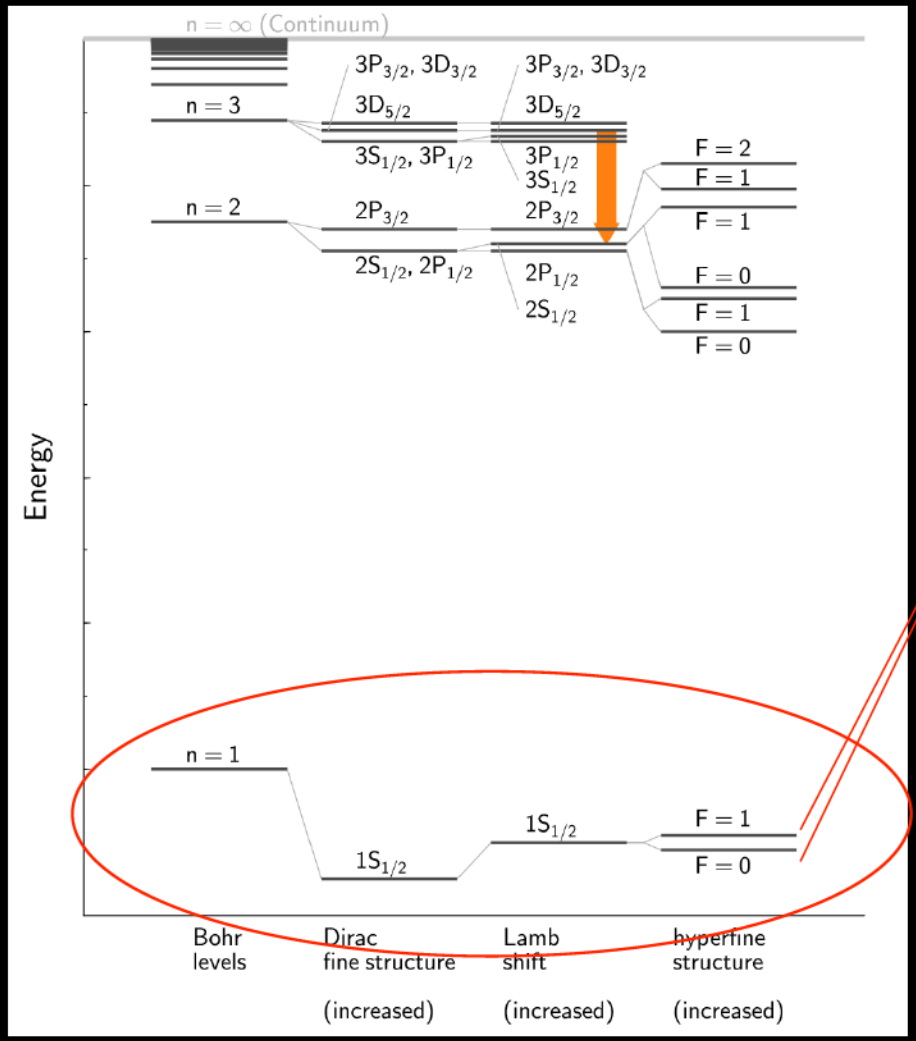
"A great mystery now confronts us: When and how did the first galaxies form out of cold clumps of hydrogen gas and start to shine—when was our cosmic dawn? Observations and calculations suggest that this phenomenon occurred when the universe was roughly half a billion years old, when light from the first stars was able to ionize the hydrogen gas in the universe from atoms into electrons and protons—a period known as the epoch of reionization... Astronomers must now search the sky for these infant galaxies and find out how they behaved and interacted with their surroundings."

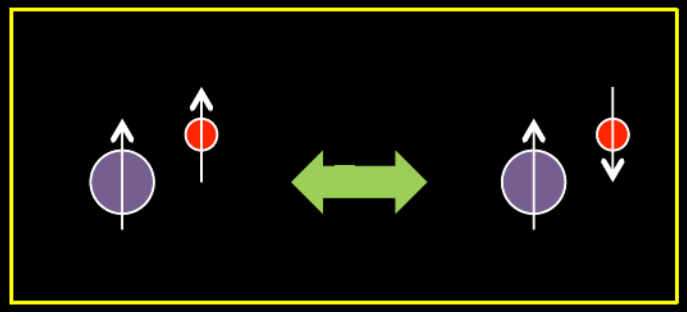




"What were the first objects to light up the Universe and when did they do?"

Hydrogen Atom





$n = 1, F = 1 \rightarrow 0$

$E_{10} = h\nu = 5.8743253\ \mu eV$

$T_* = E_{10}/k = 0.068\ K$

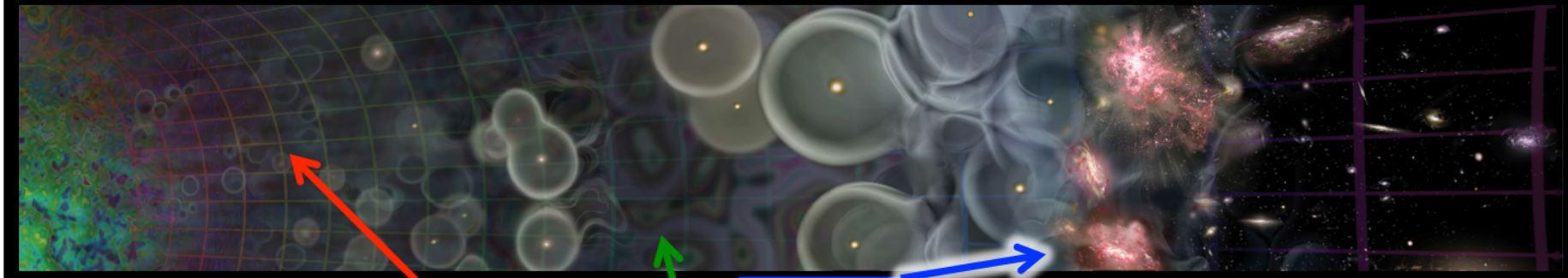
$\nu = 1420.405752\ MHz$

$\lambda = 21\ cm$

$z \sim 7$	175 MHz (λ1.7m)
$z \sim 20$	70 MHz (λ4m)
$z \sim 80$	17 MHz (λ17m)

Cosmic Dawn & Dark Ages

Hydrogen Signal



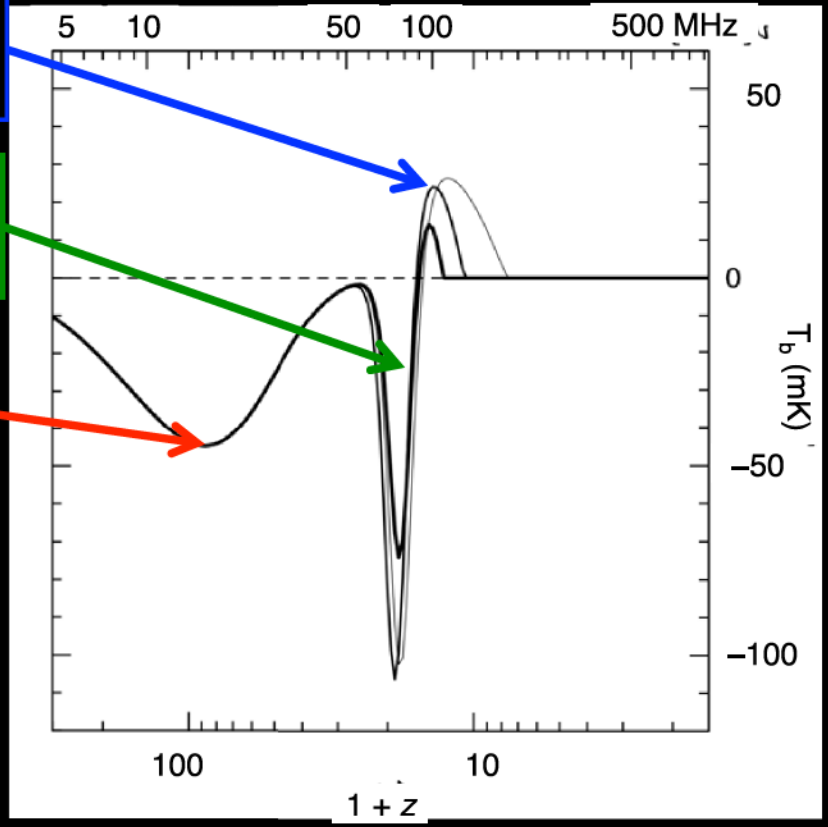
Neutral Hydrogen

Spin-flip transition provides probe of neutral intergalactic medium before and during formation of first stars

EoR

First LIght

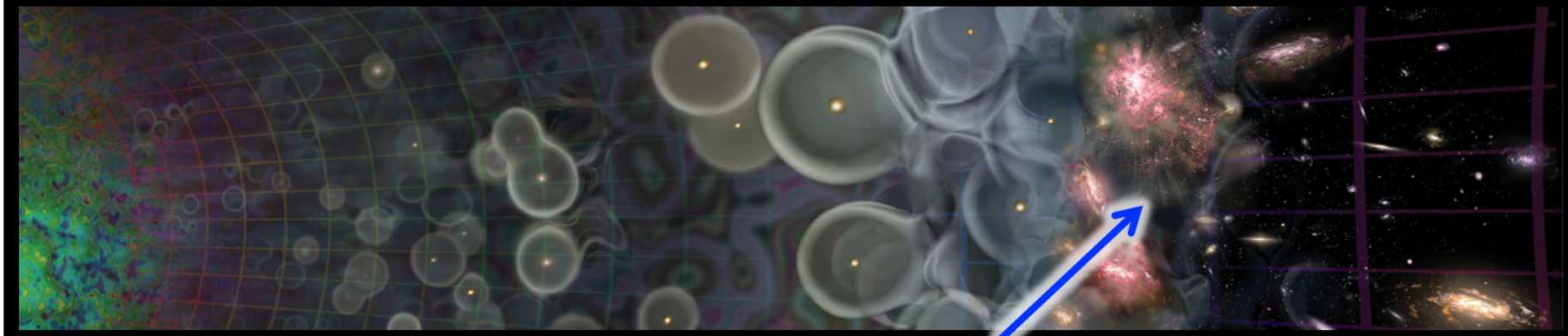
Dark Ages



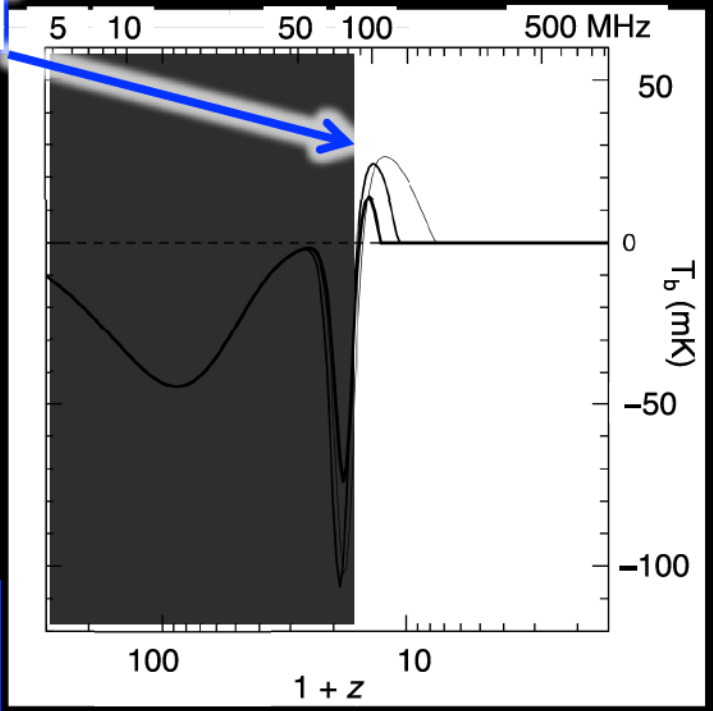
$\nu = 1420 \text{ MHz}/(1 + z)$

$\lambda = 21 \text{ cm } (1 + z)$

Epoch of Reionization
Hydrogen Signal



EoR



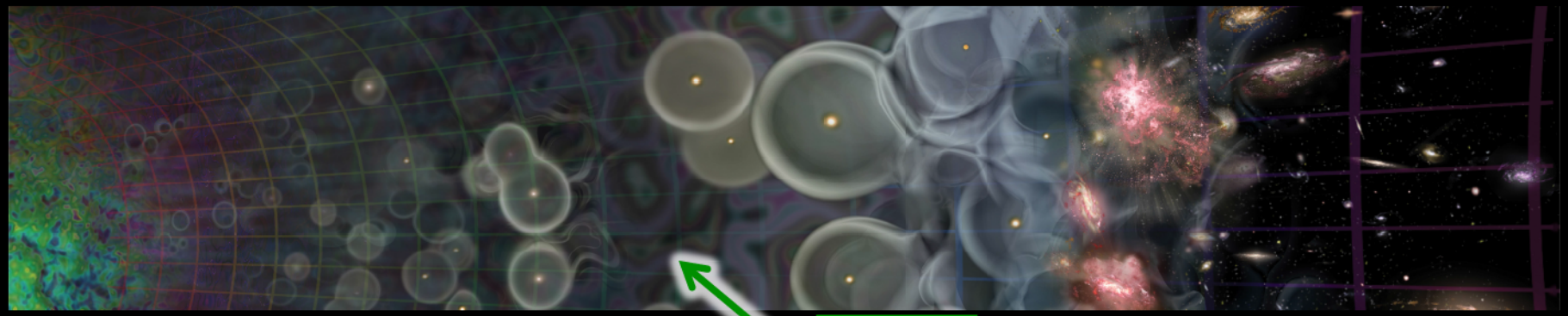
- Gas being heated rapidly
- T_s exceeds T_{CMB}, 21 cm line in emission
- Signal persists until neutral gas destroyed by increasing temperature of IGM

  Focus of many emerging and proposed arrays

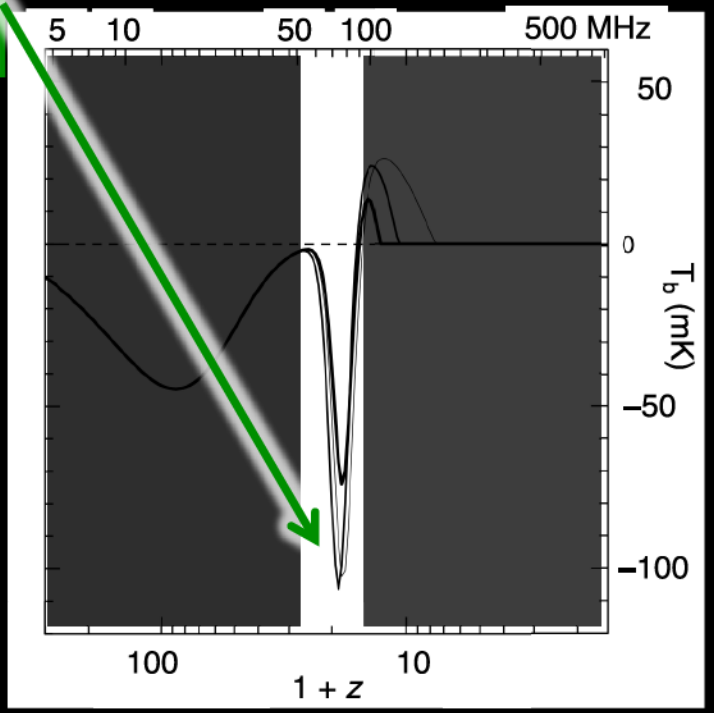
$\nu = 1420 \text{ MHz}/(1 + z)$

$\lambda = 21 \text{ cm } (1 + z)$

First Light
Hydrogen Signal



First Light

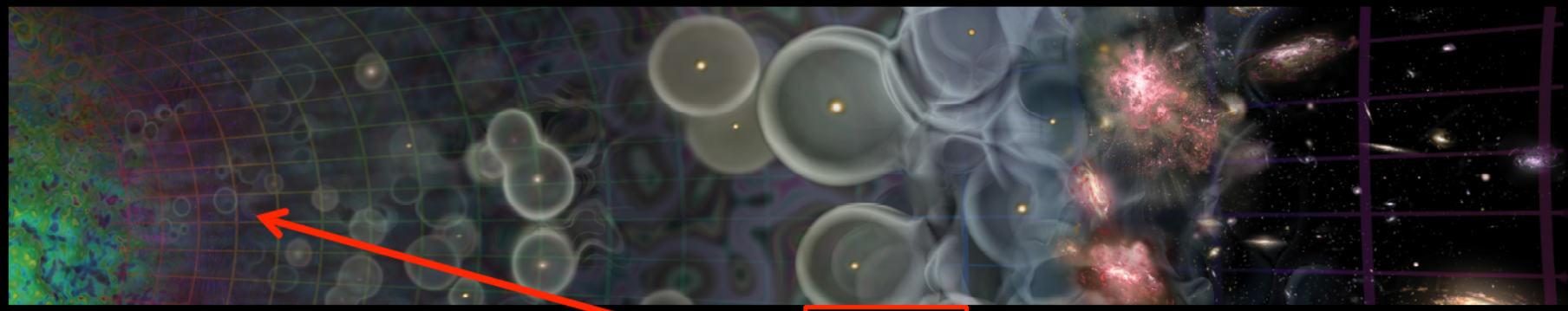


- Wouthuysen-Field effect couples UV radiation from first stars and 21 cm transition
- Gas *much* cooler than CMB, 21 cm line in absorption until …
- First heating (first accreting black holes?) from X-rays
  - X-rays penetrate much further into gas

$\nu = 1420 \text{ MHz}/(1 + z)$

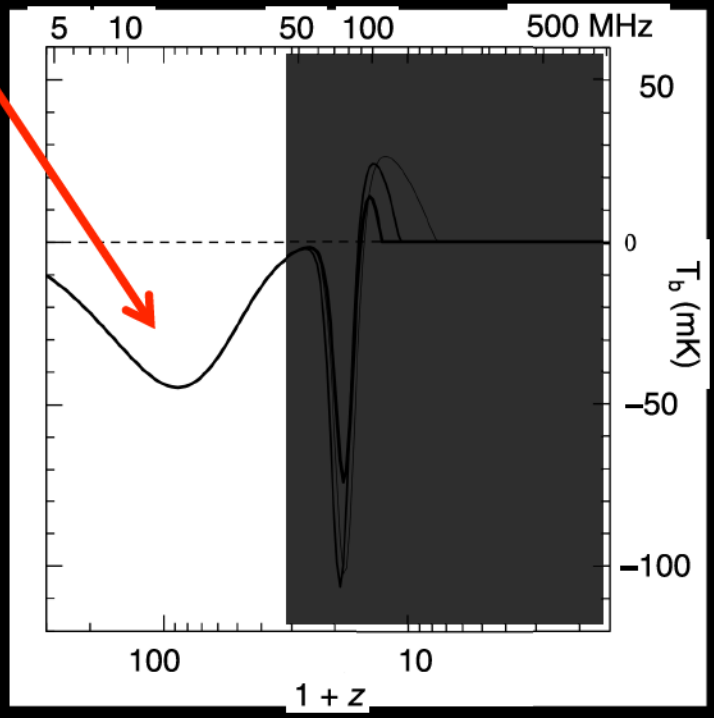
$\lambda = 21 \text{ cm } (1 + z)$

Dark Ages
Hydrogen Signal



Dark Ages

- Gas cools faster than radiation field
  $T_{gas} \propto (1+z)^4$, $T_{CMB} \propto (1+z)^3$
- 21 cm line in absorption …
- Until expansion dilutes gas that collisions are no longer effective
- Many more modes than CMB!



$\nu = 1420 \text{ MHz}/(1+z)$

$\lambda = 21 \text{ cm } (1+z)$

Cosmic Dawn & Dark Ages

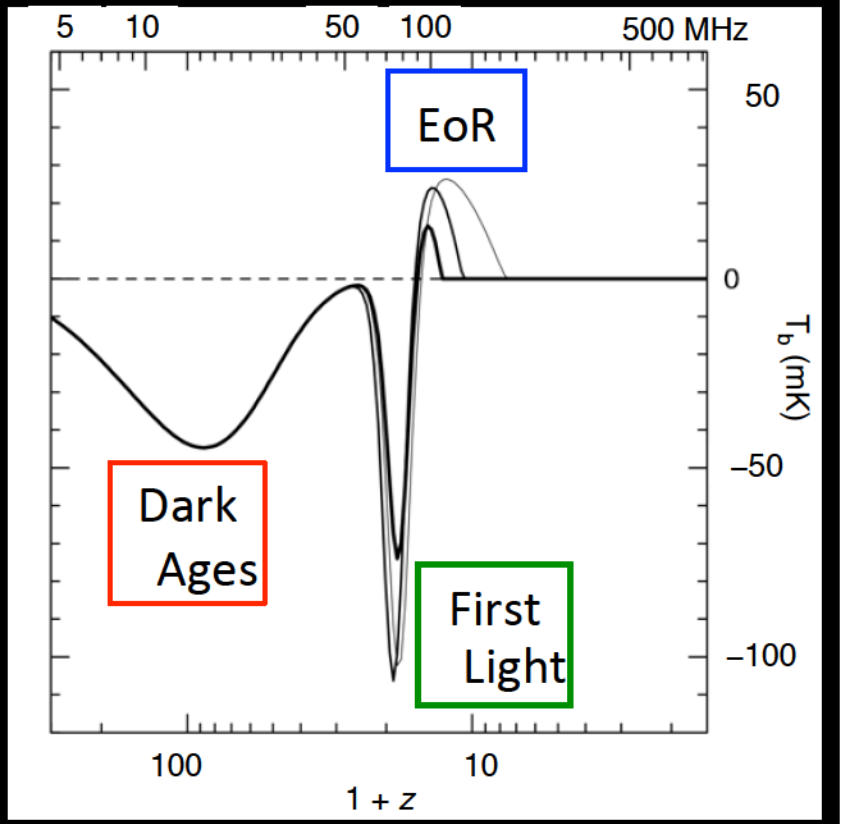
Hydrogen Signal

Cosmic Origins

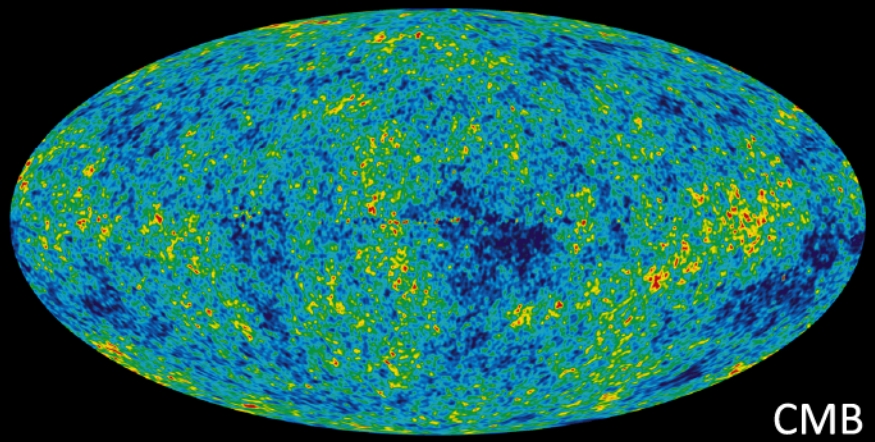
- EoR
  - Heating of the IGM
  - No ionospheric absorption
- First Light
  - First ionizing sources (stars), first heating sources (accreting BHs)
  - Ionospheric absorption becoming important

Physics of the Cosmos

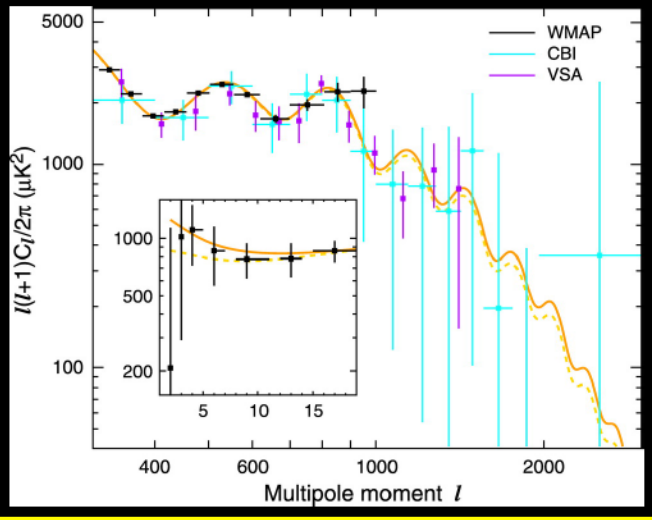
- Dark Ages
  - Fundamental cosmological parameters
  - Ionospheric absorption and reflections significant



H I Imaging and Power Spectra

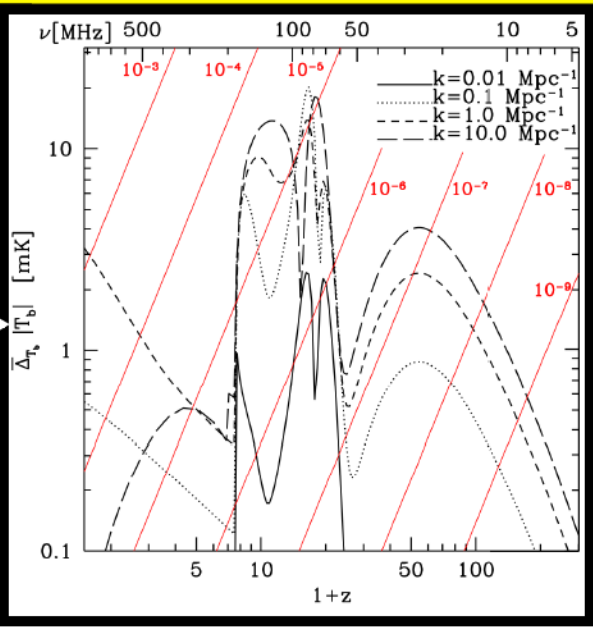


CMB



Alvarez et al.

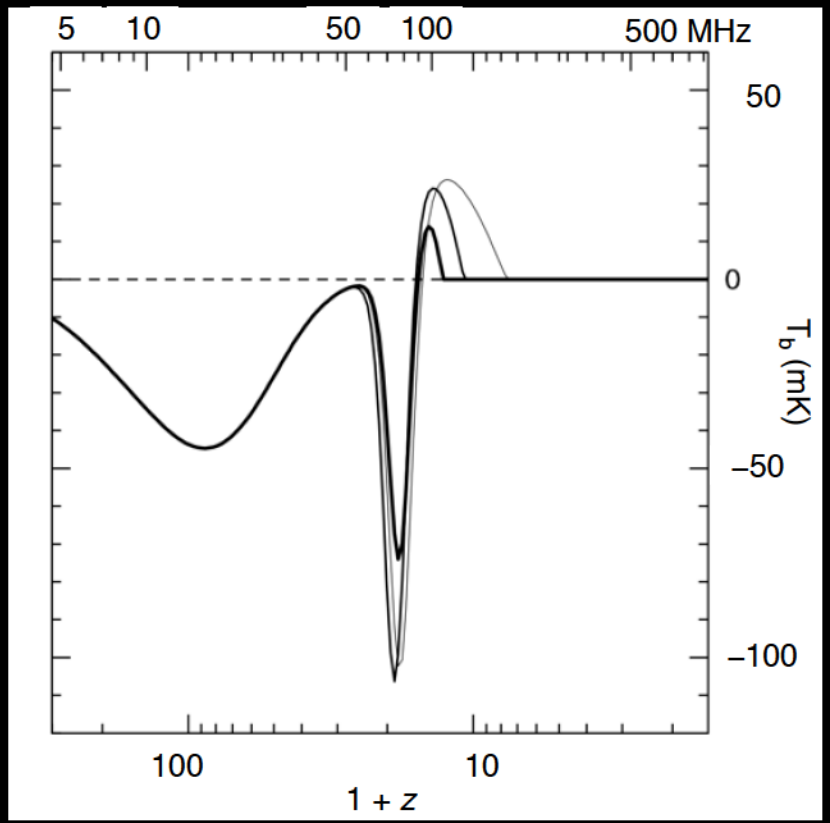
H I power spectrum



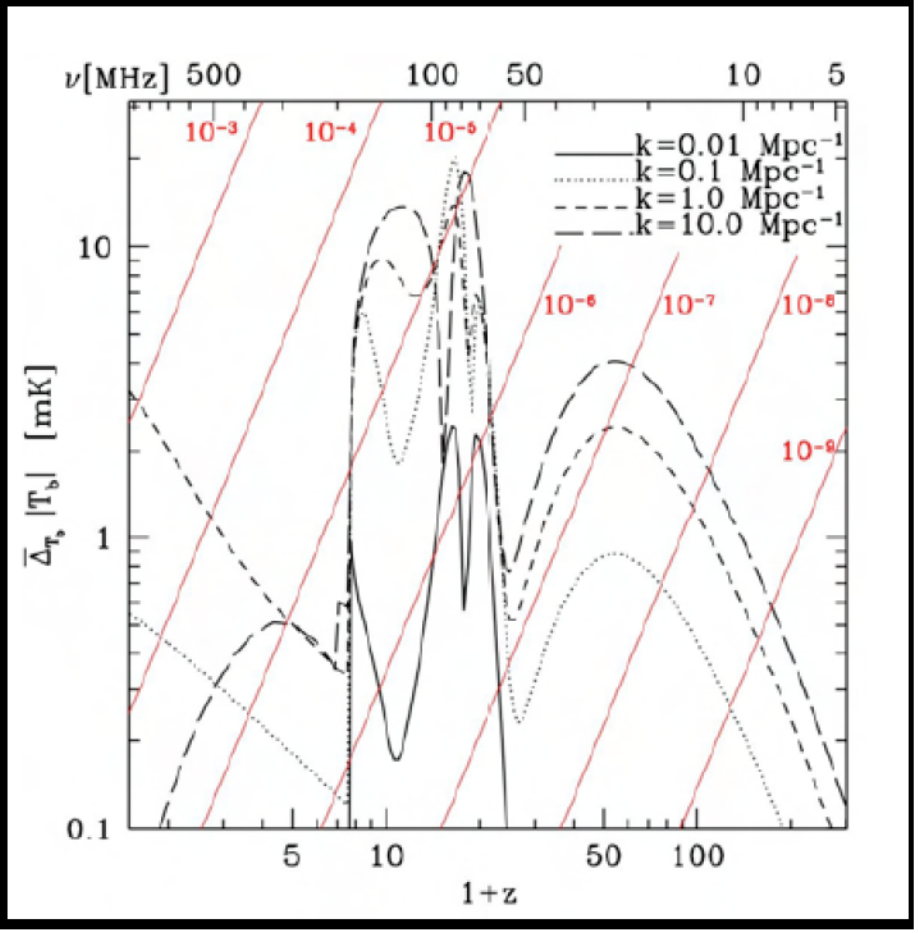
Cosmic Dawn & Dark Ages

Technical Implementation

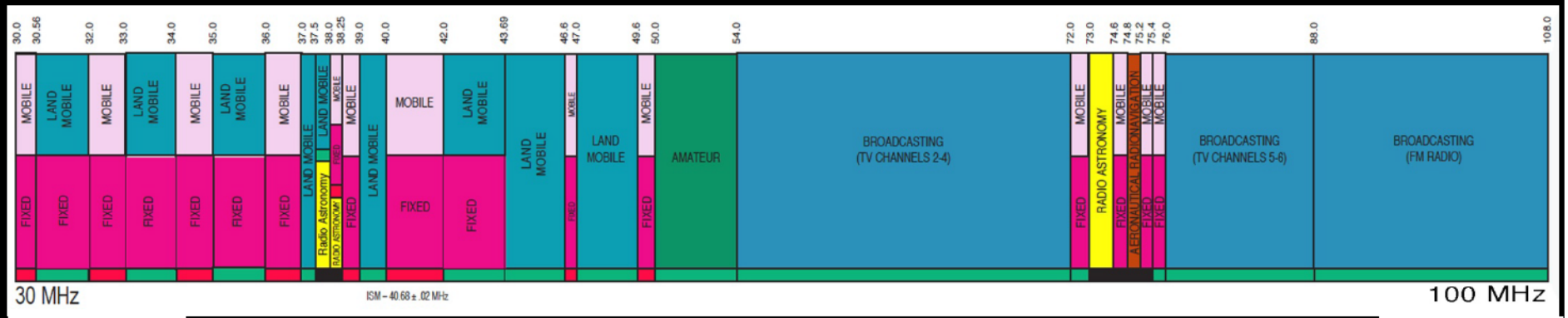
Sky-averaged spectrum



H I fluctuation spectrum



Radio Spectrum



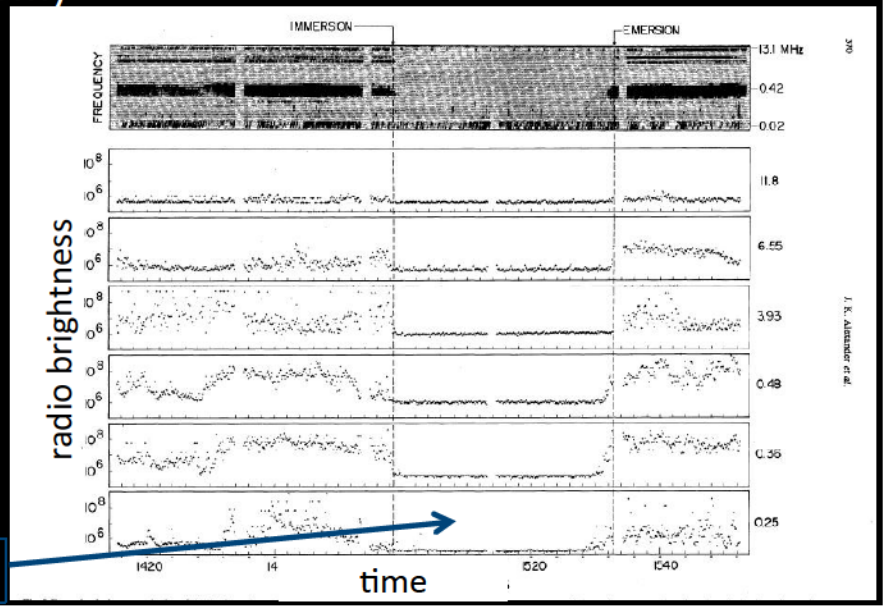
50 Myr since Big Bang

Portion of radio spectrum relevant for 21 cm observations of Cosmic Dawn and Dark Ages

- Yellow = reserved for radio astronomy

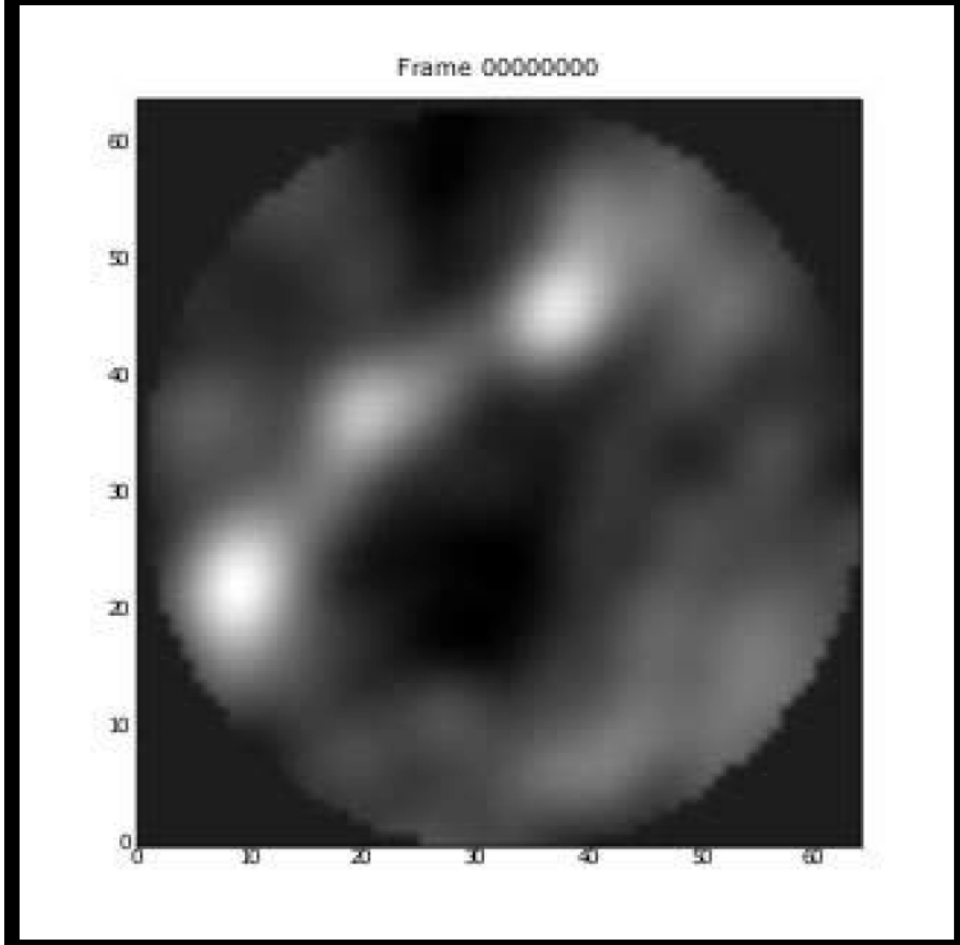
330 Myr since Big Bang

- Data from Radio Astronomy Explorer-2, when it passed behind the Moon, illustrating cessation of terrestrial emissions
- *Apollo* command modules lost communications when behind the Moon.



RAE-2 behind Moon

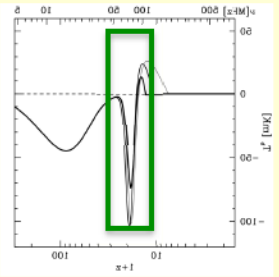
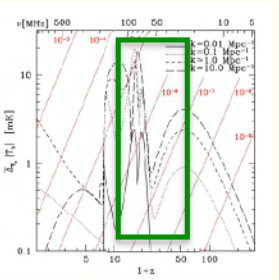
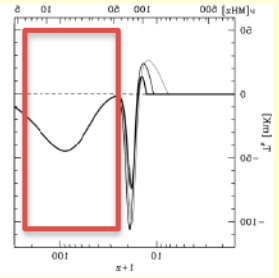
Ionospheric Effects
Technical Implementation Challenge



- Observations with Long Wavelength Demonstrator Array
  - 61 MHz (λ5m), z ~ 20
  - Central New Mexico
  - 2006 November

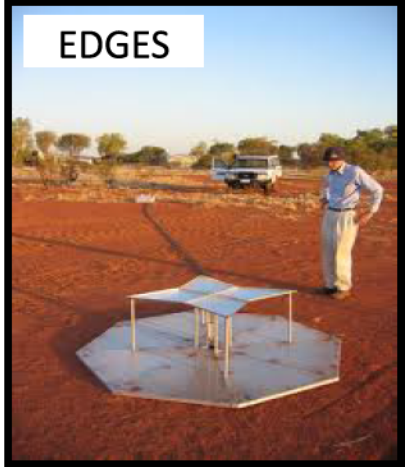
➢ No place on the planet dark at these frequencies (wavelengths)

Roadmap
Dark Ages & Cosmic Dawn

Way-station	Scientific Challenge	
10 yr	Determine when First Light occurred by measuring the sky-averaged 21 cm spectrum over the redshift range of at least $10 < z < 35$	
20 yr	Track the development of structures during First Light by measuring the H I fluctuation spectrum over at least $10 < z < 35$	
30 yr	Track the evolution of the Universe during the Dark Ages by measuring *at least* the sky-averaged 21 cm spectrum at $z \sim 80$	

From the Ground …


GMRT


EDGES


MWA


LOFAR

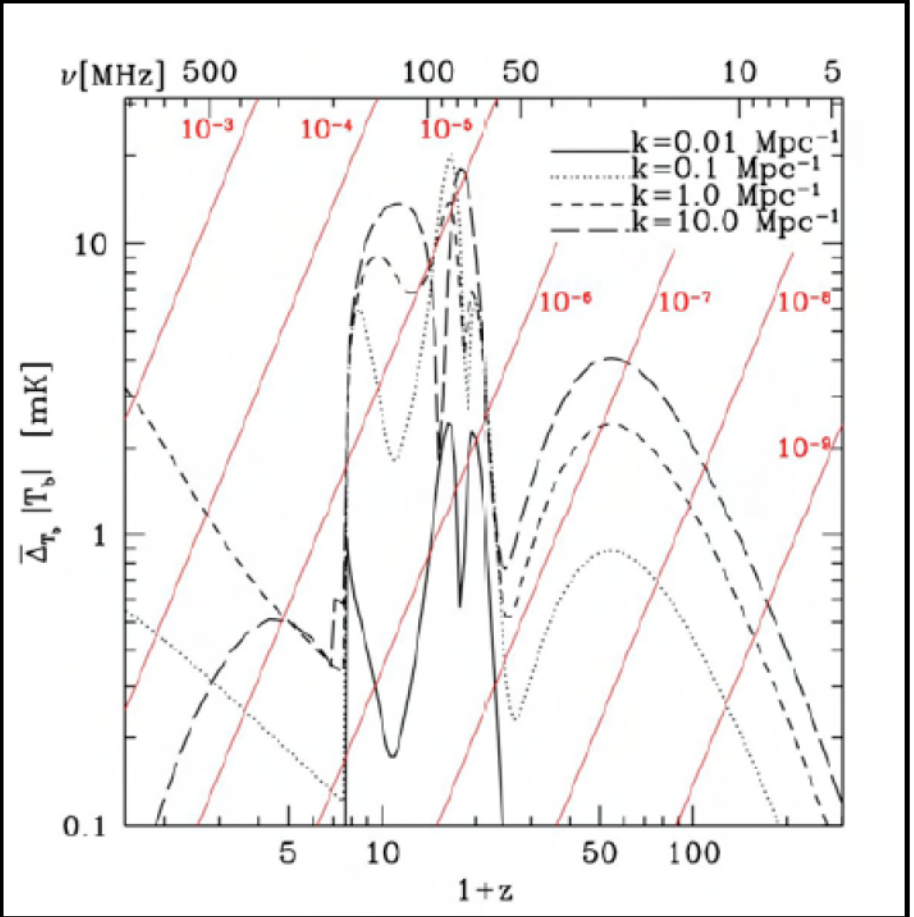

PAPER


LWA-1

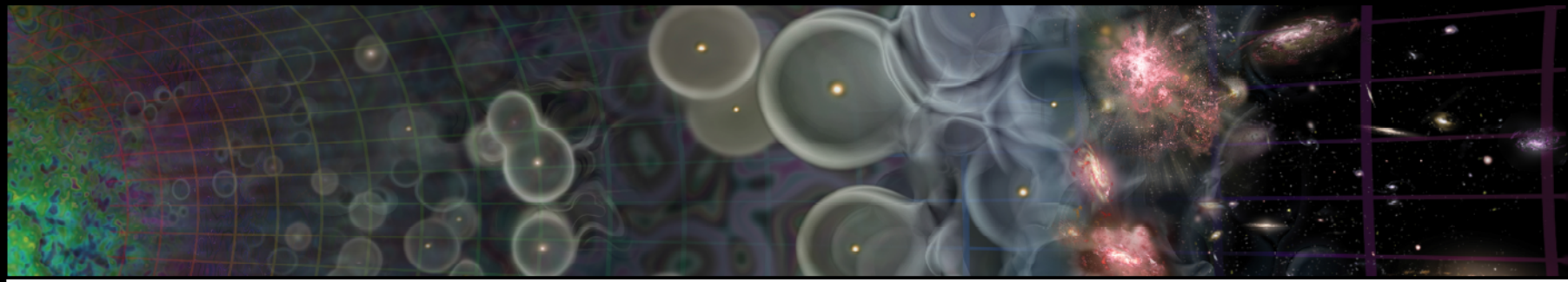
Cosmic Dawn & Dark Ages
Technical Challenges

- Low-mass, wide bandwidth, high precision receptors
  - i.e., antenna + electronics
  - – Astrophysics must lead
  - – NGR Technology Fellowship (J. Bowman, ASU)
- Low-power, rad tolerant, analog and digital electronics
  - Cross-cutting technology
- Autonomous low-power generation or storage
  - Cross-cutting technology?
- Low-mass, high capacity rovers
  - Cross-cutting technology

H I fluctuation spectrum



Roadmap
Dark Ages & Cosmic Dawn



Way-station	Scientific Challenge
10 yr	Determine when First Light occurred by measuring the sky-averaged 21 cm spectrum over the redshift range of at least $10 < z < 35$
20 yr	Track the development of structures during First Light by measuring the H I fluctuation spectrum over at least $10 < z < 35$
30 yr	Track the evolution of the Universe during the Dark Ages by measuring *at least* the sky-averaged 21 cm spectrum at $z \sim 80$