## Material Observed by Missions

PLASMA (STARS) — JWST, HST
MOLECULAR GAS — ALMA
ATOMIC GAS — HERA, DARE
COBE, WMAP, Planck

## Signal History

21-cm Spectrum: 20 mK to ~150 mK (Brightness Temperature)

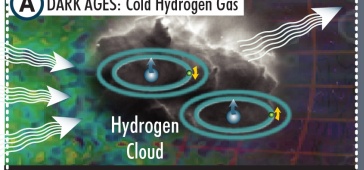
| | | | | | | |
|---|---|---|---|---|---|---|
| Redshift | 94 | 27 | 21 | 13 | 8 | 0 |
| Frequency [MHz] | 15 | 50 | 65 | 100 | 160 | 1420 |
| Time (M Years) | 18 | 120 | 170 | 340 | 650 | 13670 |

Big Bang — Cosmic Dark Ages — Cosmic Dawn — Reionization

## History of the Universe

## History of IGM Hydrogen Gas

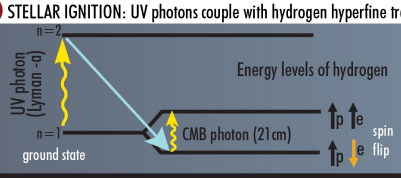
**A DARK AGES: Cold Hydrogen Gas**




Hydrogen seen in absorption against the CMB.

A. Hydrogen gas adiabatically cools faster than the CMB after decoupling so 21-cm signal is in absorption against the CMB. DARE will probe the end of the Dark Ages close to B.

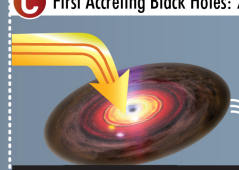
**B STELLAR IGNITION: UV photons couple with hydrogen hyperfine transition**




CMB photons and UV photons from first stars interact with cold hydrogen atoms producing a deep absorption trough in the observed spectrum.

B. Magnetic interactions of $p^+$ and $e^-$ spins produce hyperfine splitting of ground state. Absorbtion of ultraviolet photon induces spin-flip via excitation to n=2 level followed by decay to other hyperfine level.

**C First Accreting Black Holes: X-ray heating**




First accreting black holes begin heating hydrogen via X-Rays.

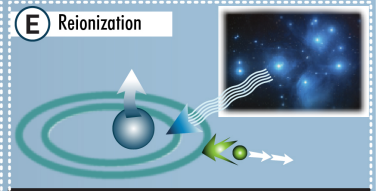
C. By measuring the onset and rate of heating, DARE will detect the first accreting black holes via X-ray heating of neutral hydrogen in the IGM.

**D Beginning of Reionization**

Beginning of Reionization, corresponding to redshifted 21cm heated hydrogen in emission.

D. DARE will constrain the early phases of reionization by measuring the neutral hydrogen fraction.

**E Reionization**



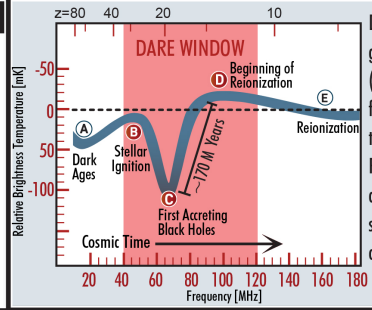
Intergalactic medium (IGM) is completely ionized by stars.

E. Once reionization is completed and neutral hydrogen is destroyed, the 21cm signal disappears.

## DARE Science Story

| REST FREQUENCY | | OBSERVED FREQUENCY |
|---|---|---|
| 21.1 cm | RED SHIFT | 651 cm |
| 1420 MHz z=0 | ν=1420/(1+z) MHz | 46 MHz z=30 |

Frequency maps directly to redshift for the 21-cm line due to the Universe's expansion so measurements of frequency extrema (see figure to the right) determine when the first stars and galaxies form.




DARE measures the global 21-cm spectrum (left) including the frequencies (redshifts) of the extrema within Regions B, C, and D to determine the onset of star/galaxy formation and their characteristics.

| SCIENCE OBJECTIVES | | Determine when the first stars ignited & their characteristics | Determine when the first black holes began accretion & their characteristics | Determine Reionization history of the early Universe | Determine if there is evidence for exotic physics in Dark Ages |
|---|---|---|---|---|---|
| SCIENCE MEASUREMENTS | Physical Parameters | • Redshift at which luminous sources produce first significant UV flux<br>• Distinguish Pop III vs. Pop II stars via efficiencies of UV ($\xi_\alpha$) production | • Redshift of X-ray heating from first black holes<br>• Efficiency of X-ray heating ($\xi_x$) | • Redshift at which Reionization begins<br>• Neutral hydrogen fraction ($x_{HI}$) and kinetic gas temperature ($T_k$) at z~11 | Heating or ionization in the early Universe caused by exotic physics such as Dark Matter decay |
| | Observables | • Measure frequencies of extrema in Regions B with accuracies of 1%<br>• Measure $\xi_\alpha$ with accuracy of 25% | • Measure frequency of extremum in Region C with accuracy of 1%<br>• Measure $\xi_x$ with rms accuracy of 15% | • Measure frequency of Region D extremum with accuracy of 2%<br>• Measure $x_{HI}$ to accuracy of 5%, and $T_k$ to 10%. | Distinguish between shapes of models for star formation & Dark Matter decay by extracting 21-cm spectrum from foregrounds |

DARE objectives are met by measuring features in the 21-cm spectrum.