**PLASMA (STARS)**

- **CORE**
  - WMAP
  - Planck

- **MOLECULAR GAS**

- **ATOMIC GAS**

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**21-cm Spectrum**

- **Redshift**
  - Frequency [MHz]
  - Temperature [K]
  - Time (M Years)
  - Brightness

- **20 mK**
  - 94
  - 27
  - 21
  - 13
  - 8
  - 100
  - 340
  - 160
  - 1420
  - 13670

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**Big Bang**

**Cosmic Microwave Background**

**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 21-cm signal.

**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. Absorption of ultraviolet photons induces spin-flip via excitation to n=2 level followed by decay to other hyperfine levels.

**C** First Galaxies & Black Holes

- First stars and black holes.

**D** Beginning of Reionization

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

**E** Reionization

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

- Intergalactic medium (IGM) is completely ionized by stars.

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**DARE Spectrum**

**REST FREQUENCY**

- 21.1 cm
- 1420 MHz
- \( \nu = 1420/(1+z) \text{ MHz} \)

**OBSERVED FREQUENCY**

- 46 MHz

- 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 Window**

**DARE OBJECTIVES**

- Determine when the first stars ignited & their characteristics.
- Determine when the first black holes began accreting & their characteristics.
- Determine Reionizations history of the early Universe.
- Determine if there is evidence for exotic physics in Dark Ages.

**SOURCES MEASUREMENTS**

- **Physical Parameters**
  - Redshift at which luminous sources produce first significant UV flux
  - Distinguish Pop III vs. Pop II stars via efficiencies of UV (L_i) production

- **Observables**
  - Measure frequencies of extremes in Regions with accuracy of 7%
  - Measure 21 cm with accuracy of 10%