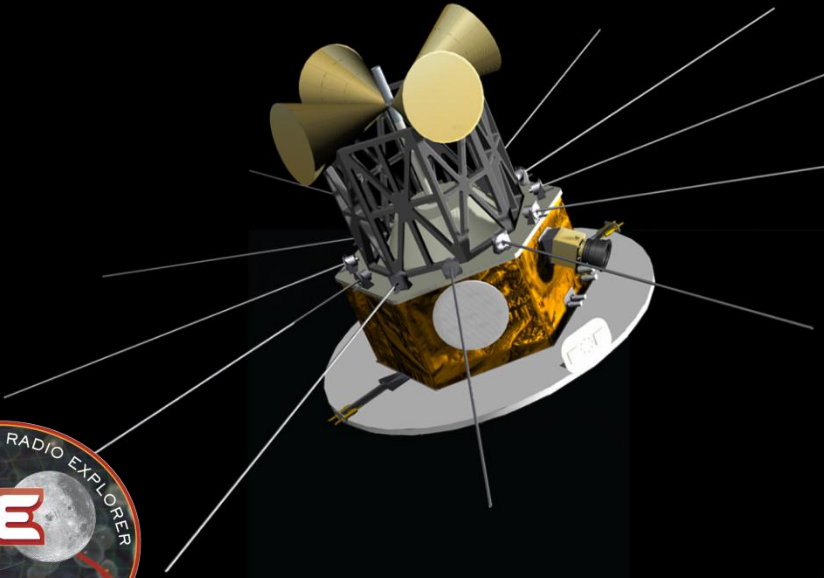
Into the Dark Ages:

DARE

DARK AGES RADIO EXPLORER

Jack Burns
University of Colorado Boulder
and
NASA Lunar Science Institute



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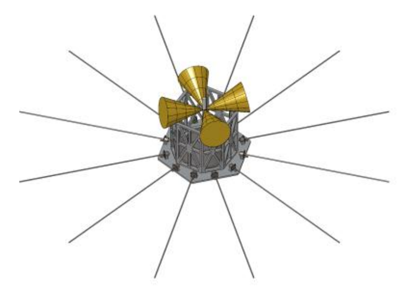
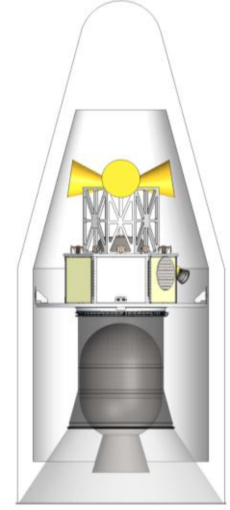




DARE PROJECT TEAM

Principal Investigator:
Jack Burns, U. Colorado

Deputy Principal Investigator:
Joseph Lazio, JPL

Project Manager:
Daniel Andrews, ARC

Deputy Project Manager:
Jill Bauman, ARC

Spacecraft PM:
Joan Howard,
Ball Aerospace

Instrument Manager:
John Oswald, JPL

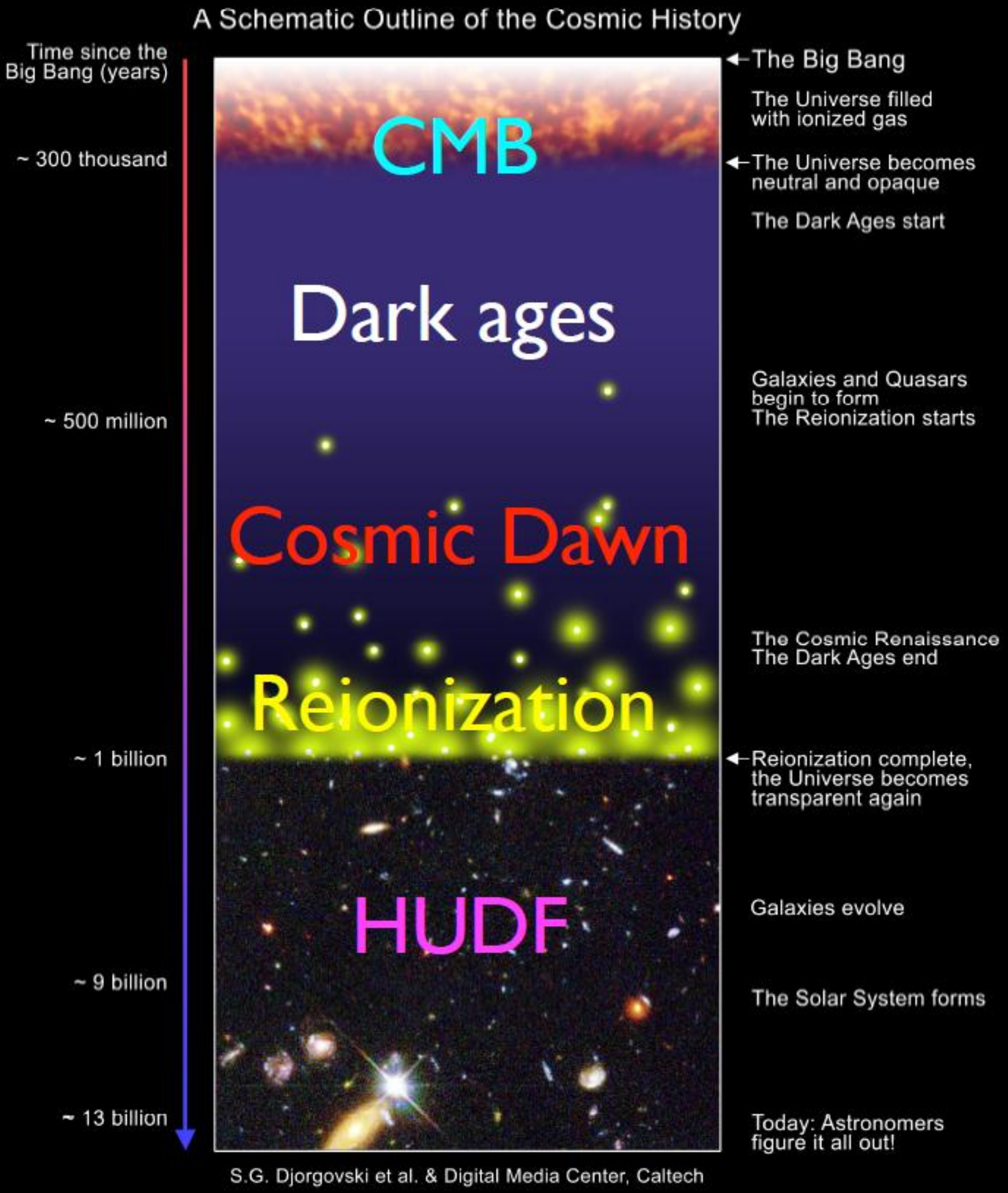
Collaborator: Michael Bicay, ARC

Science Co-Investigators

Stuart Bale, UC Berkeley
Judd Bowman, Arizona State Univ.
Richard Bradley, Natl. Radio Astronomy Obsv.
Christopher Carilli, Natl. Radio Astronomy Obsv.
Steven Furlanetto, UCLA
Geraint Harker, Univ. of Colorado
Abraham Loeb, Harvard University
Jonathan Pritchard, Harvard-Smithsonian Center for Astrophysics

PARTNERSHIPS

The First Billion Years



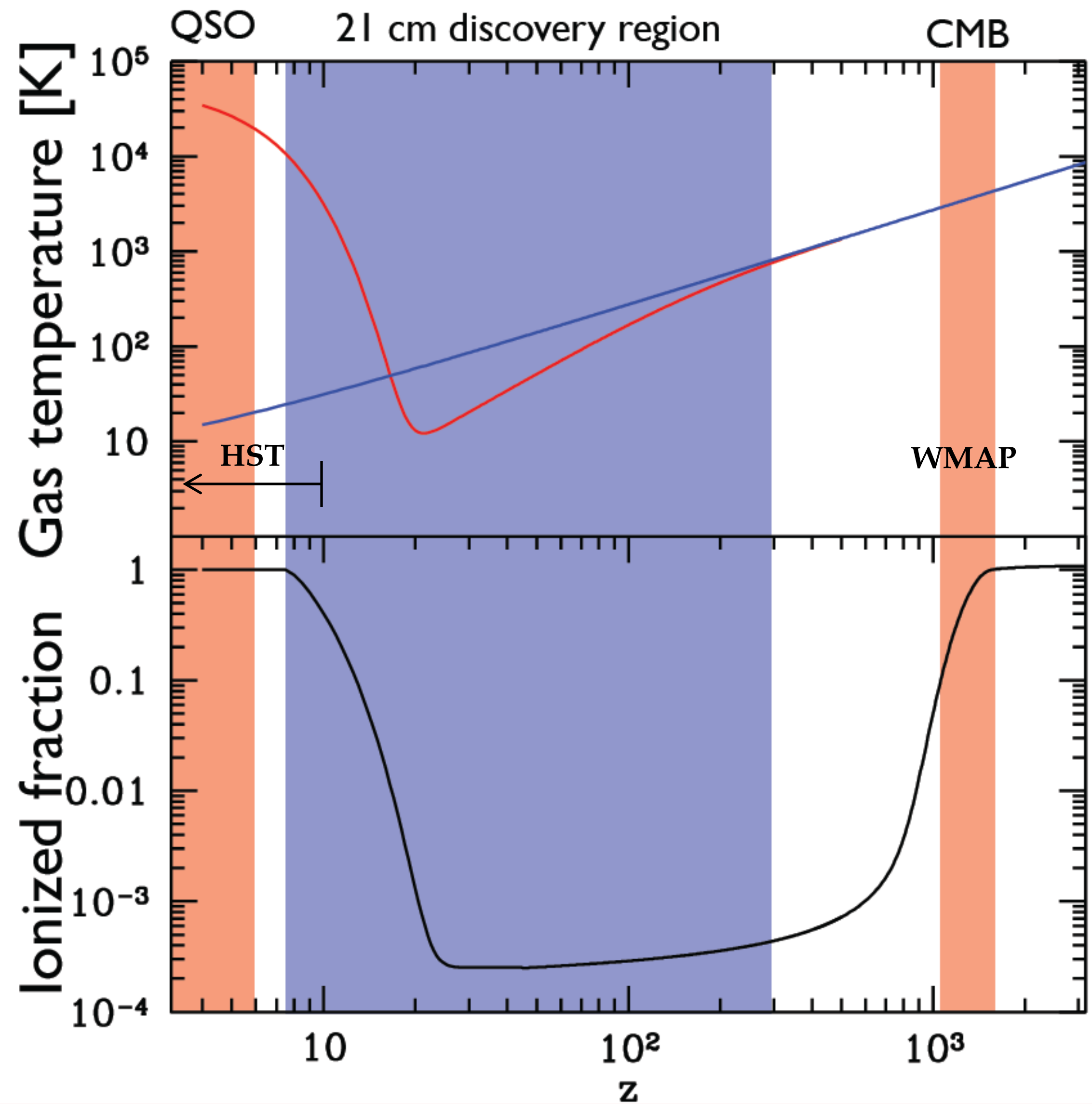
S.G. Djorgovski et al. & Digital Media Center, Caltech

z=1100

z~20-30

z~6

The Evolution of the IGM

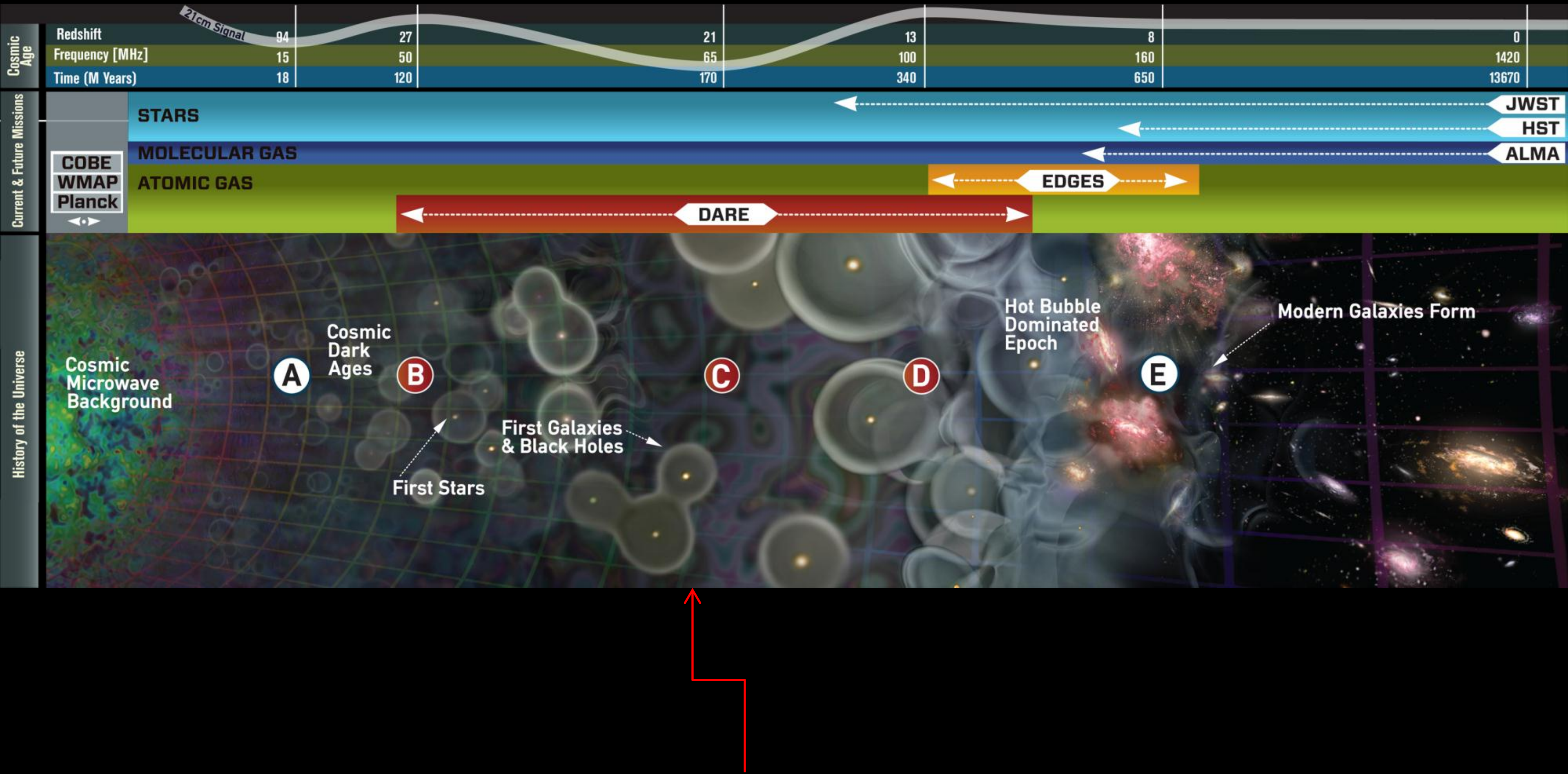


We know nothing concrete about the thermal history of the Universe between z=1100 and z=6

We know little or nothing about galaxies at z>10

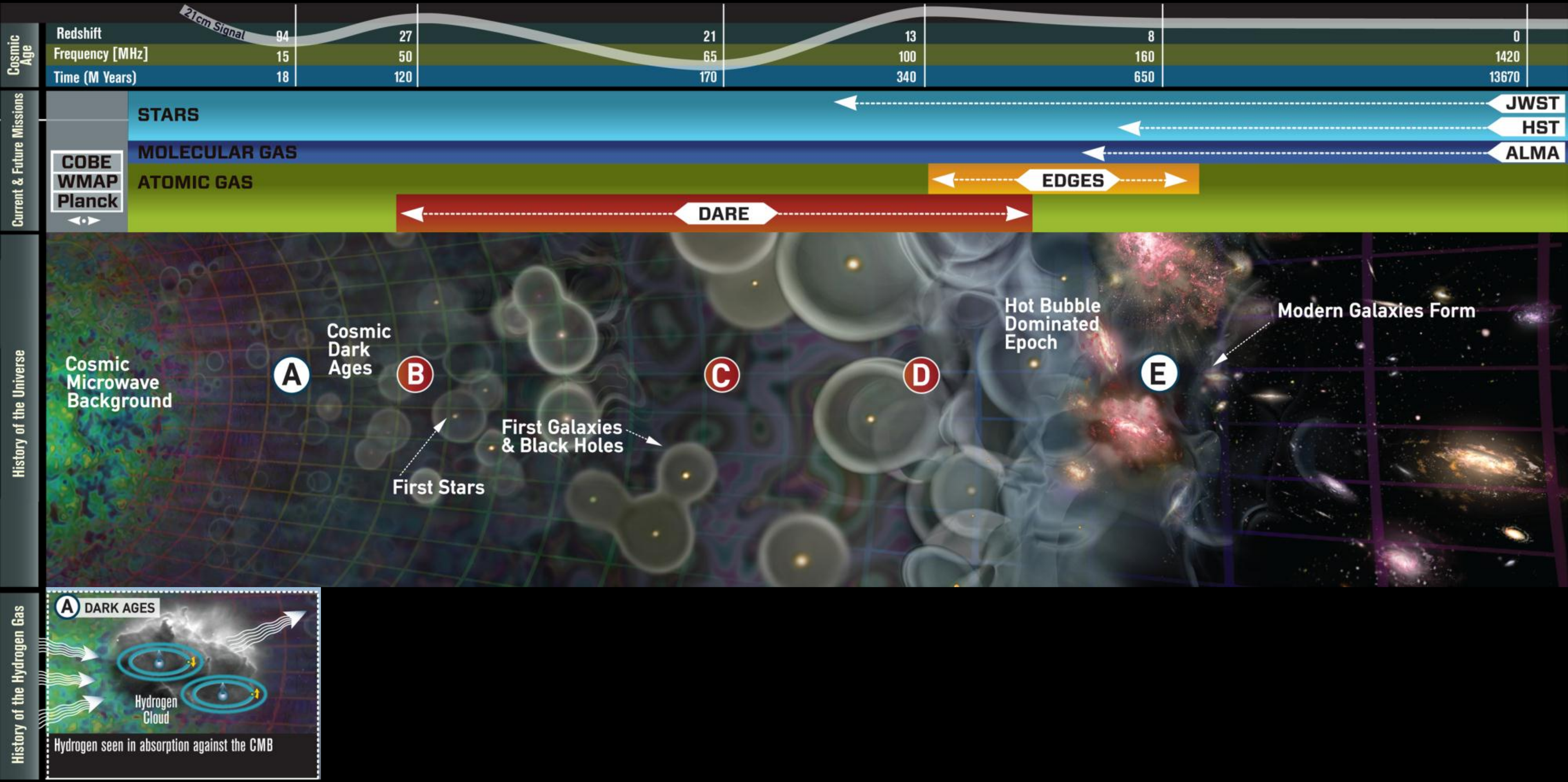
Courtesy of J. Pritchard

The History of Hydrogen

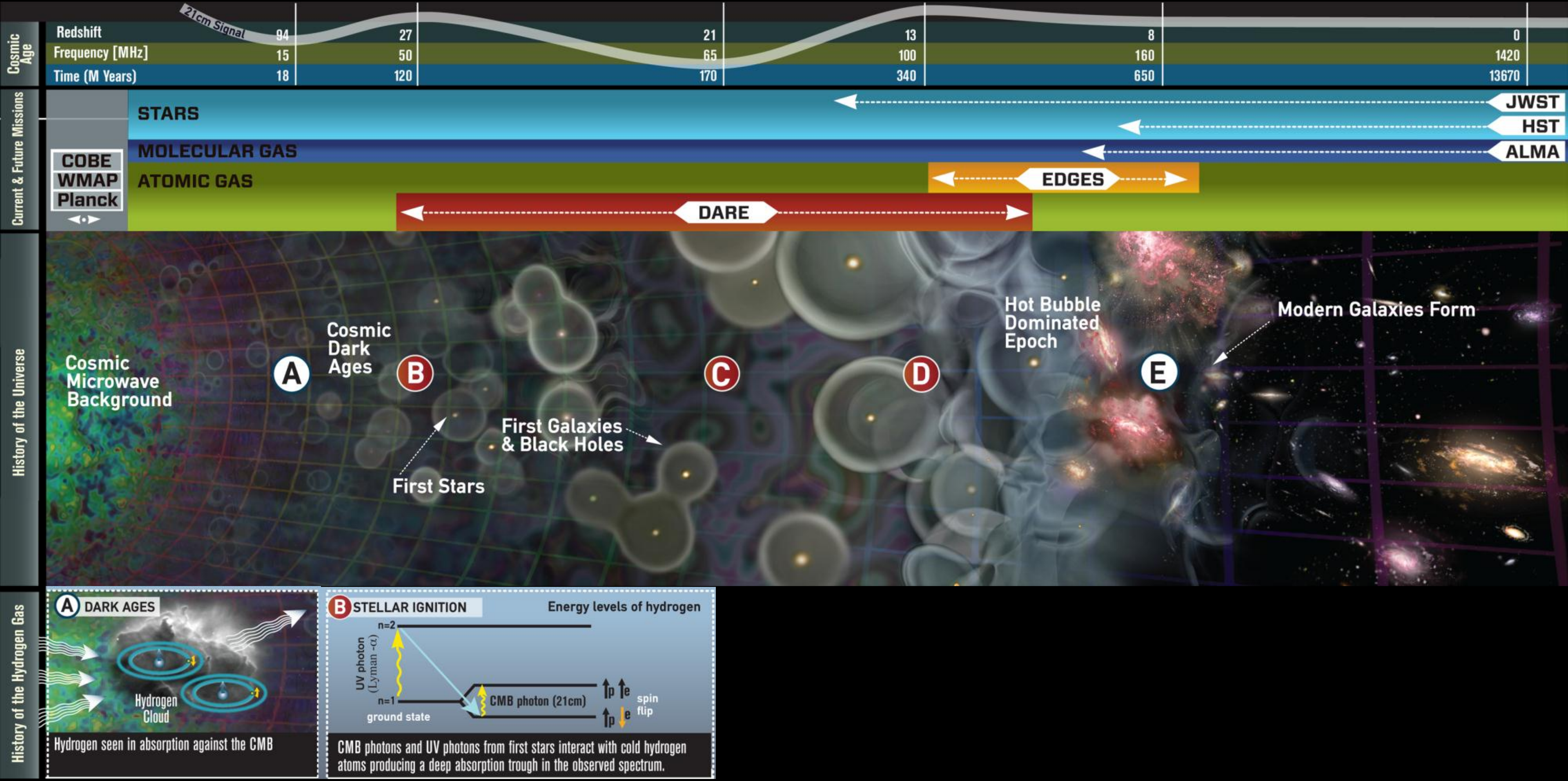


adapted from A. Loeb, 2006, *Scientific American*, 295, 46

The History of Hydrogen



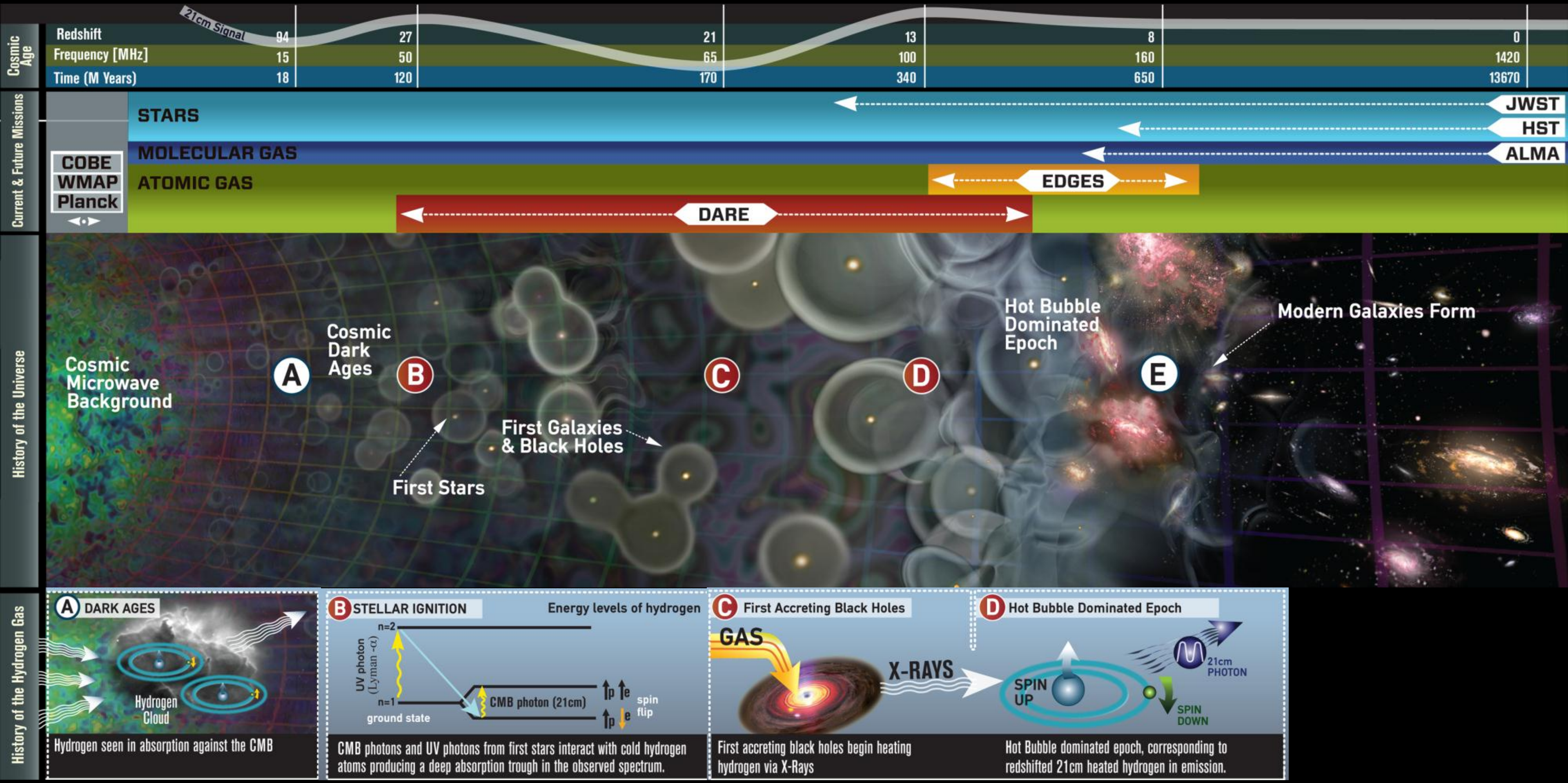
The History of Hydrogen



Hydrogen seen in absorption against the CMB

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

The History of Hydrogen



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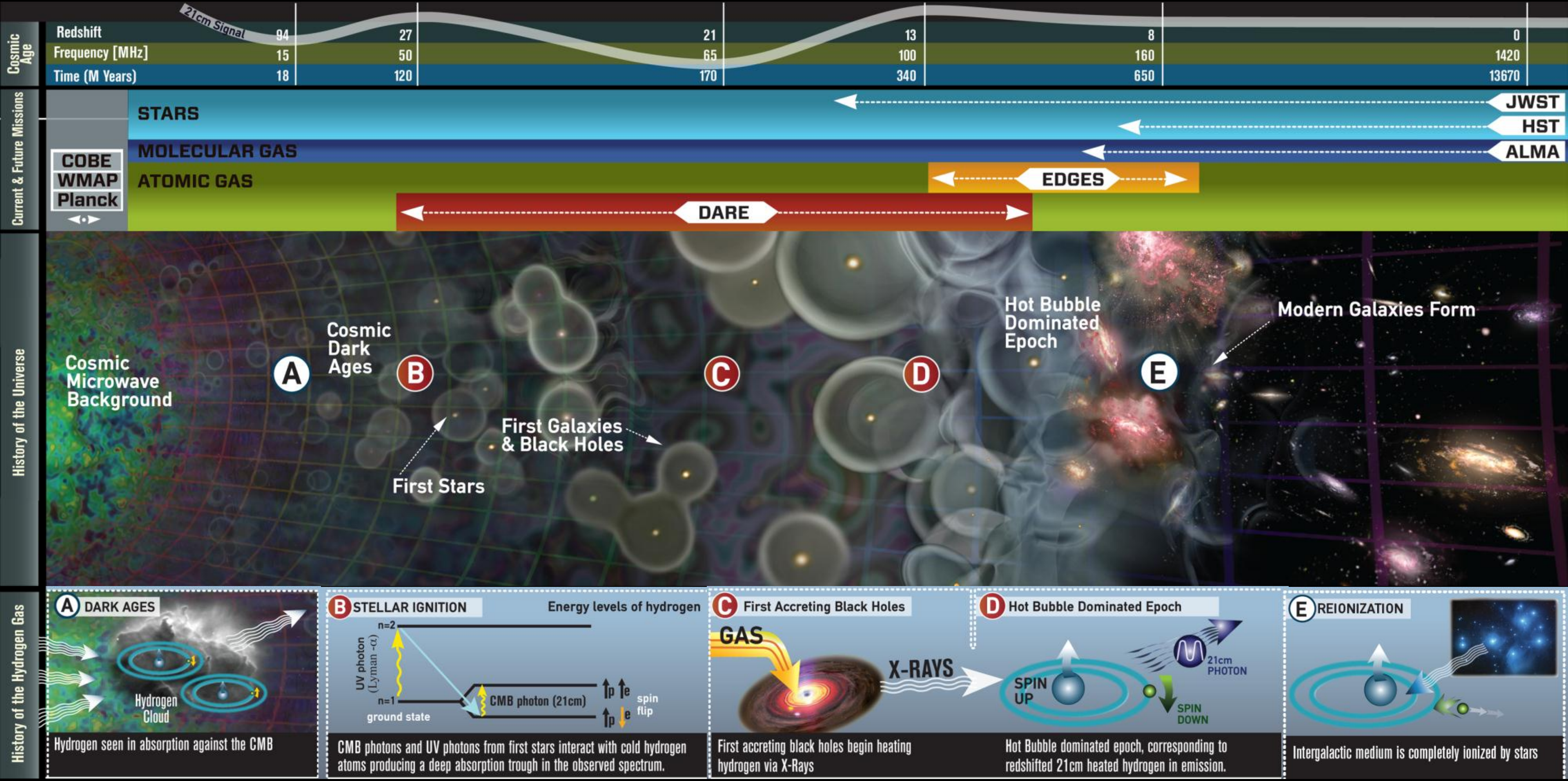
First accreting black holes begin heating hydrogen via X-Rays

Hot Bubble dominated epoch, corresponding to redshifted 21cm heated hydrogen in emission.

The History of Hydrogen



Hydrogen seen in absorption against the CMB

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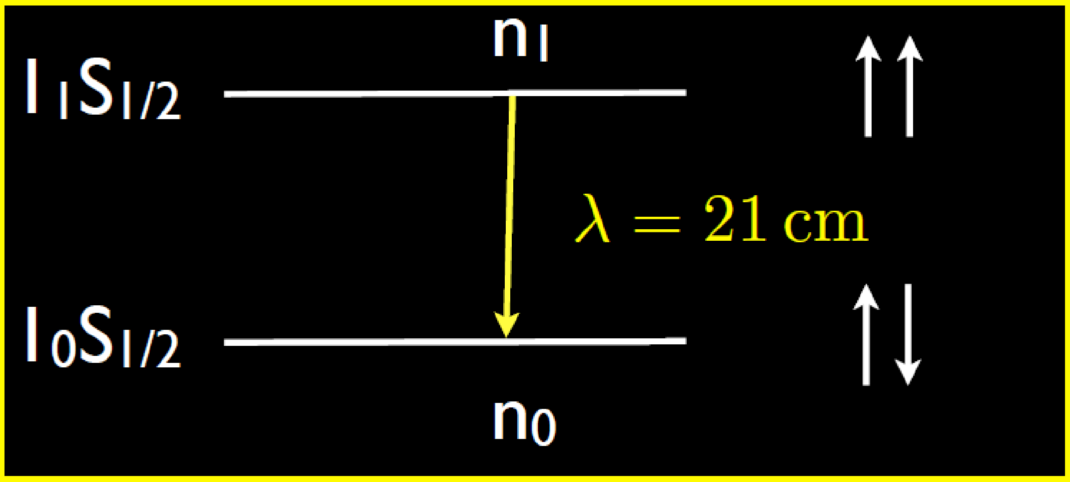
Intergalactic medium is completely ionized by stars

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:

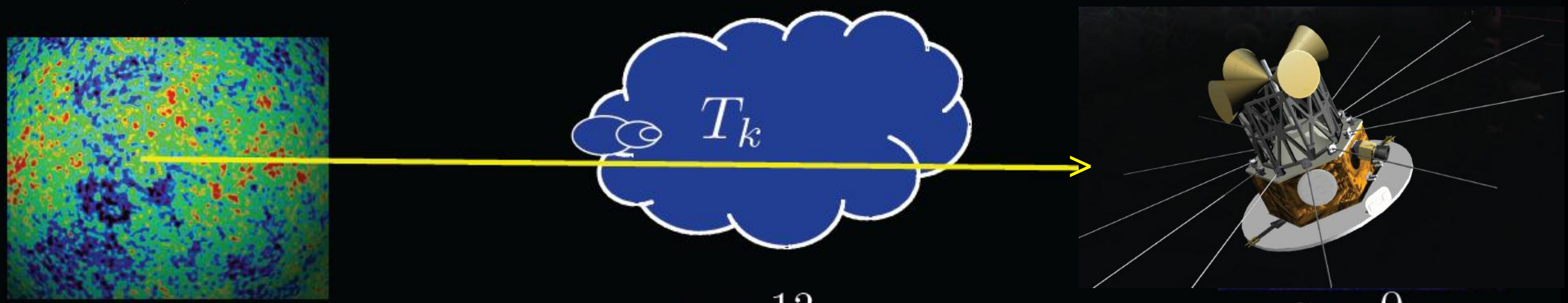
$$200\,\mathrm{MHz} \rightarrow z = 6$$
$$100\,\mathrm{MHz} \rightarrow z = 13$$
$$70\,\mathrm{MHz} \rightarrow z \approx 20$$

$$t_{\mathrm{Age}}(z = 6) \approx 1\,\mathrm{Gyr}$$
$$t_{\mathrm{Age}}(z = 10) \approx 500\,\mathrm{Myr}$$
$$t_{\mathrm{Age}}(z = 20) \approx 150\,\mathrm{Myr}$$

Courtesy of J. Pritchard

The 21-cm Line in Cosmology

T_γ T_S T_b



$z = 13$ $z = 0$

$\nu = 1.4\,\mathrm{GHz}$ $\nu = 100\,\mathrm{MHz}$

CMB acts as back light

Neutral gas imprints signal

Redshifted signal detected

neutral fraction

baryon density

spin temperature

peculiar velocities

brightness temperature ($P = kT_b \Delta\nu$)

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

spin temperature set by different mechanisms:

Radiative transitions (CMB)
Collisions
Wouthysen-Field effect

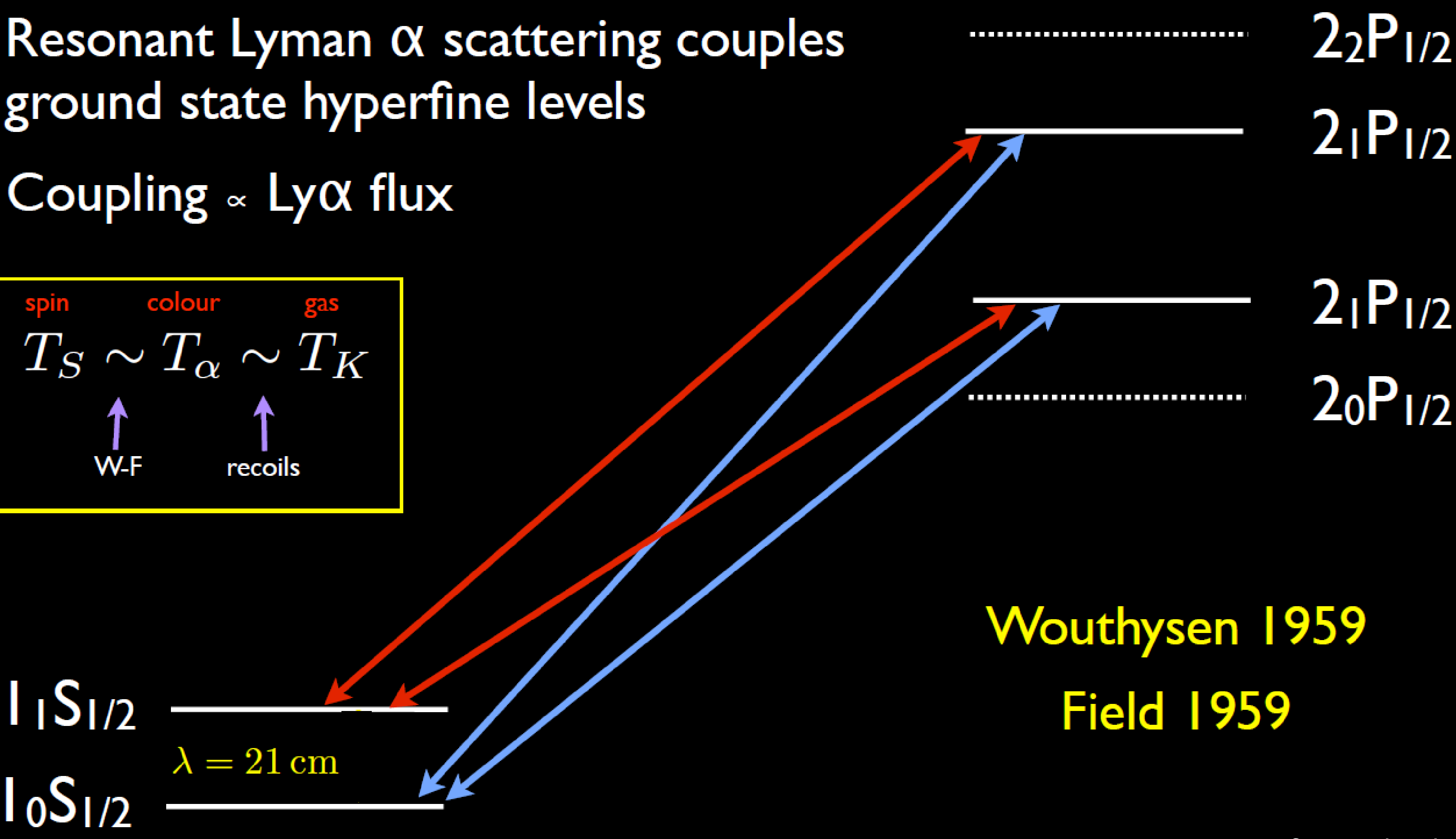
Courtesy of J. Pritchard

The Wouthysen-Field Effect

Hyperfine structure of HI

Resonant Lyman α scattering couples ground state hyperfine levels

Coupling ∝ Lyα flux



spin colour gas

$$T_S \sim T_\alpha \sim T_K$$

W-F recoils

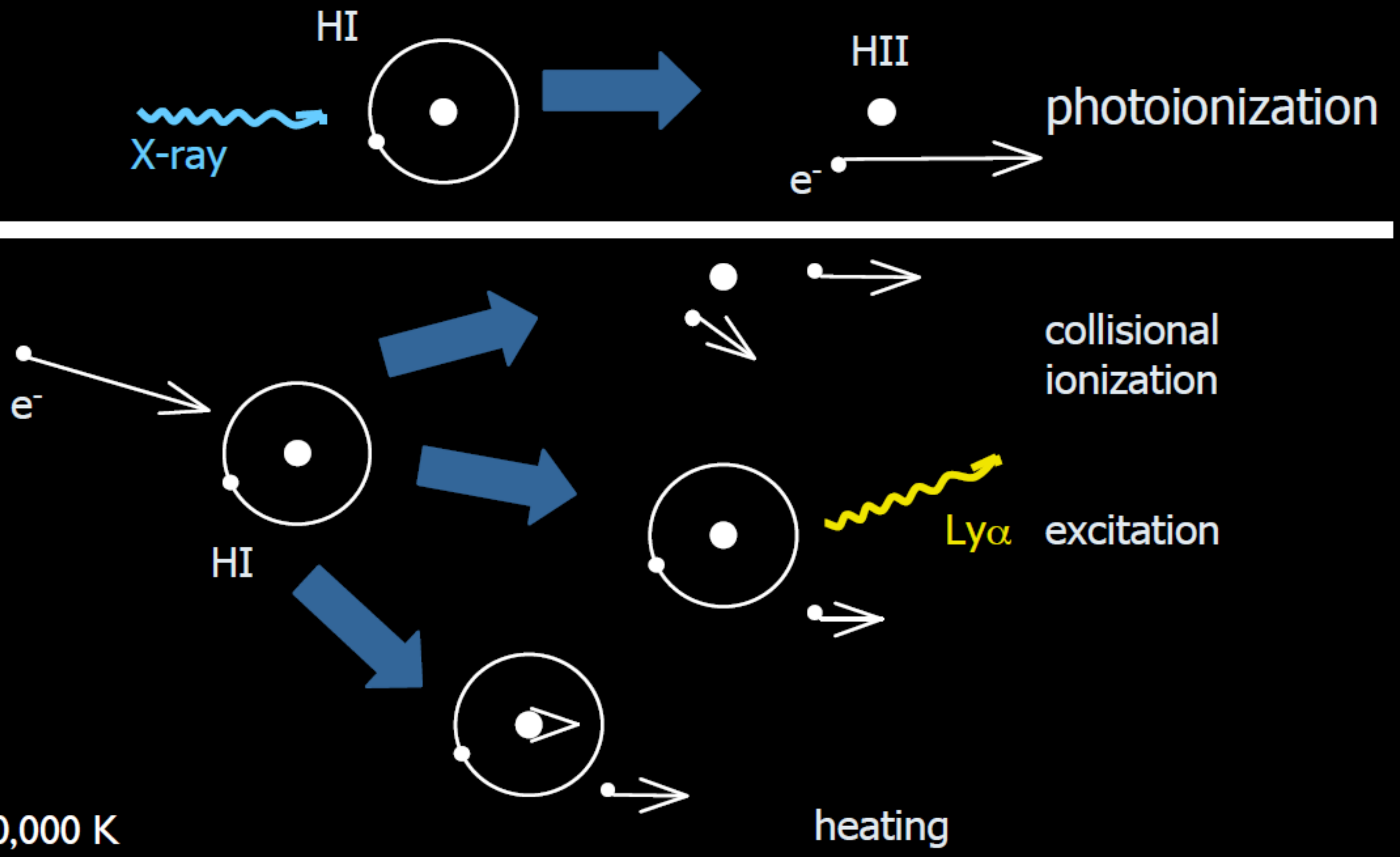
Wouthysen 1959

Field 1959

Courtesy of J. Pritchard

X-ray Heating

- X-ray energy partitioned

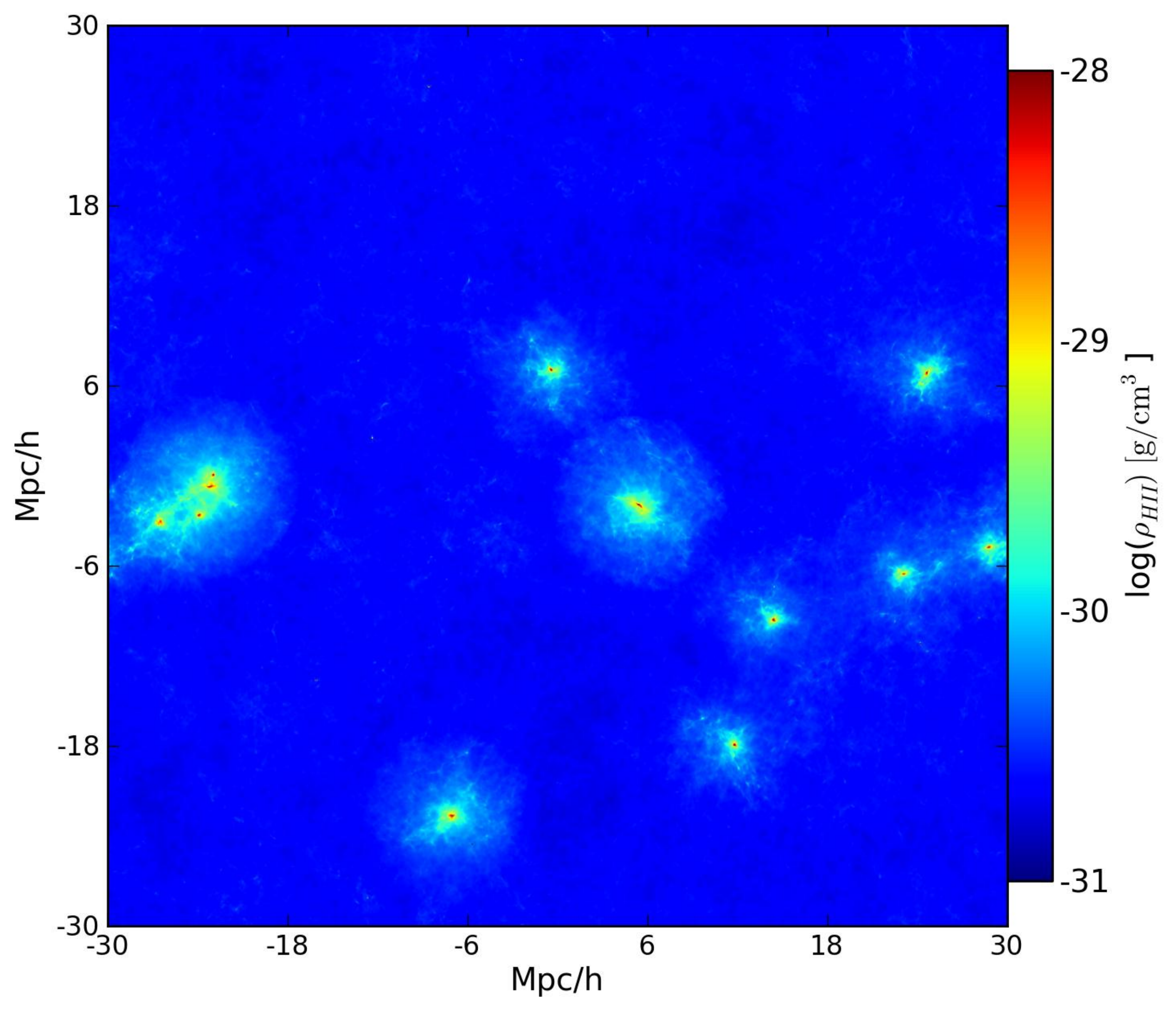


1eV=10,000 K

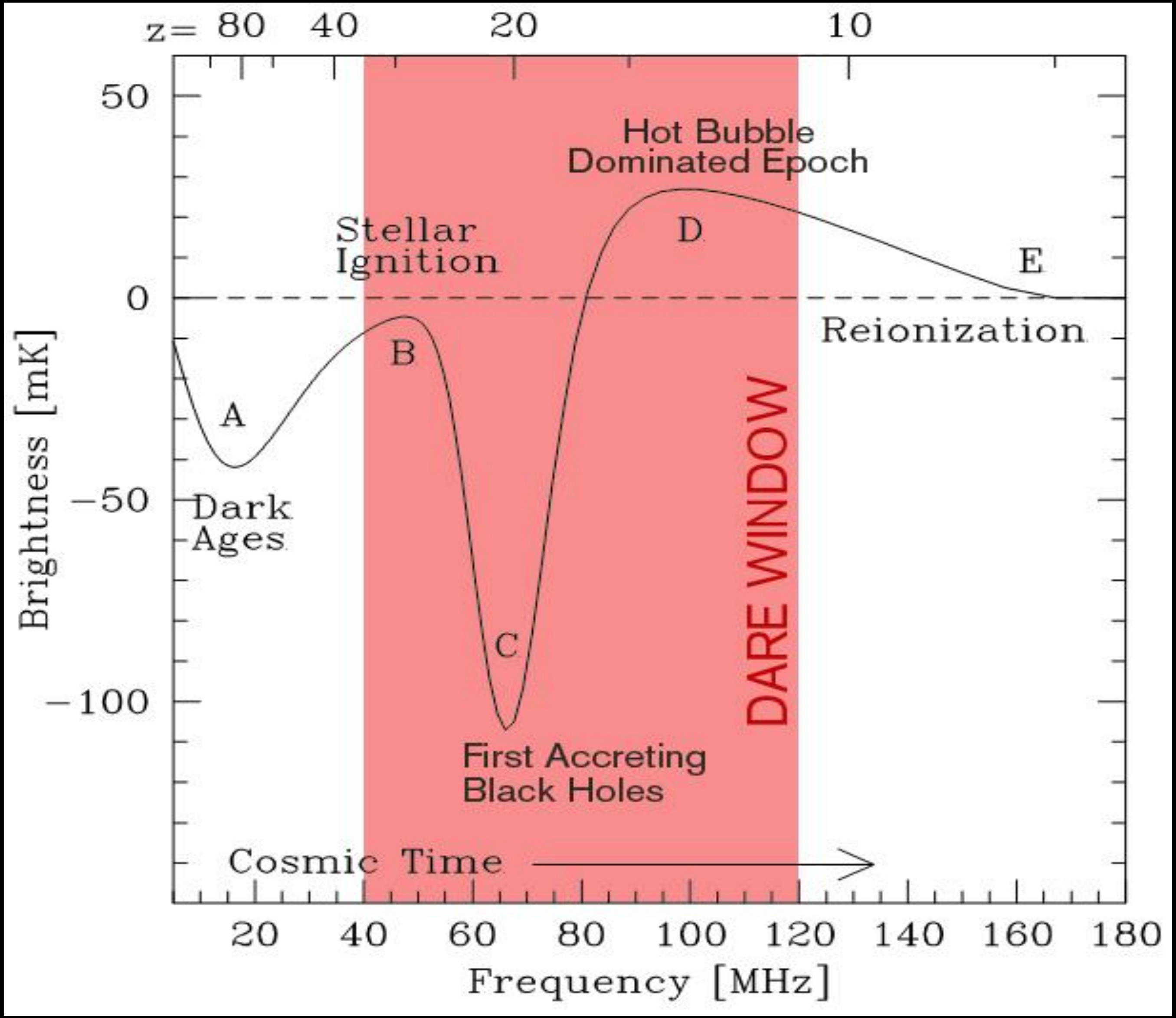
Shull & van Steenberg 1985, Furlanetto & Johnson 2010

Initial Results from Enzo Simulations of X-ray Heating

J. Mirocha, J. Burns, J. Wise

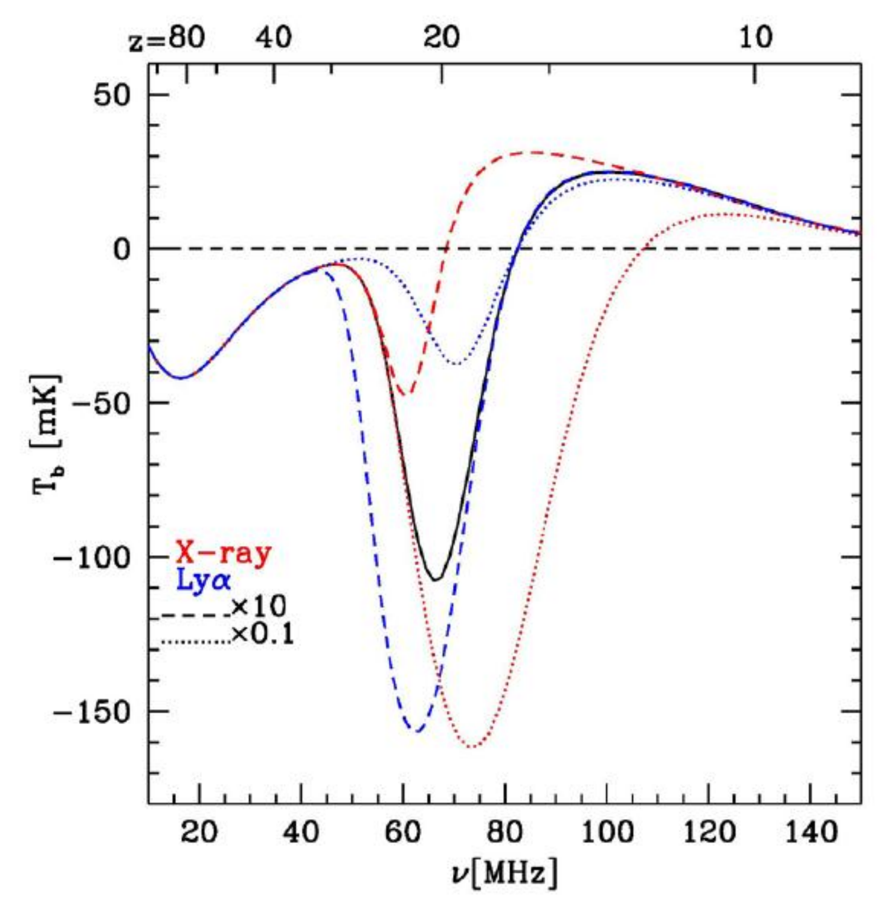


DARE will focus on determining or constraining *Turning Points* B, C, D

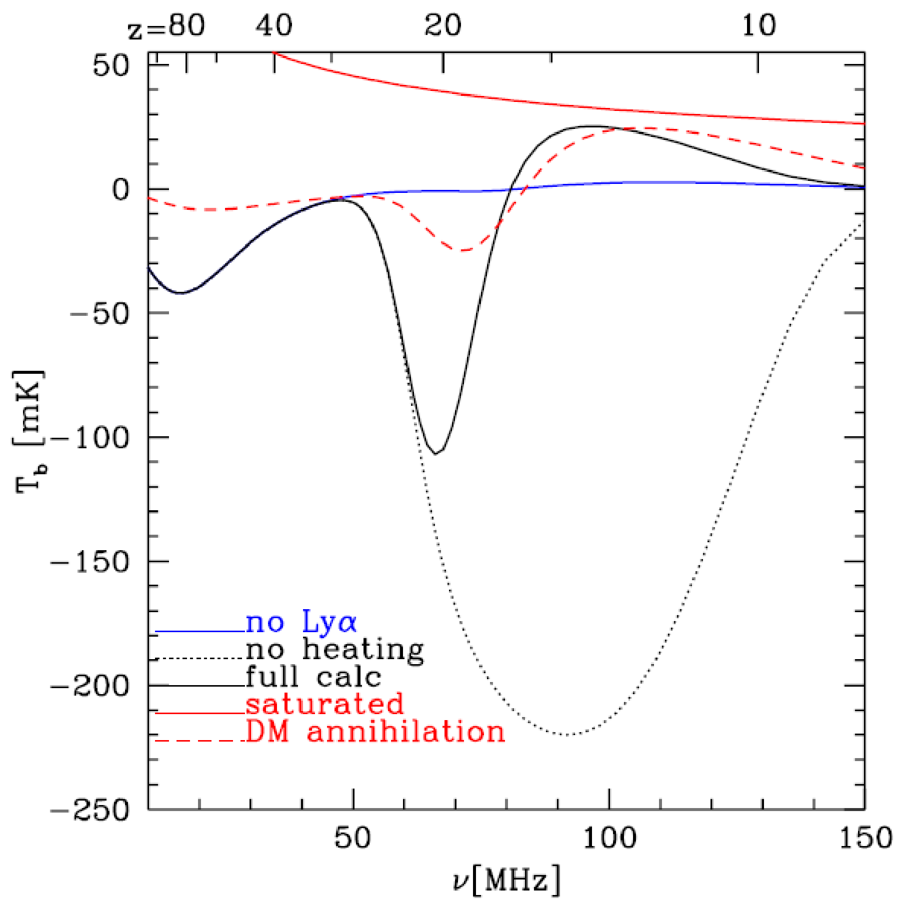


Adapted from Pritchard & Loeb, 2010, *Phys. Rev. D,* 82, 023006

But, what about other scenarios?



X-ray heating & Ly-α vary by factor of 10



Additional physics

The Science of DARE

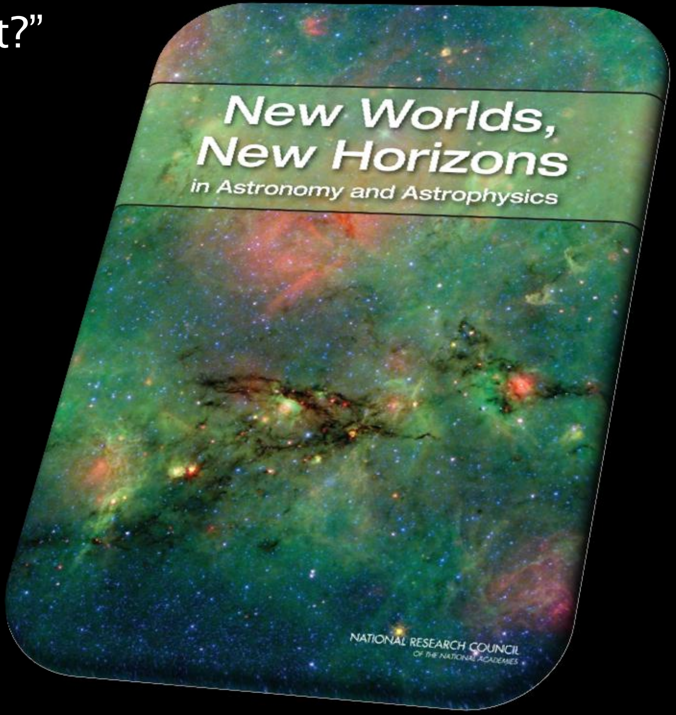
From Astro2010 Decadal Survey: "What were the first objects to light up the universe and when did they do it?"

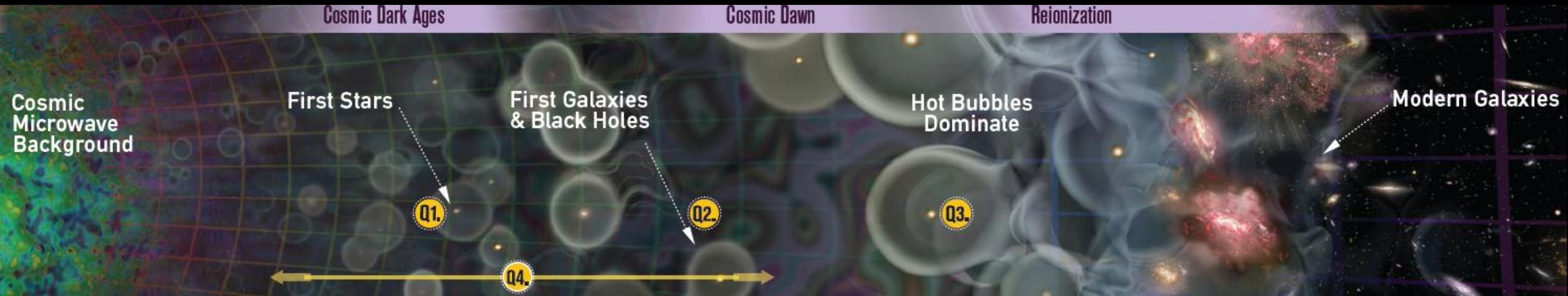
DARE tests the hypothesis:
The Universe underwent a previously unobserved major phase transition driven by radiation from the first stars and accreting black holes.

DARE SCIENCE OBJECTIVE:

FIRST STARS & BLACK HOLES

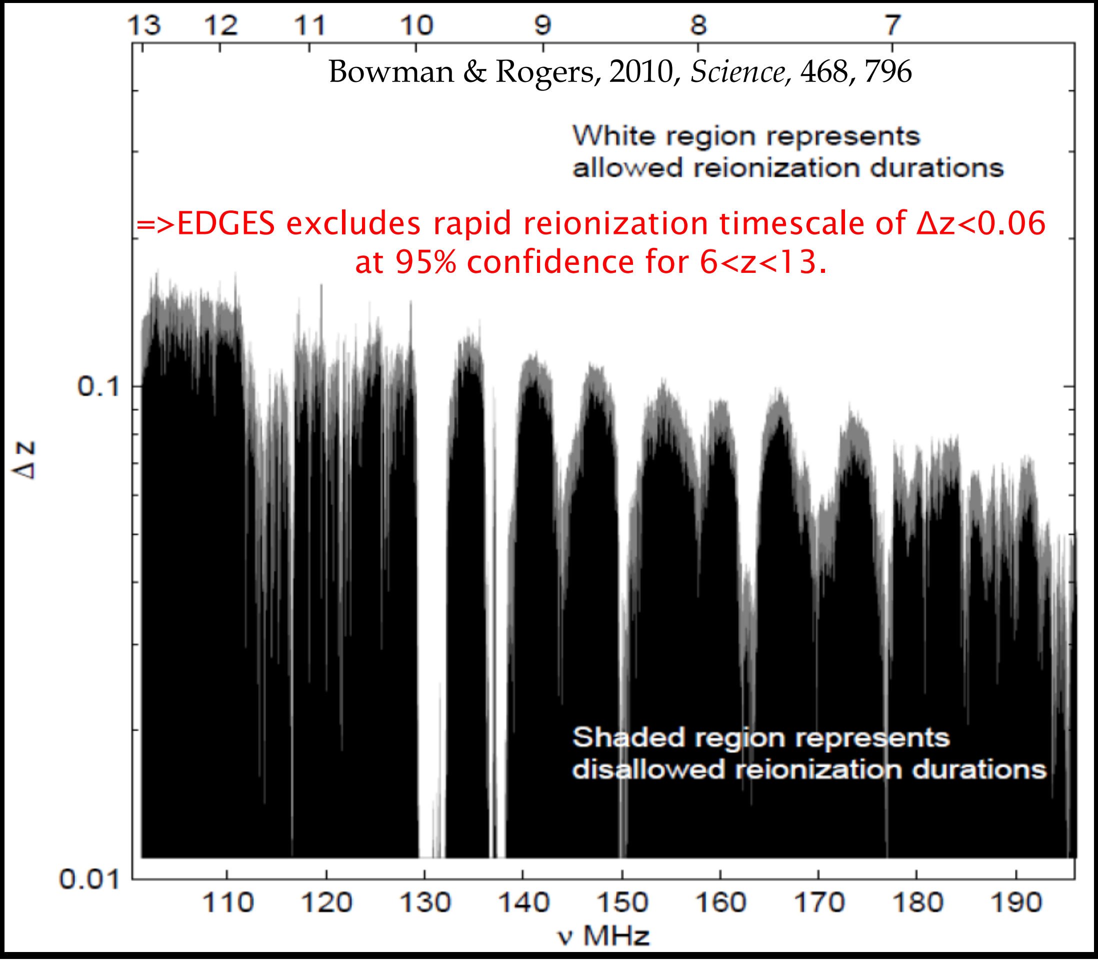
- **Q1.** WHEN DID THE FIRST STARS FORM?
- **Q2.** WHEN DID THE FIRST ACCRETING BLACK HOLES FORM?
- **Q3.** WHEN DID THE HOT BUBBLE-DOMINATED EPOCH AND REIONIZATION BEGIN?
- **Q4.** WHAT SURPRISES DOES THE END OF THE DARK AGES HOLD?

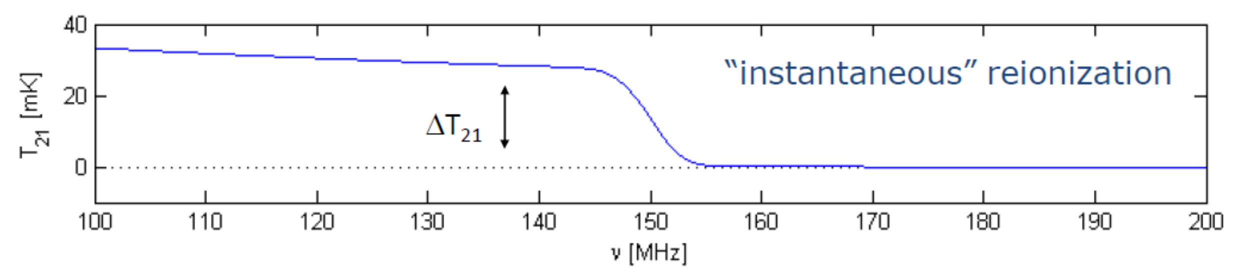




Experiment to Detect the Global Epoch of Reionization Signal (EDGES): Pathfinder for DARE

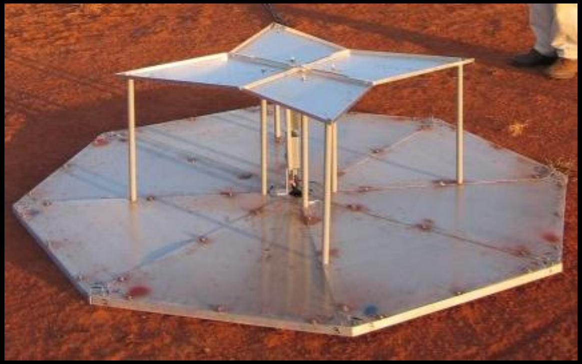
EDGES dipole at MWA site in Western Australia

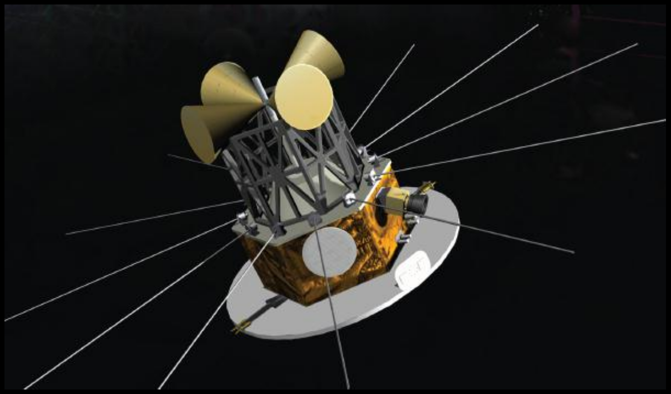




Lessons from EDGES

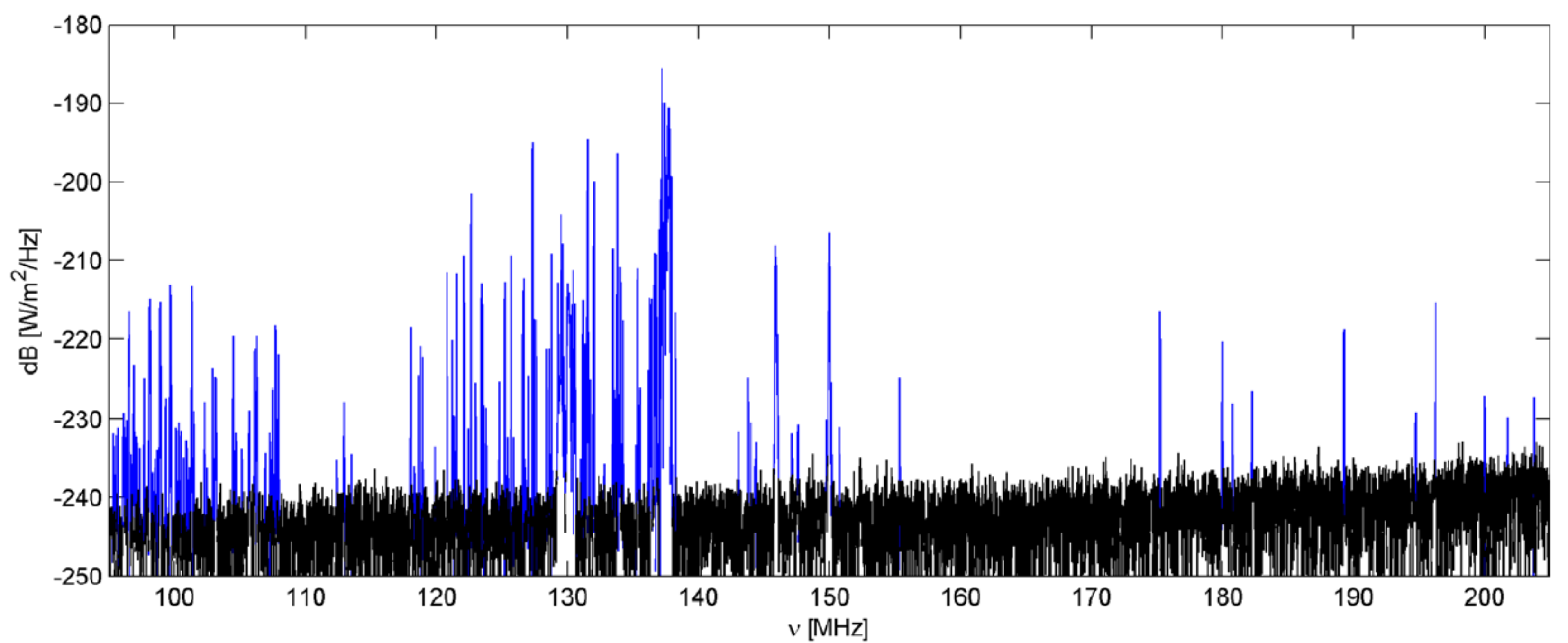
Technical problems for ground-based experiments	DARE
Complex environment Prevents transferring laboratory calibration of the antenna impedance and beam pattern to the deployed instrument, limits the accuracy of in situ calibration, and increases frequency of calibration operations.	**Simple environment** Simple, compact, stable geometry of S/C enables accurate modeling of the antenna and facilitates in-situ calibration.
Multipath reflections Trees, mountains, and other structures can reflect sky noise, resulting in complicated constructive and destructive spectral interference patterns in the spectrum above the 1 mK threshold.	**No multipath** No external structures are in proximity to the S/C.
RFI is always present!	**No RFI from Earth** Full RF spectrum is usable for science with low-EMI from DARE S/C environment. Sources of other RFI is predictable and calibrated out
Dynamic range is difficult to achieve A/D converters must use large bit-depths and be highly linear to accommodate RFI. Particularly susceptible to internal clock stability errors and digital noise. EDGES receiver modeled to have 6 mK artifacts.	**Easy to achieve needed dynamic range** A/D converter can use low bit-depth, industry standard specifications. Receiver based on 50 years of proven RF flight hardware.
The Earth's ionosphere Radio waves from terrestrial emitters can be reflected from meteor trails or ionospheric density structures	**No effective ionosphere**



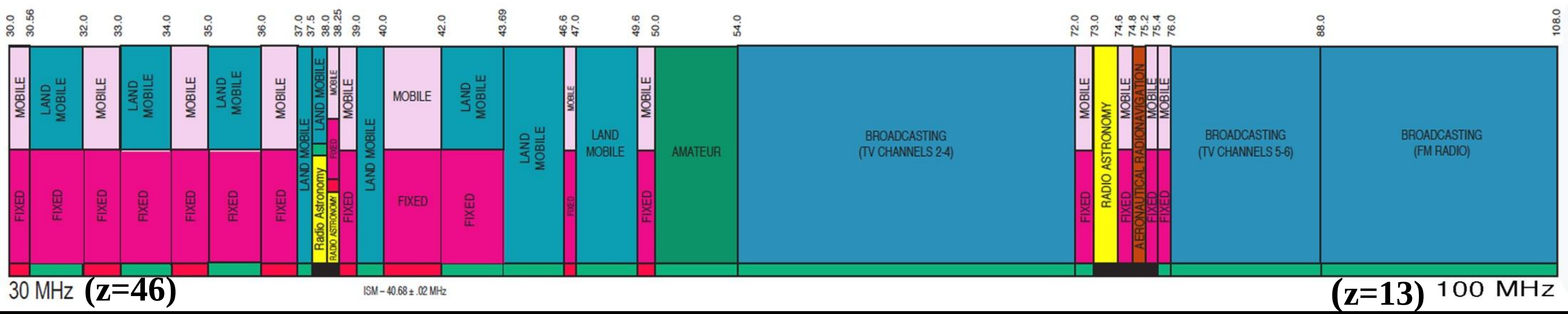


Analogous to why
COBE went
to space

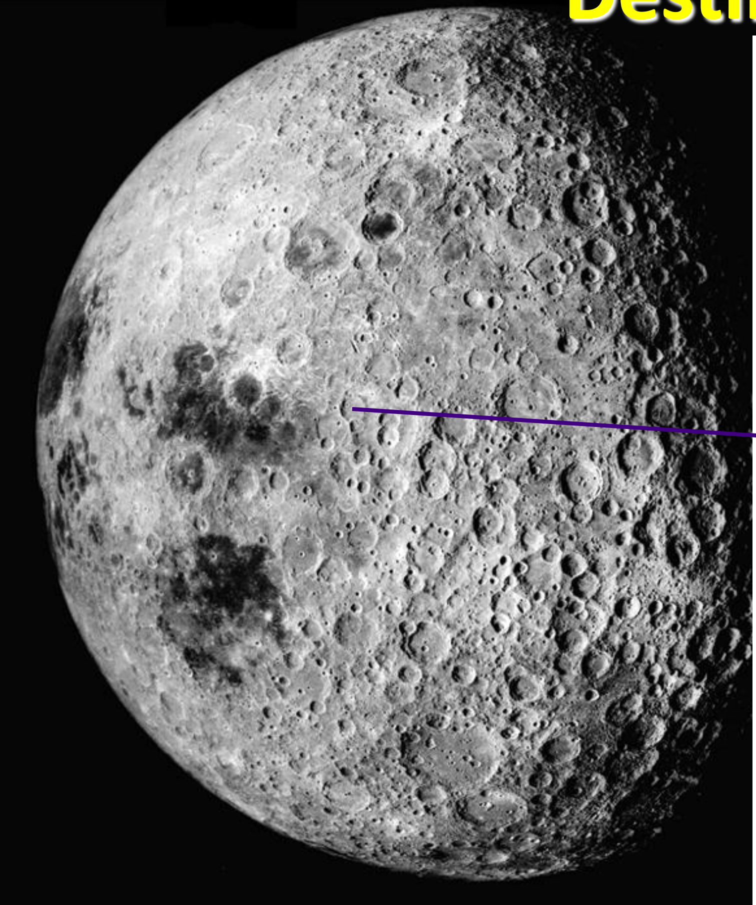
Radio Frequency Interference at MWA Site



Lunar Advantage: No Interference!



Destination: Moon!



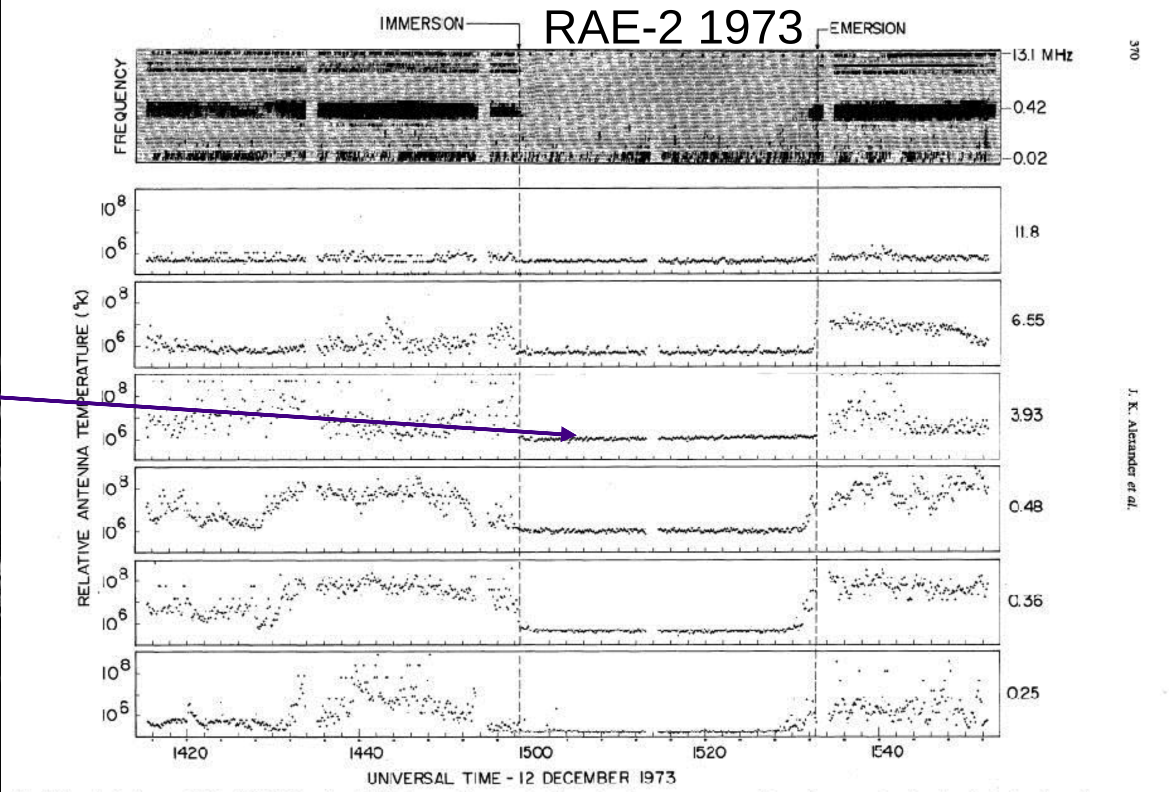
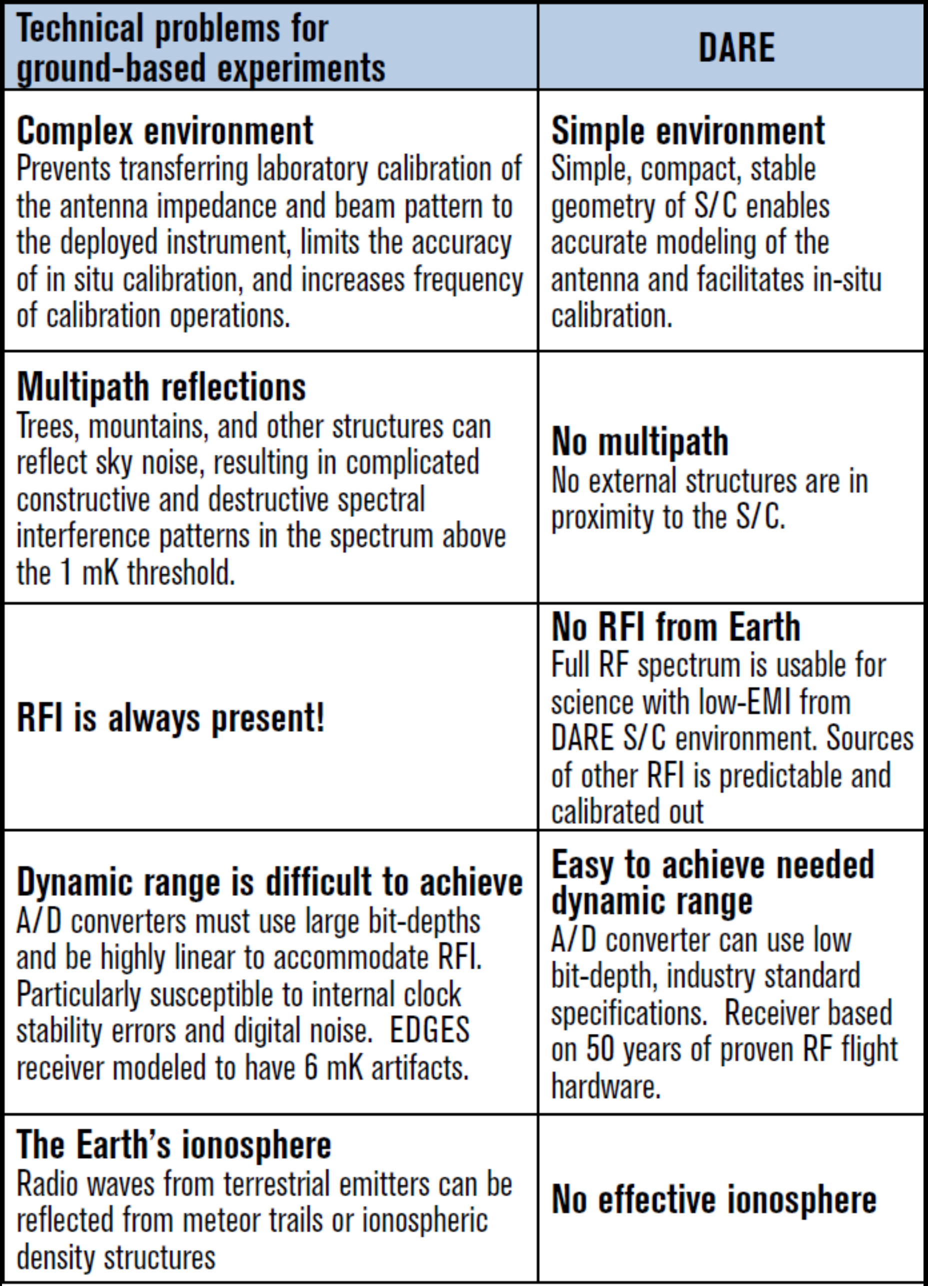


Fig. 5. Example of a lunar occultation of the Earth as observed with the upper-*V* burst receiver. The top frame is a computer-generated dynamic spectrum; the other plots display intensity vs. time variations at frequencies where terrestrial noise levels are often observed. The 80-s data gaps which occur every 20 m are at times when in-flight calibrations occur. The short noise pulses observed every 144 s at the highest frequencies during the occultation period are due to weak interference from the Ryle-Vonberg receiver local oscillator on occasions when both that receiver and the burst receiver are tuned to the same frequency

Lessons from EDGES



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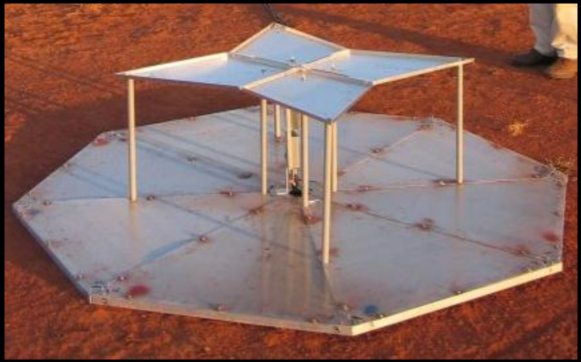
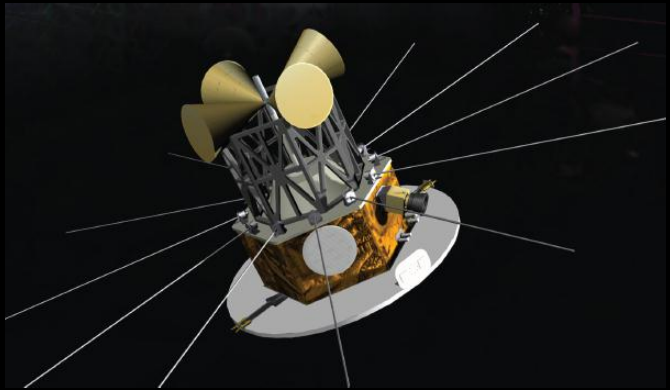
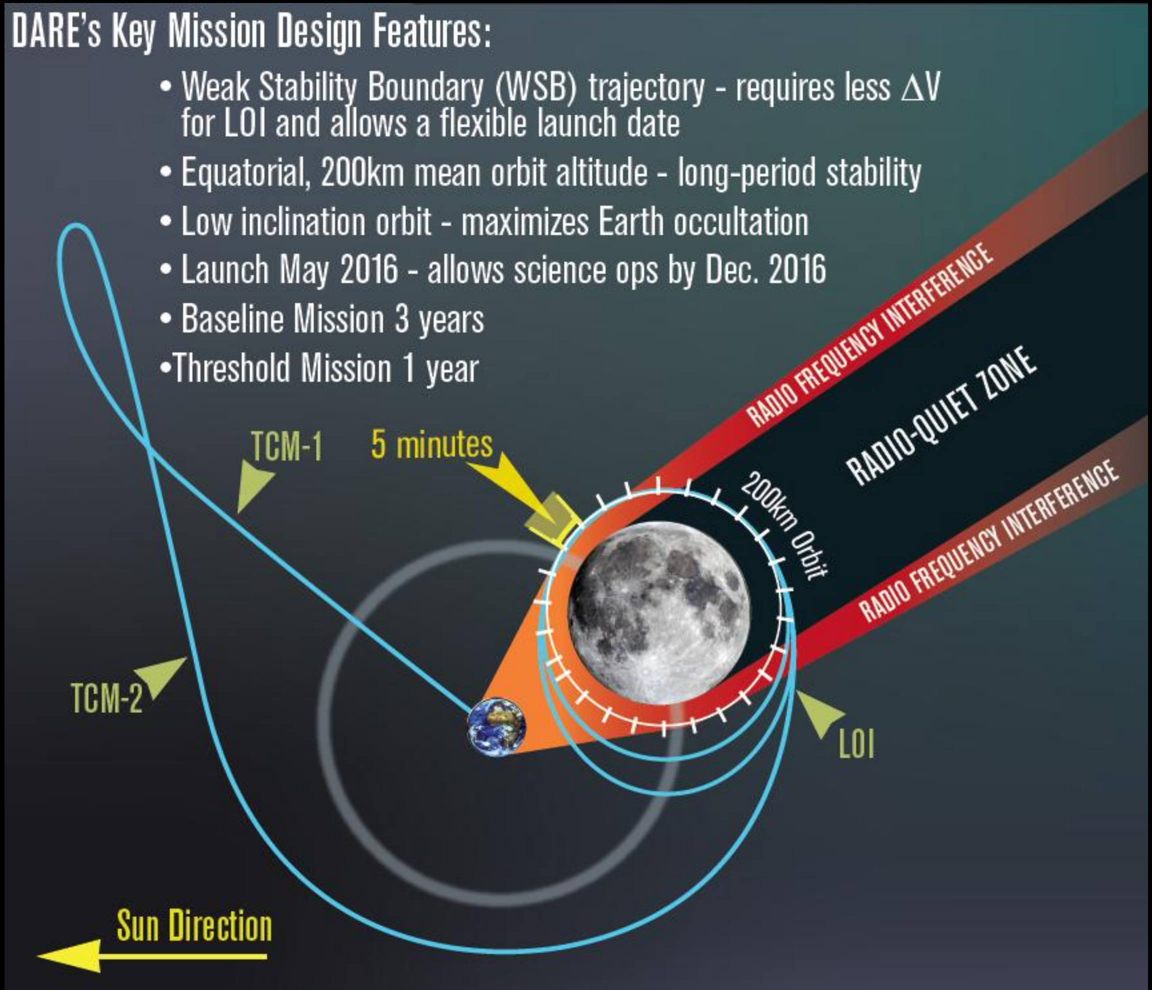




Analogous to why
COBE went
to space

DARE's Biggest Challenge: *Foregrounds*

Highest foreground (RFI) eliminated by being above lunar farside!

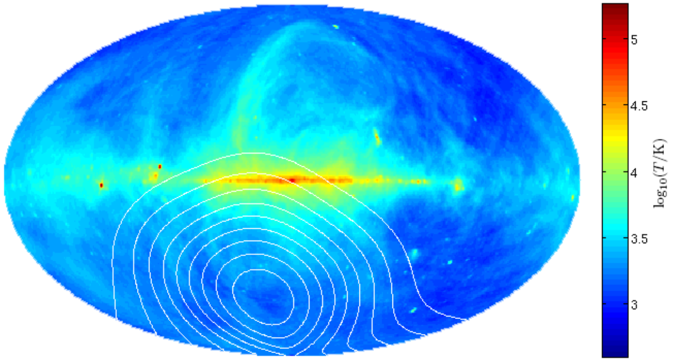


DARE's Key Mission Design Features:

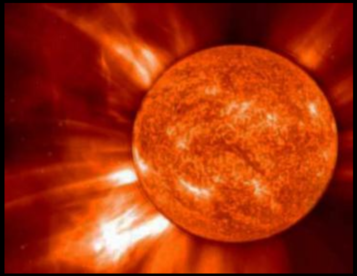
- Weak Stability Boundary (WSB) trajectory - requires less ΔV for LOI and allows a flexible launch date
- Equatorial, 200km mean orbit altitude - long-period stability
- Low inclination orbit - maximizes Earth occultation
- Launch May 2016 - allows science ops by Dec. 2016
- Baseline Mission 3 years
- Threshold Mission 1 year

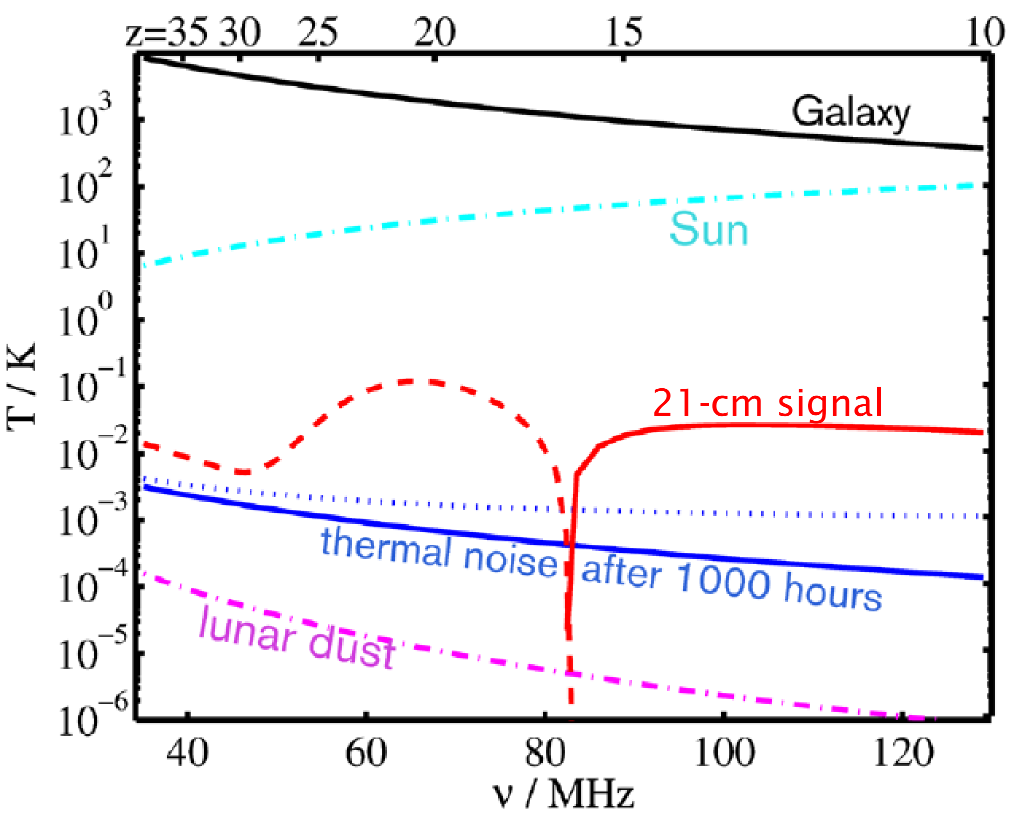
DARE's Biggest Challenge: *Foregrounds*

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

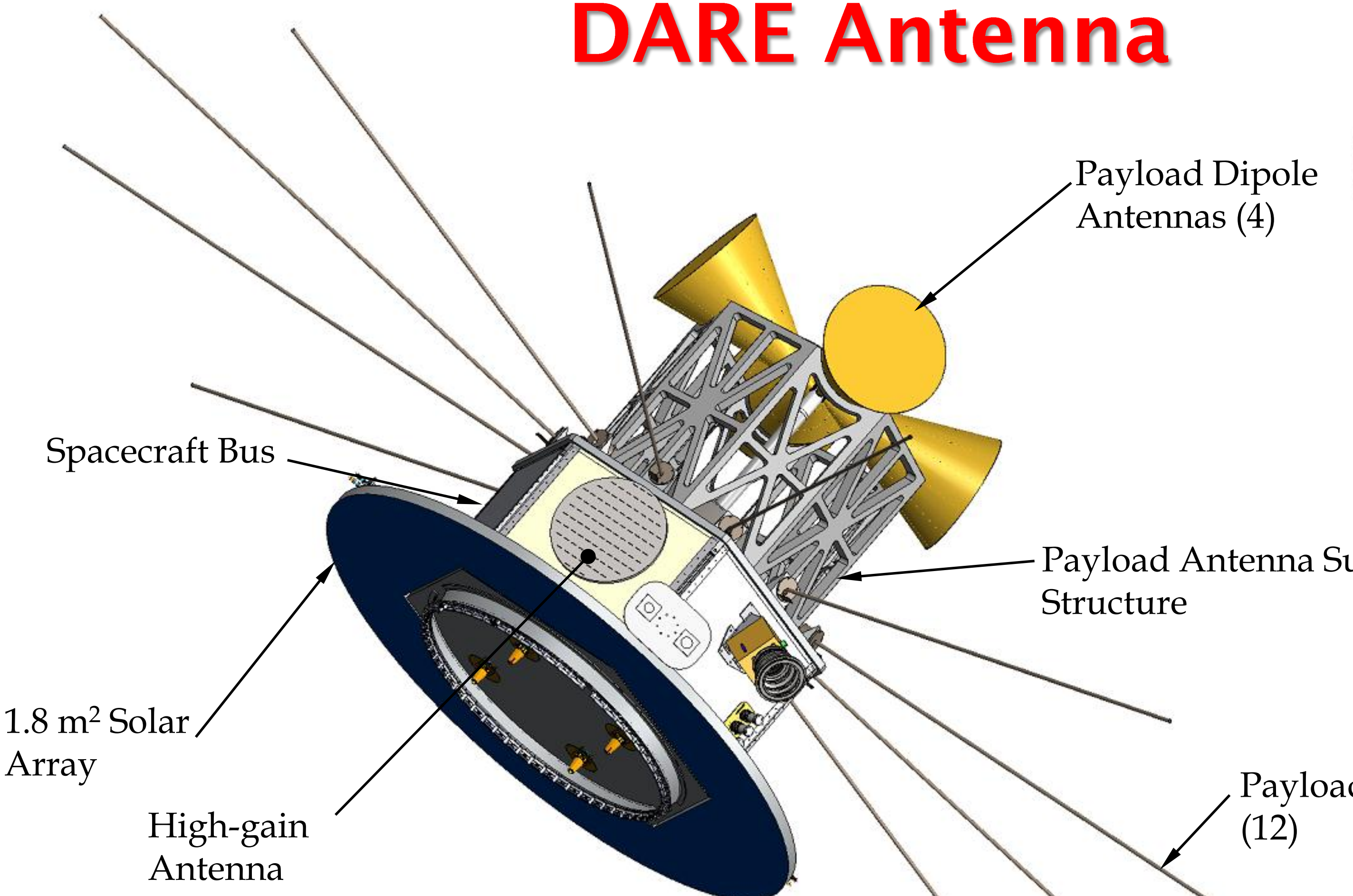


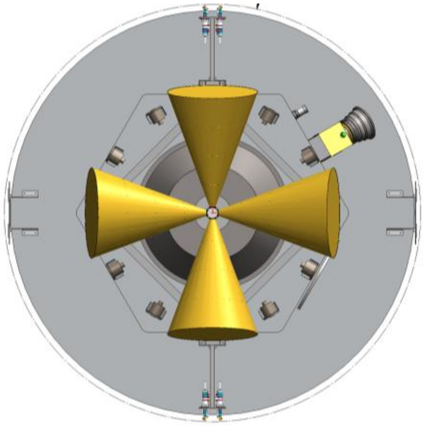
2) Solar system objects: Sun, Jupiter, Moon





DARE Antenna





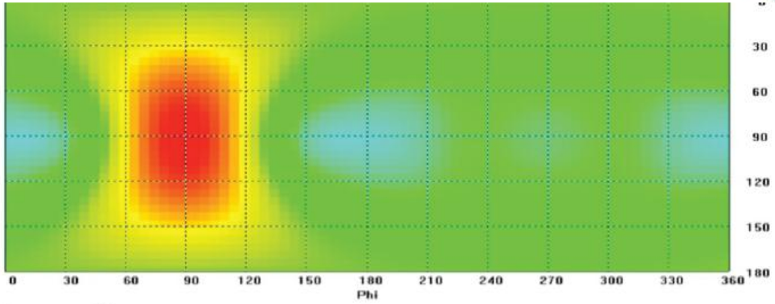
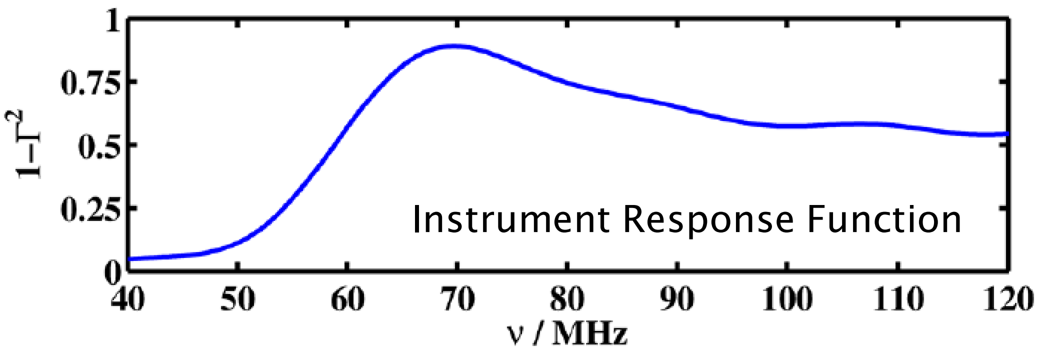
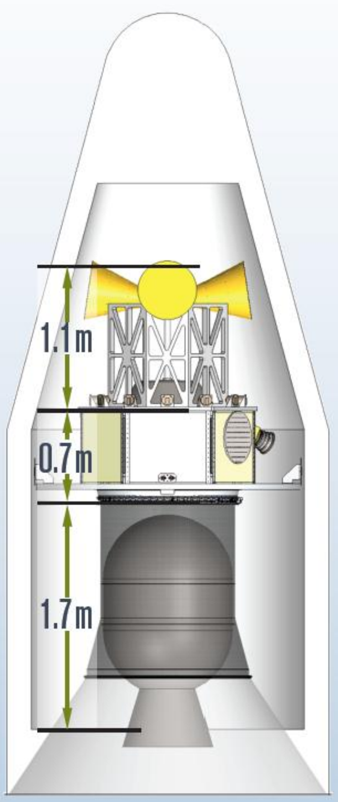


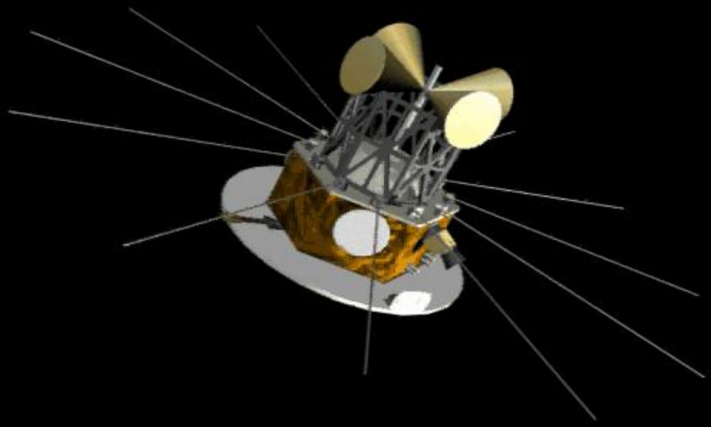
Figure E.1-2. Simulated beam pattern as a function of angle at 75 MHz. Color scale is -33.2 dBi (blue) to 6.8 dBi (red).



DARE Spacecraft



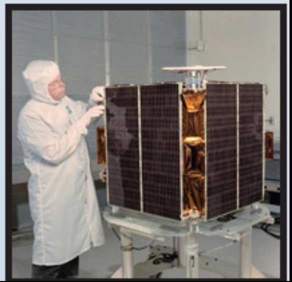
Stowed Spacecraft fits within standard 4m fairing envelope



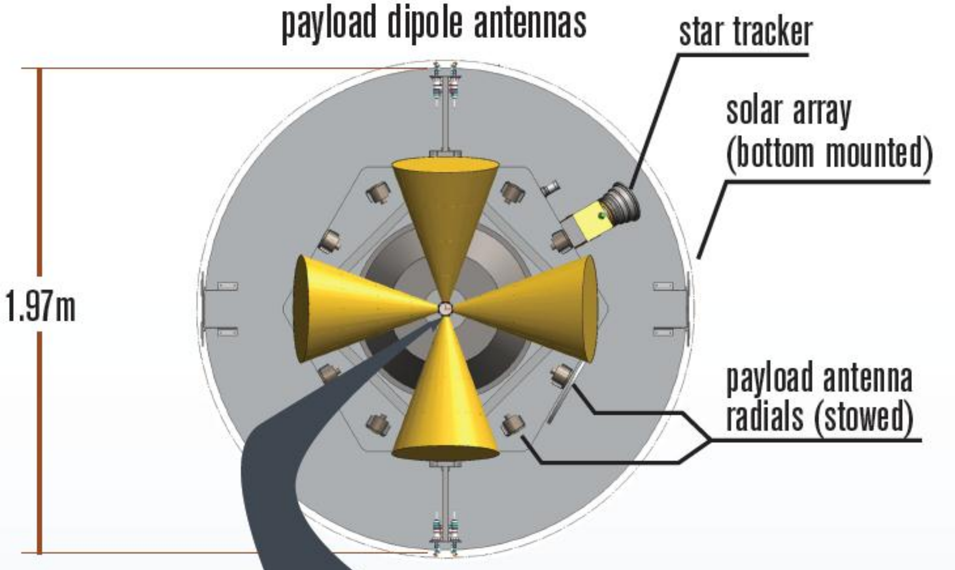
The DARE S/C, consisting of an integrated suite of flight-proven components, traces its high heritage to Kepler, Deep Impact, WISE and STPSat2. Main design features include:

- proven RF-quiet bus
- unobscured instrument antenna FOV
- simple, light-weight, & low-risk monopropellant propulsion system
- parallel integration & reduced schedule risk using modular construction
- uninterrupted science (even with missed ground contacts) using large data storage.

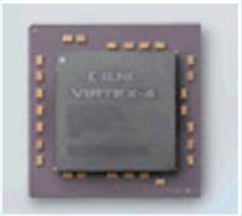
Ball has demonstrated capability in constructing RF quiet S/C as evidenced by DARPASat, which beat MIL-STD-461E standards by 44 dB. Technology advances since DARPASat will further quiet the DARE S/C by another 10 dB.



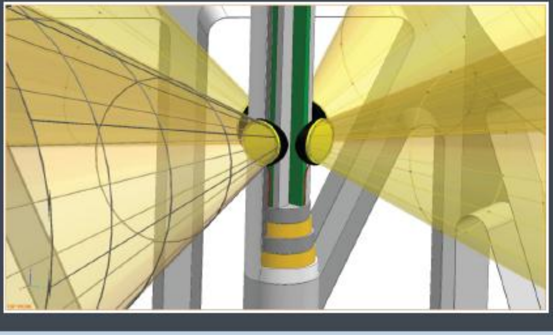
SCIENCE INSTRUMENT (top view)



digital spectrometer (on board)

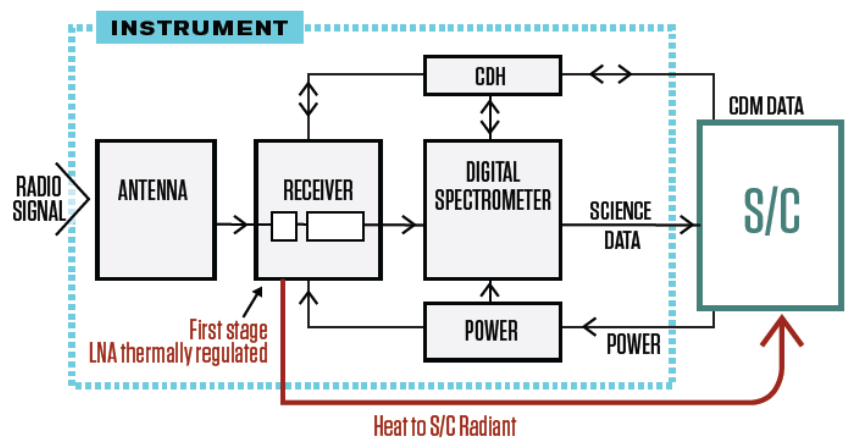


antenna and front end electronics interface

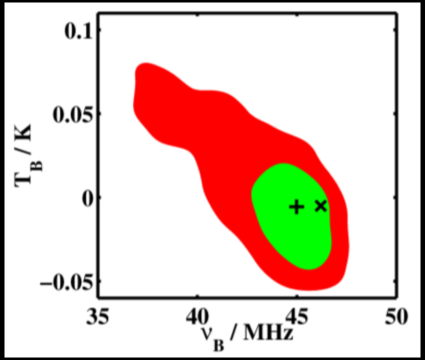


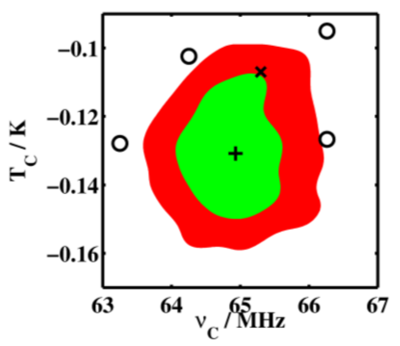
DARE carries a single, high-heritage (e.g., EDGES) Science Instrument (SI) operating at 40-120 MHz. The components of all subsystems (antenna, receiver and digital spectrometer) are currently at TRL ≥6; the integrated SI will be at TRL 6 by the end of Phase A.

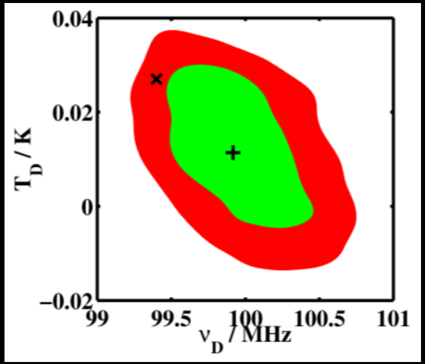
DARE Radiometer



Differential Spectral Calibration



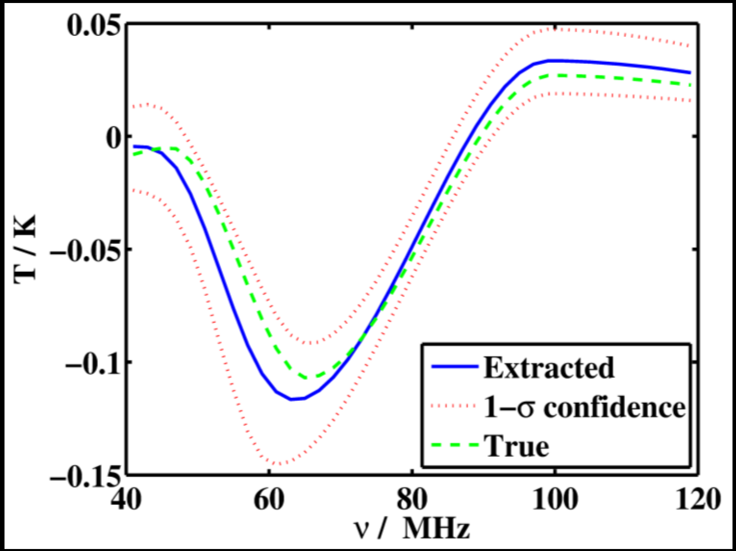




Utilize Markov Chain Monte Carlo code to fit data with model describing:

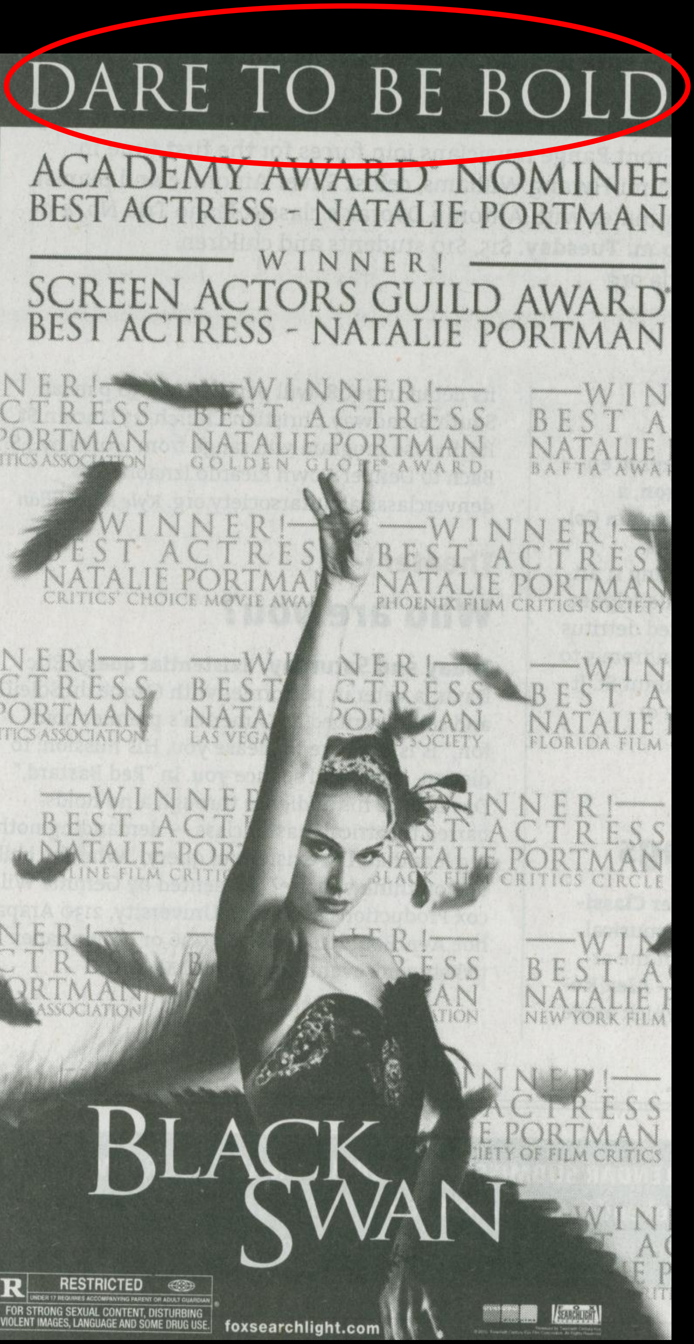
- 21-cm signal
- spatially-dependent Galaxy foregrounds
- solar system foregrounds
- instrumental response.

=> Recover maximum likelihood signal, turning points, & errors.



Turning Point		True Position	3000 hrs				1000 hrs
			lower (upper) bound	Best-fit	upper (lower) bound	% uncertainty	% uncertainty
B	z ν (MHz)	29.74 (46.20)	29.22 (47.01)	30.54 (45.03)	36.58 (37.80)	12 (10)	- -
C	z ν (MHz)	20.75 (65.30)	20.53 (65.97)	20.86 (64.99)	21.21 (63.94)	1.6 (1.6)	2.4 (2.3)
D	z ν (MHz)	13.29 (99.40)	13.13 100.55	13.21 (99.93)	13.29 (99.37)	0.6 (0.6)	1.1 (1.0)

Hi...
If you are in a bad mood,
listen to this song.
It always gets me in a good
mood.



Dark Ages Radio Explorer (DARE)

- DARE is designed to address:
    - When did the First Stars ignite?
    - When did the first accreting Black Holes turn on?
    - When did Reionization begin?
- DARE will accomplish this by
    - Constructing first sky-averaged spectrum of redshifted 21-cm signal at $11<z<35$.
    - Flying spacecraft in lunar orbit & collecting data above lunar farside - only proven radio-quiet zone in inner solar system.
    - Using biconical dipole antennas with smooth response function & Markov Chain Monte Carlo method to recover spectral *turning points* in the presence of bright foregrounds.
    - Using high heritage spacecraft bus (WISE) & technologies/techniques from EDGES.