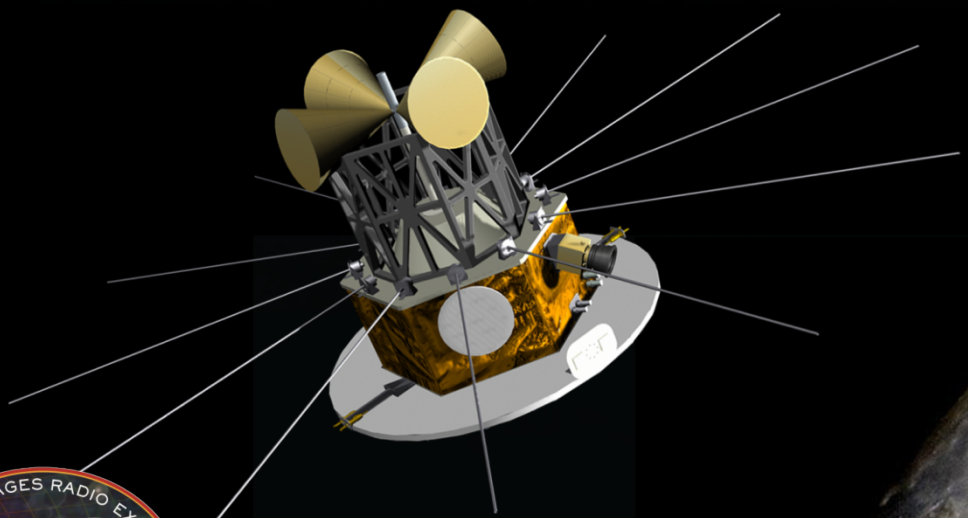
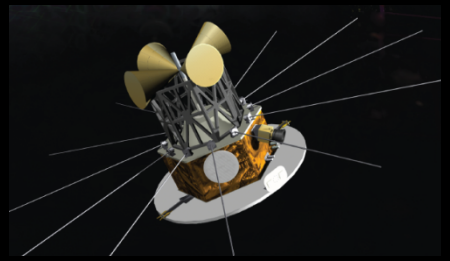
DARE

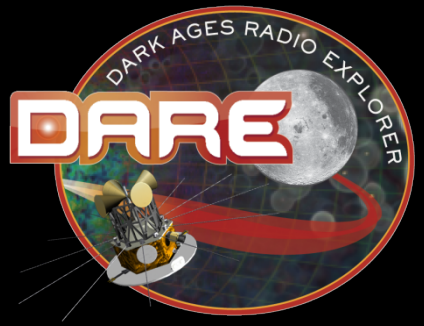
DARK AGES RADIO EXPLORER

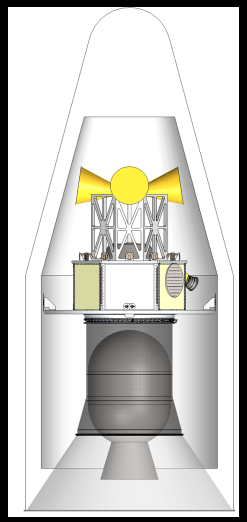
Jack Burns[1,2] and Joe Lazio[2,3]
[1]University of Colorado Boulder
[2]NASA Lunar Science Institute
[3]Jet Propulsion Lab (JPL)



Building New Worlds, New Horizons: New Science from Submillimeter to Meter Wavelenths
Santa Fe, NM
March 7, 2011







DARE PROJECT TEAM

Principal Investigator:
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Project Manager:
Daniel Andrews, ARC

Deputy Project Manager:
Jill Bauman, ARC

Spacecraft PM:
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Instrument Manager:
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Collaborator: Michael Bicay, ARC

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Richard Bradley, Natl. Radio Astronomy Obsv.

Christopher Carilli, Natl. Radio Astronomy Obsv.

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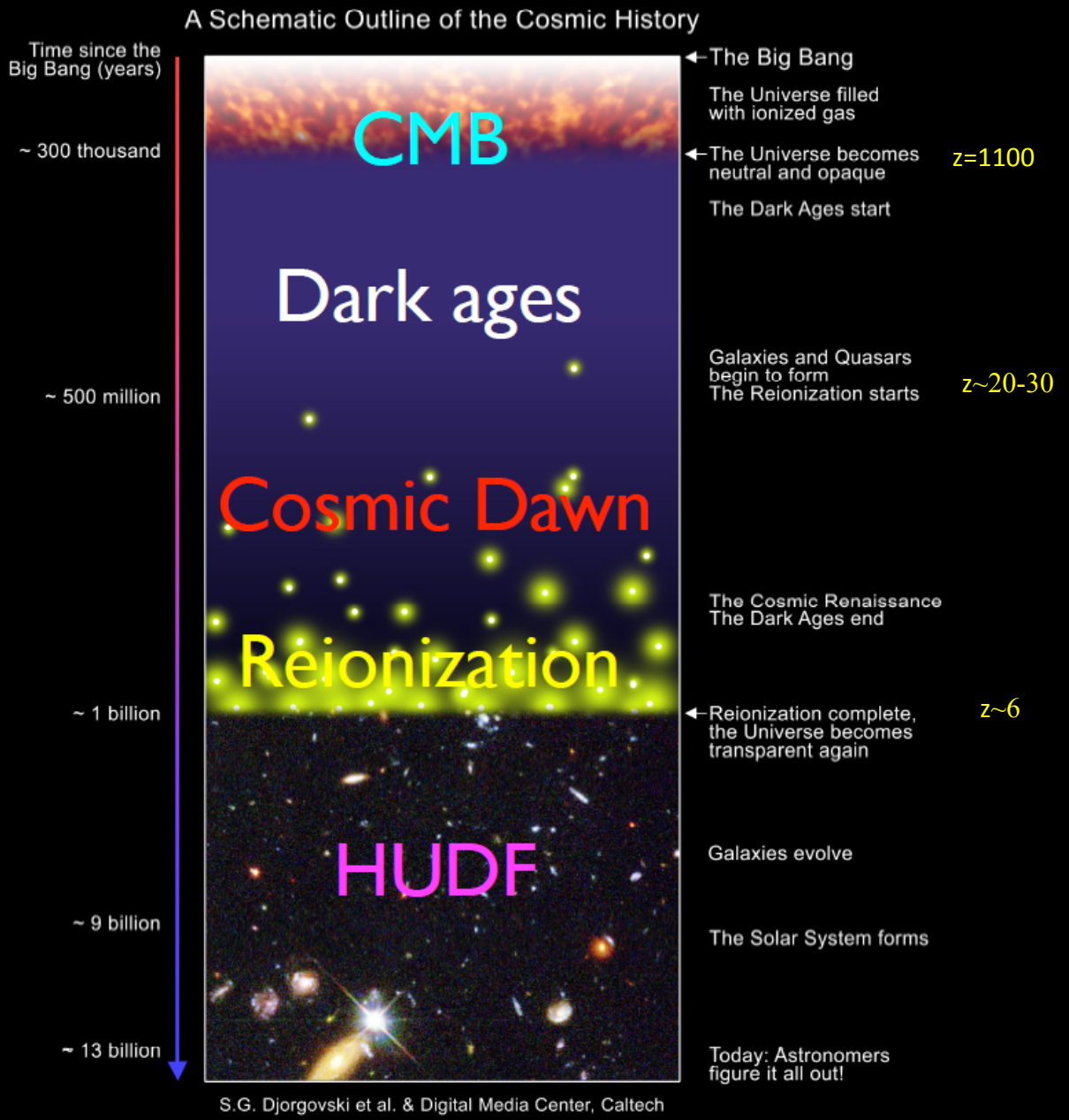
Geraint Harker, Univ. of Colorado

Abraham Loeb, Harvard University

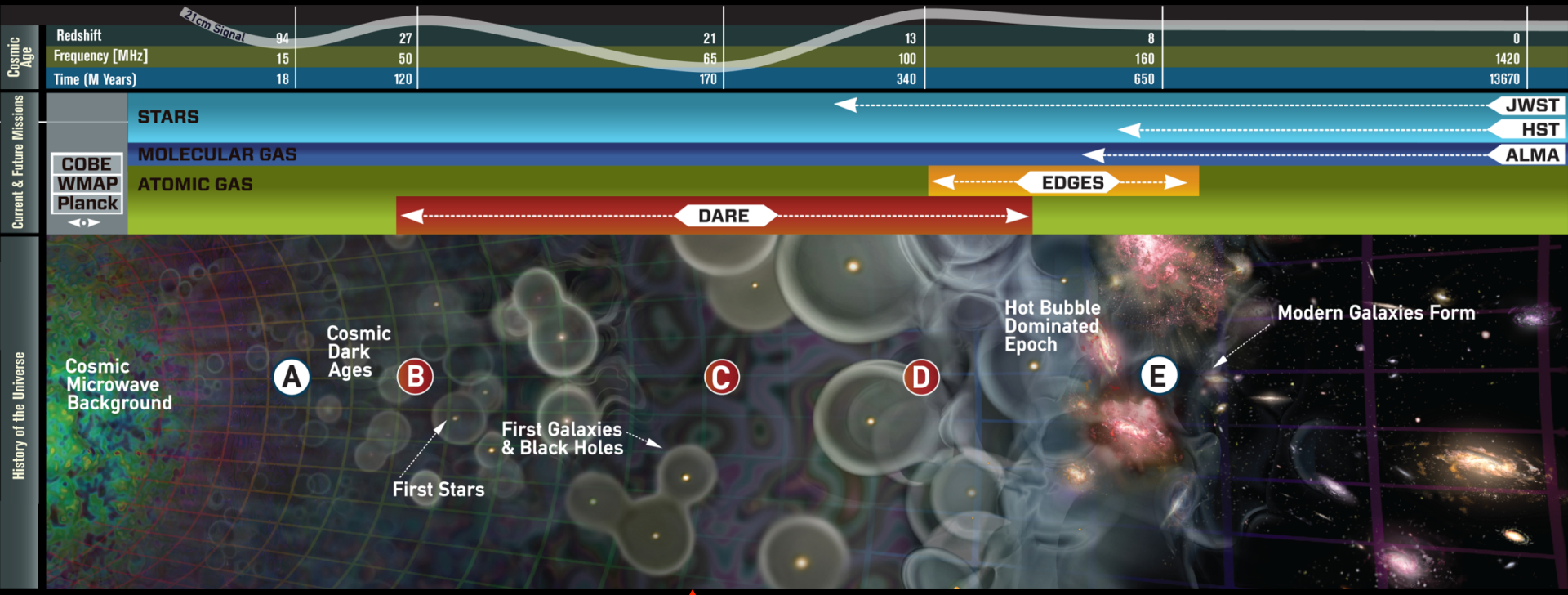
Jonathan Pritchard, Harvard-Smithsonian Center for Astrophysics

PARTNERSHIPS

The First Billion Years

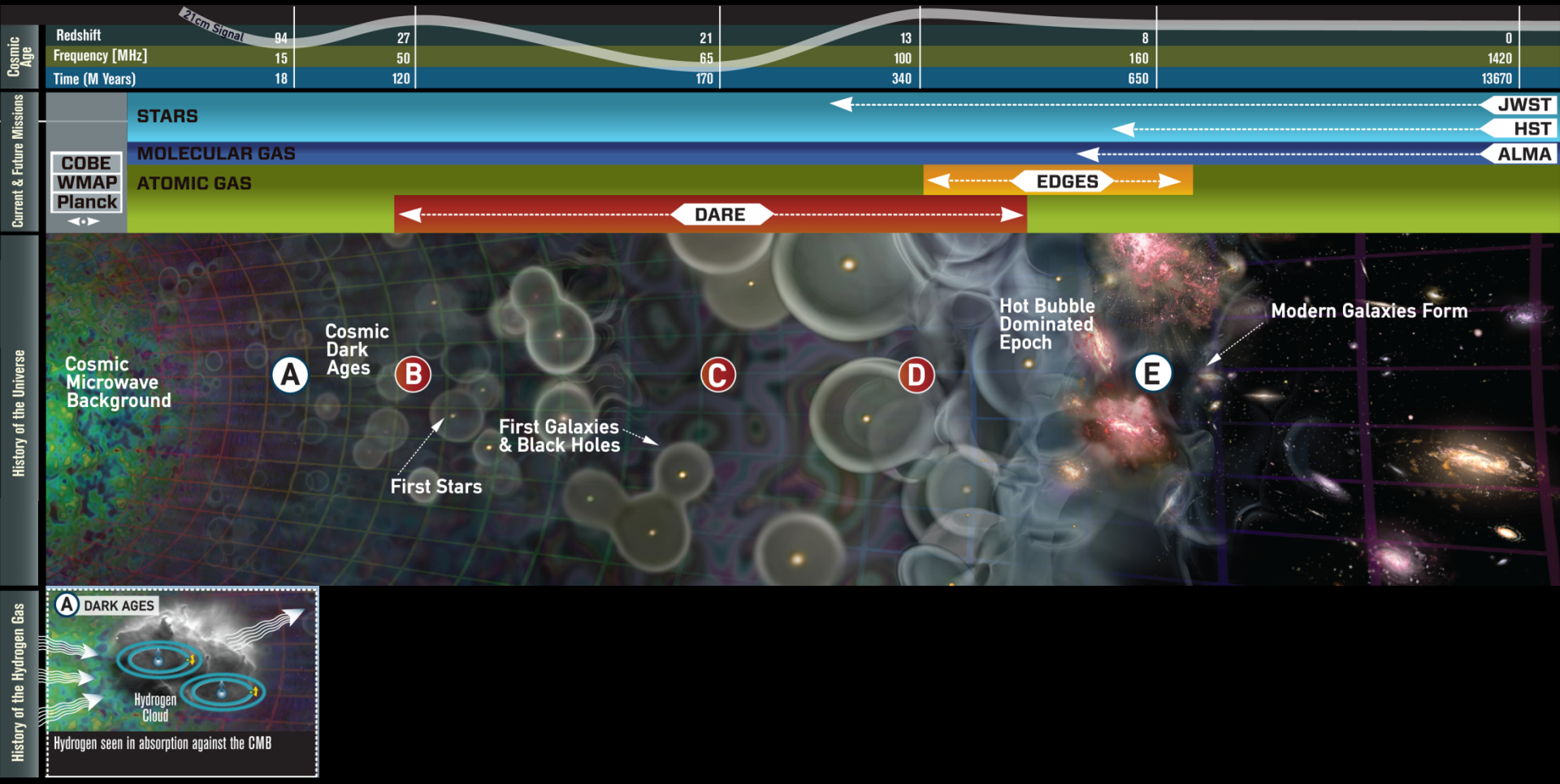


The History of Hydrogen



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

The History of Hydrogen



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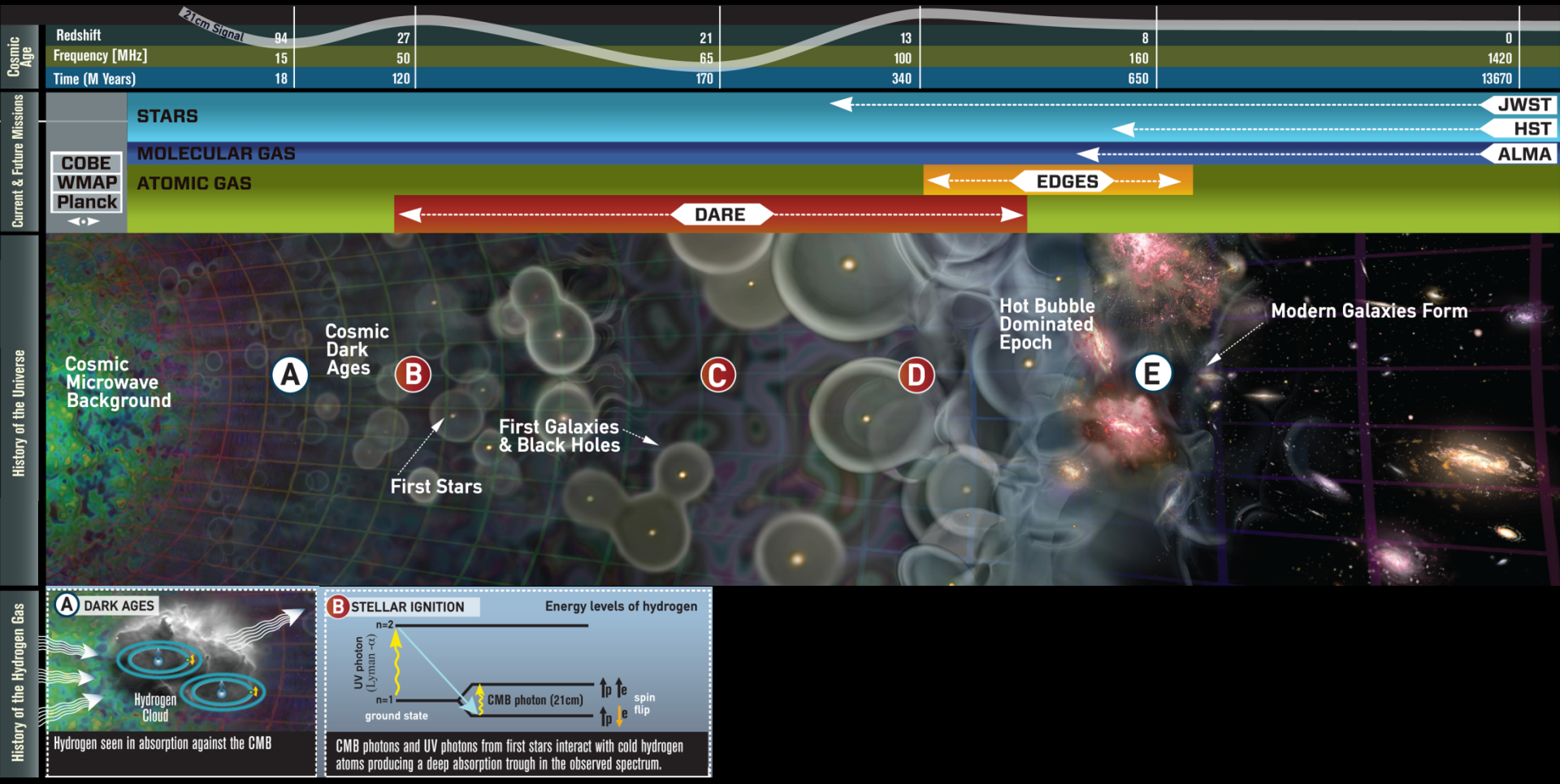
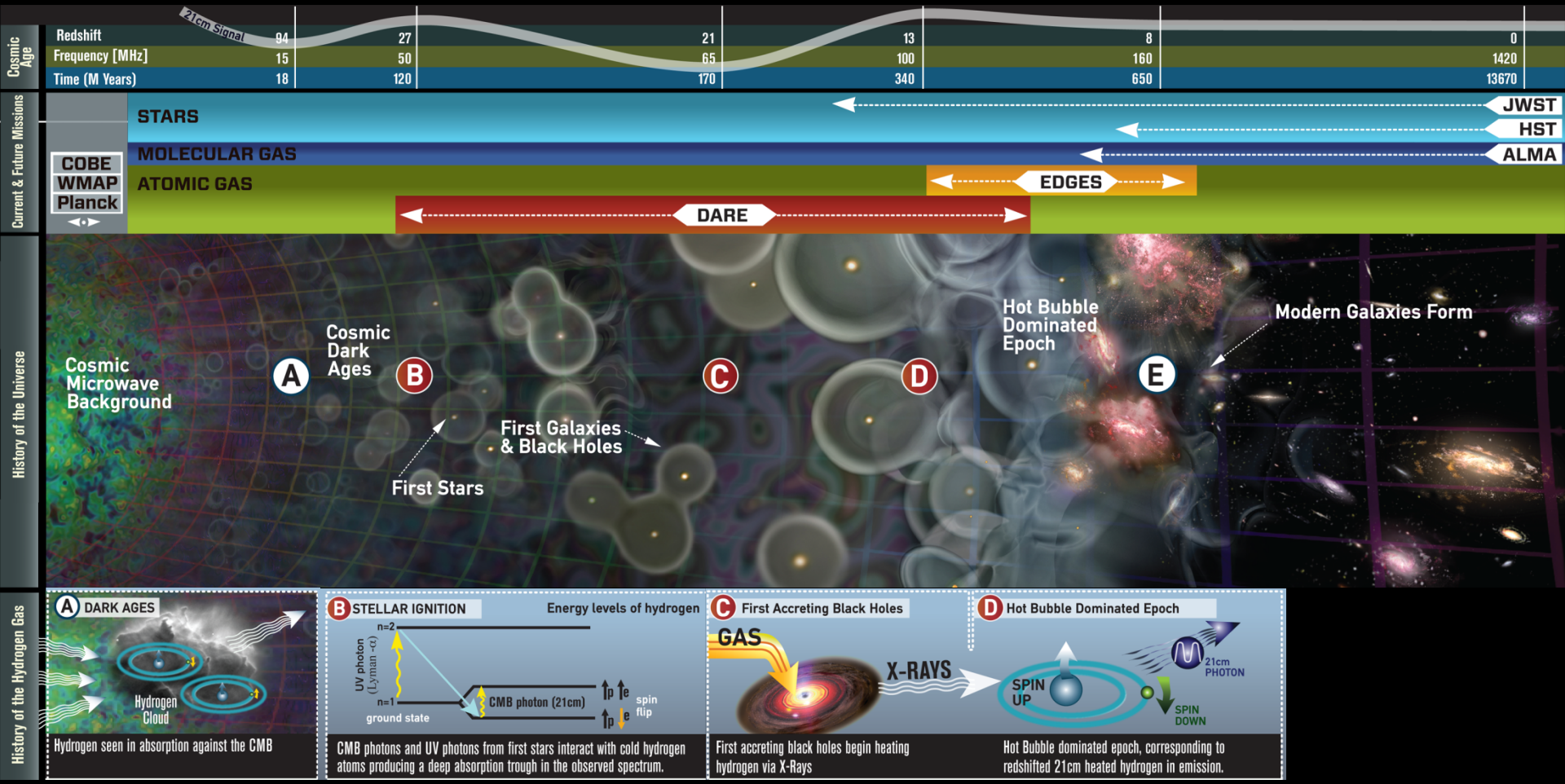
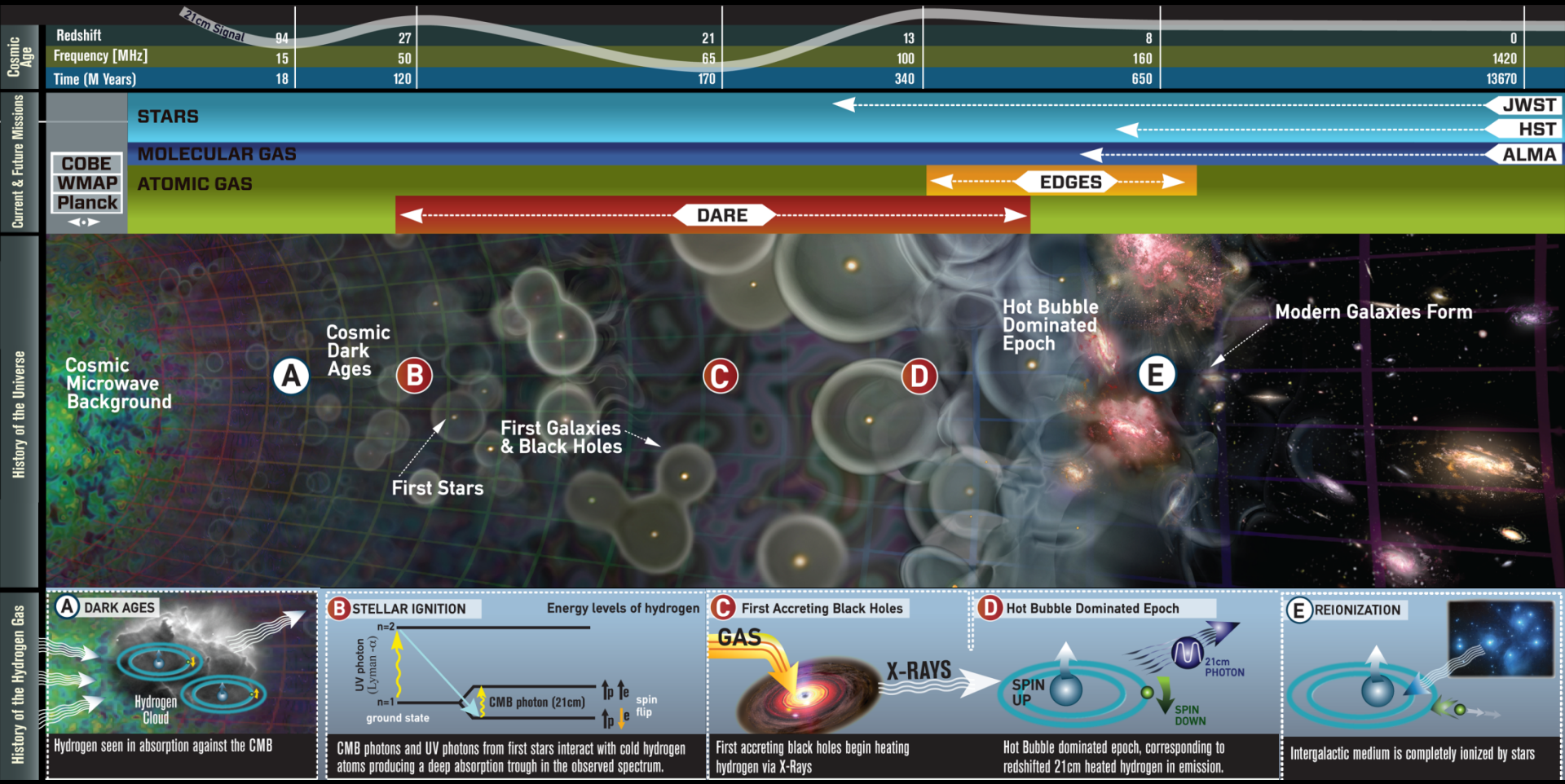


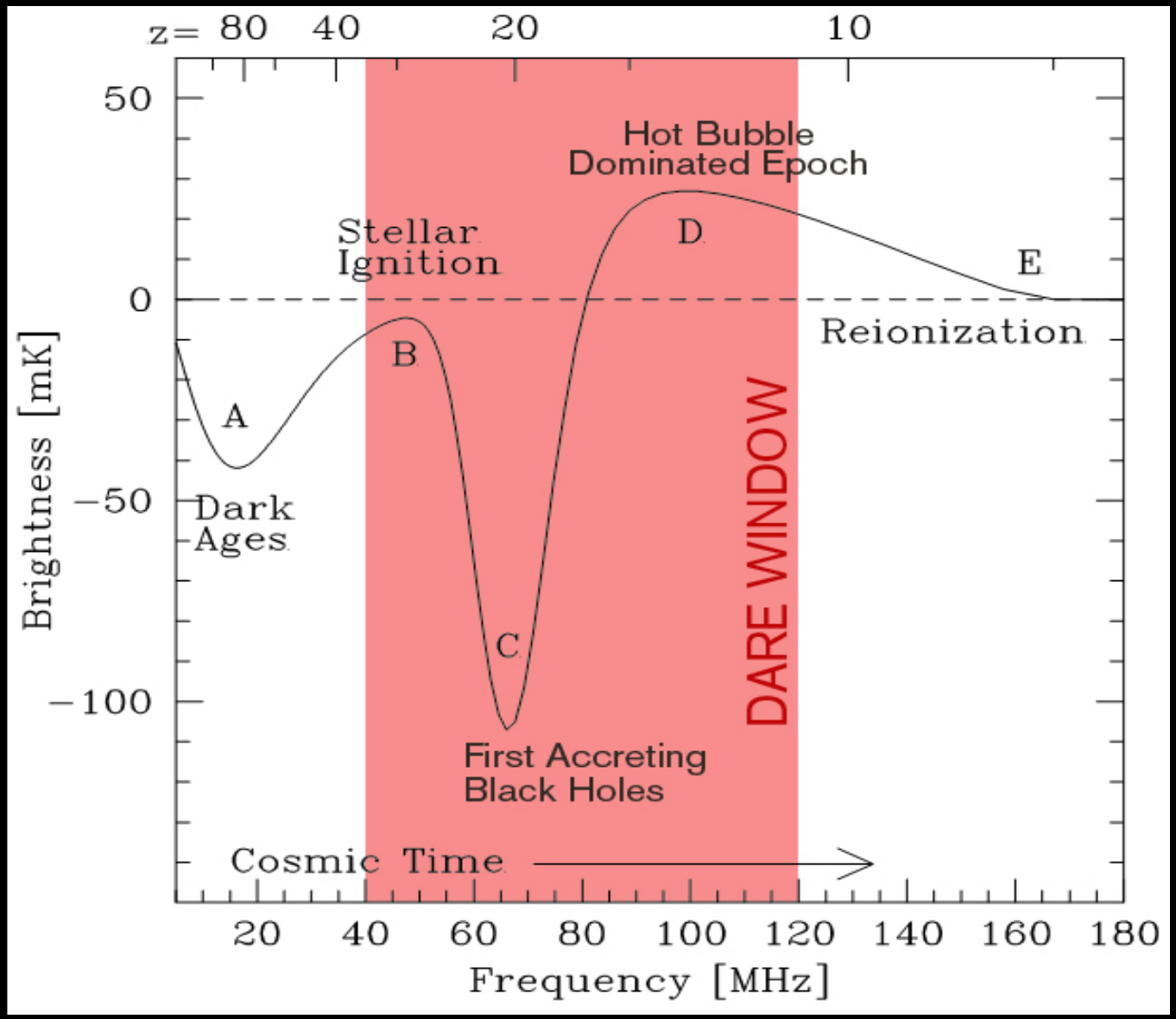
The History of Hydrogen



The History of Hydrogen



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



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

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DARK AGES RADIO EXPLORER

The Science of DARE

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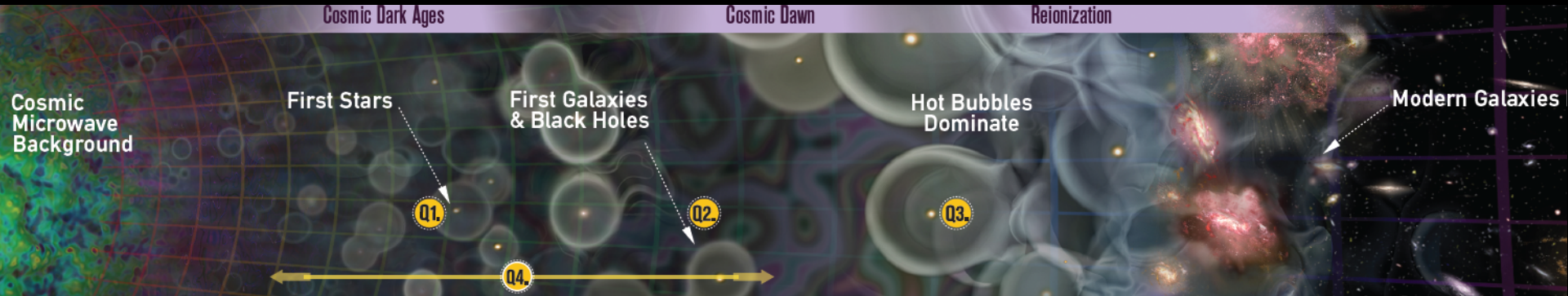
DARK AGES RADIO EXPLORER

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?

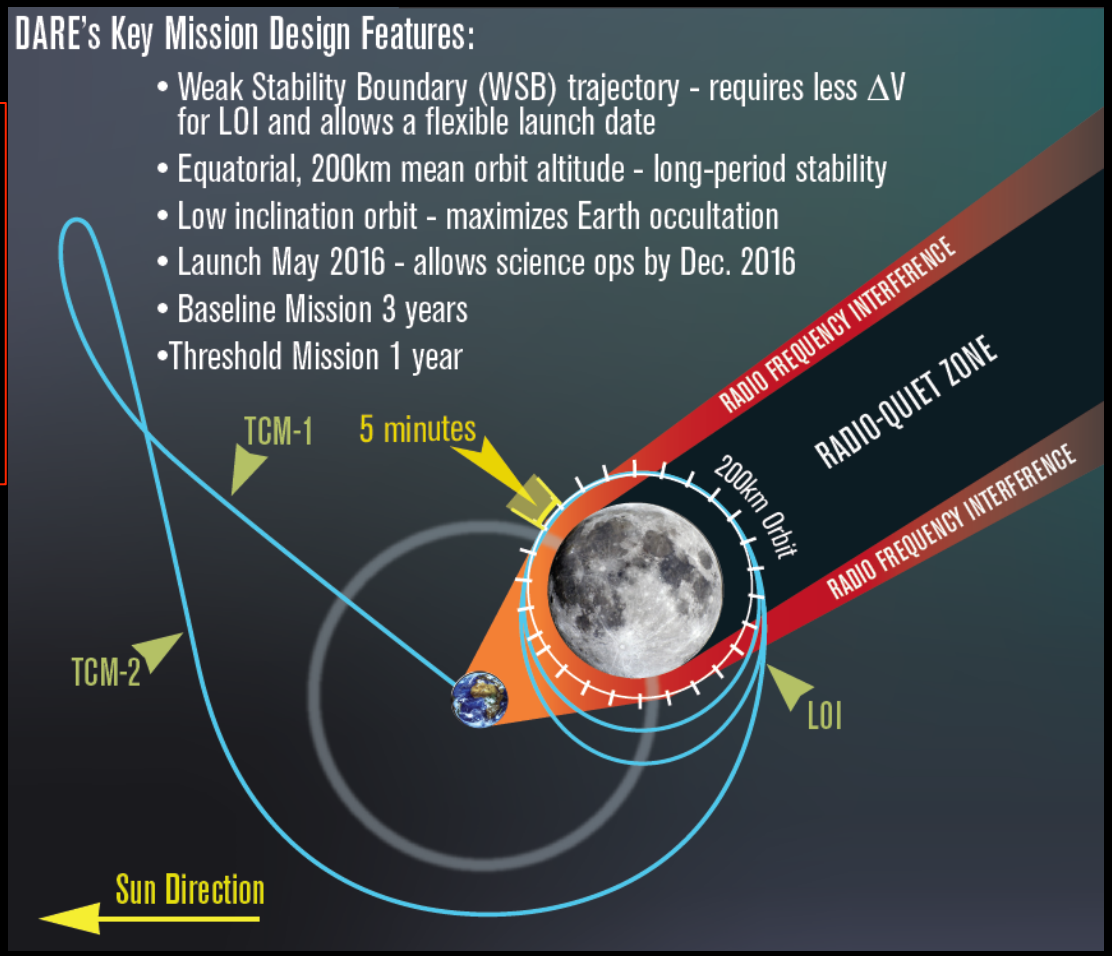


DARE's Biggest Challenge: *Foregrounds*

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

EDGES RFI Experience on Earth:

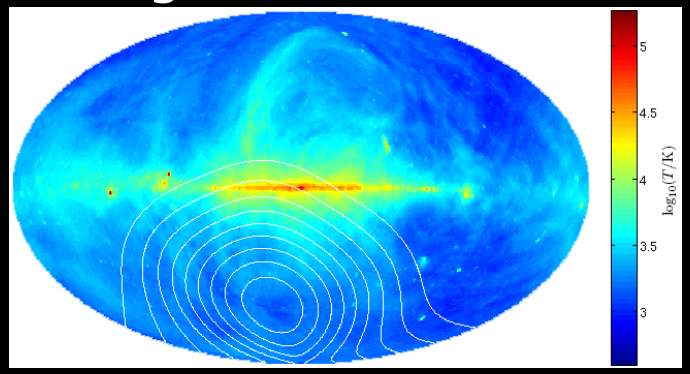
$10^{9\text{-}10}$ dynamic range difficult =>A/D converters need high bit-depths & be highly linear. Susceptible to internal clock stability errors & digital noise.



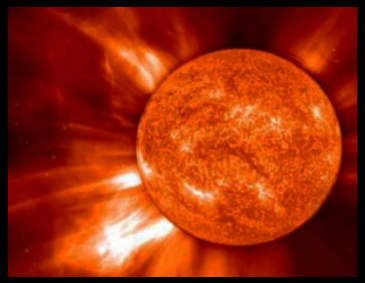
Analogous to why COBE went to space

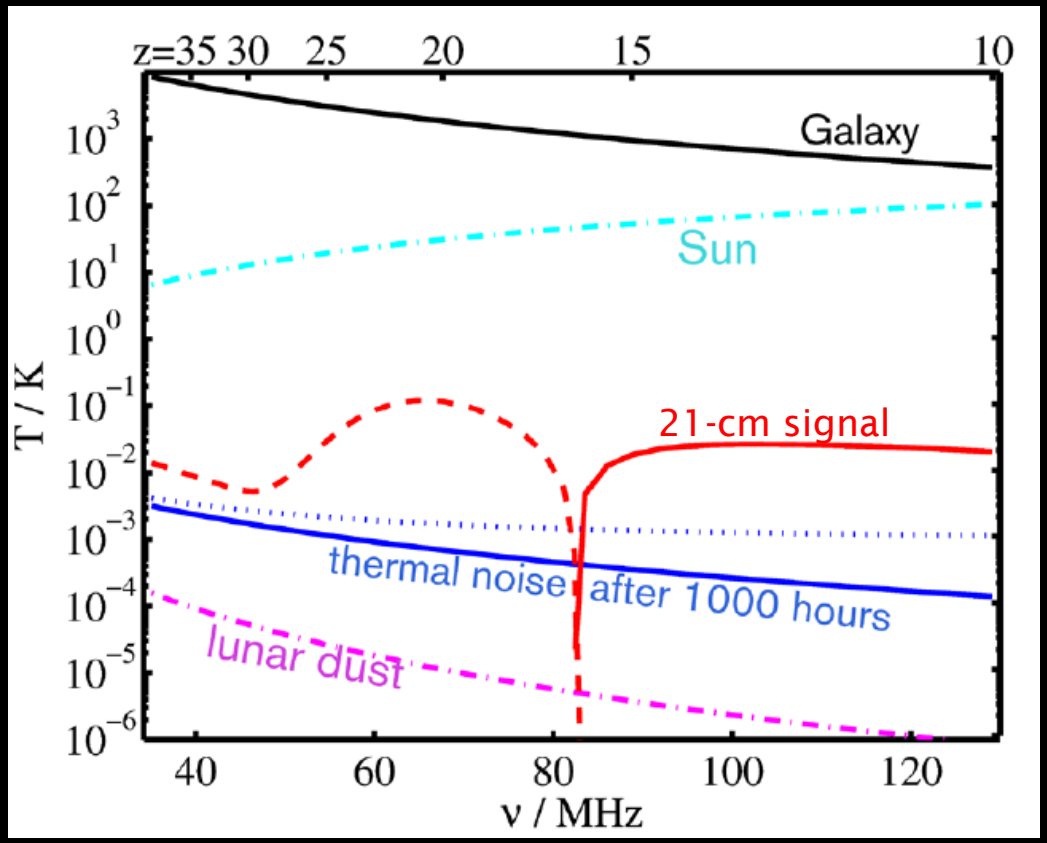
DARE's Biggest Challenge: *Foregrounds*

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

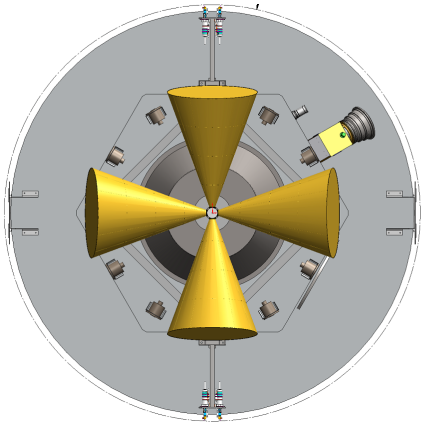


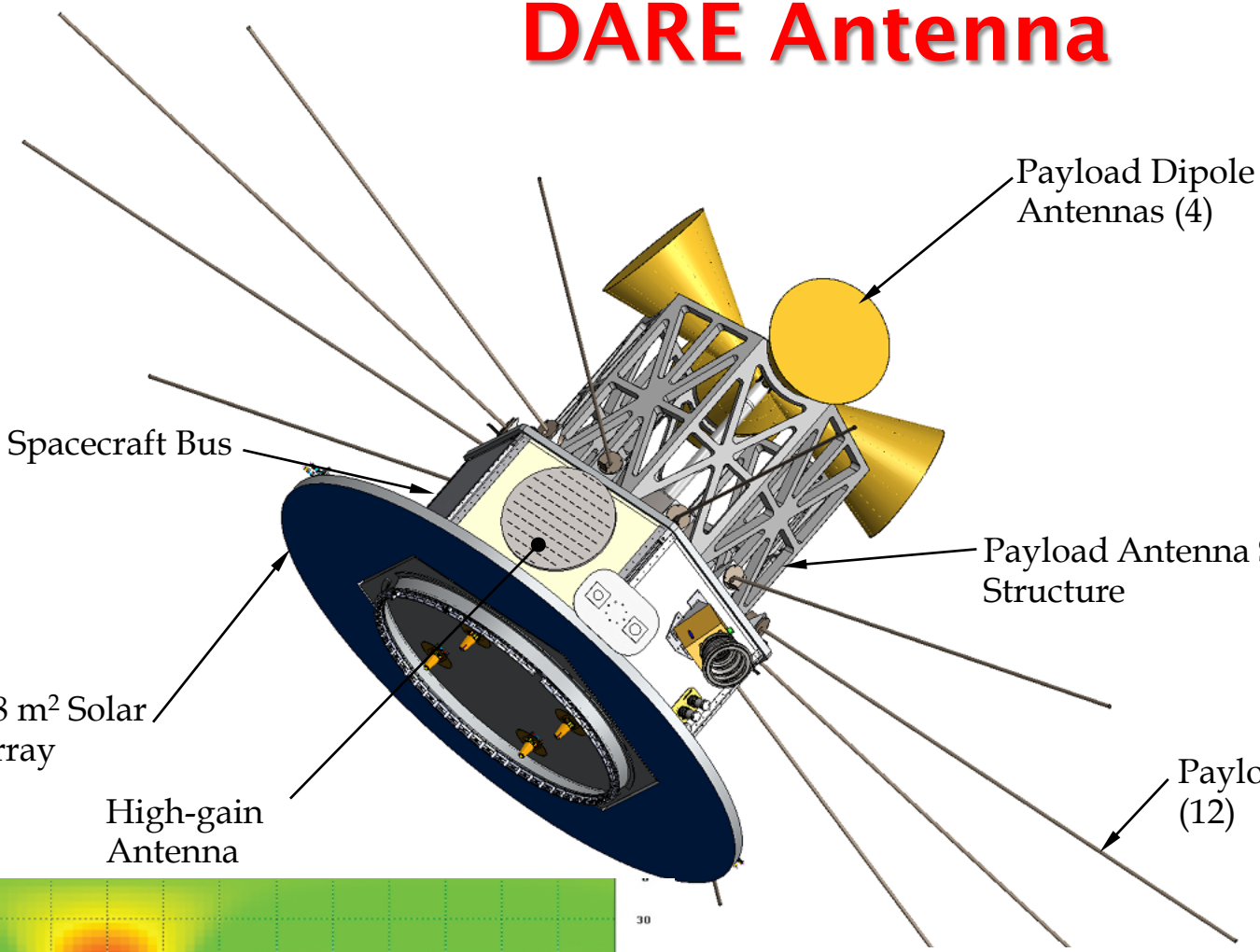
2) Solar system objects: Sun, Jupiter, Moon





DARE Antenna





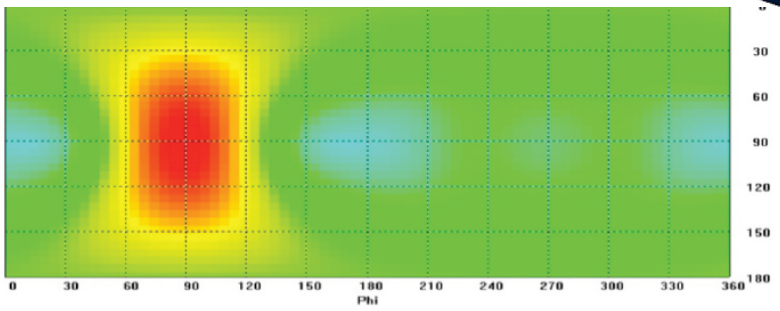
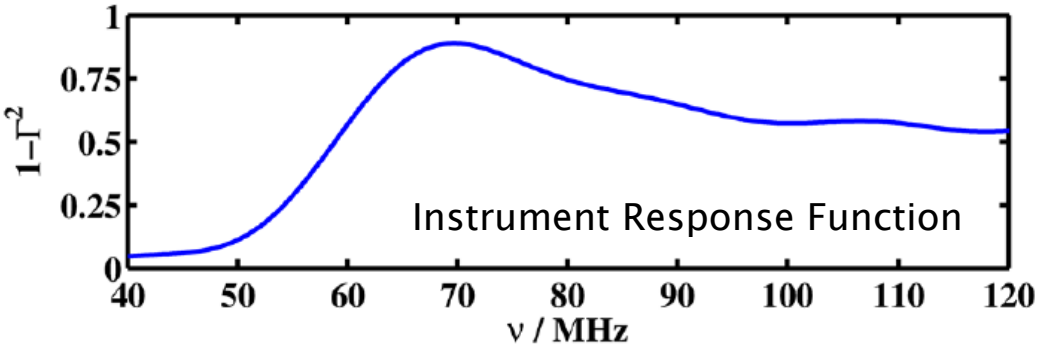


Figure E.1-2. Simulated beam pattern as a function of angle at 75 MHz. Color scale is -33.2 dBi (blue) to 6.8 dBi (red).



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DARE Spacecraft

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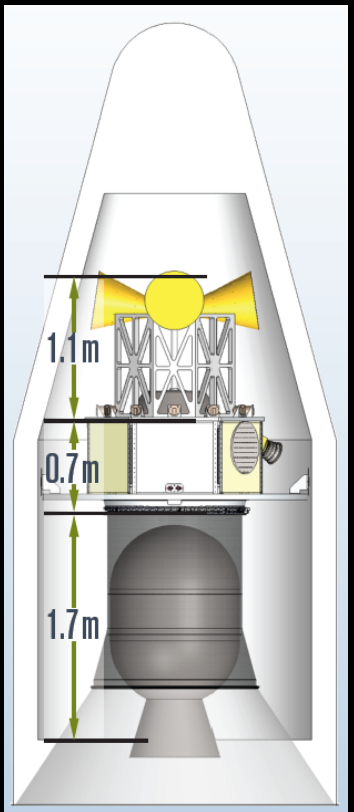
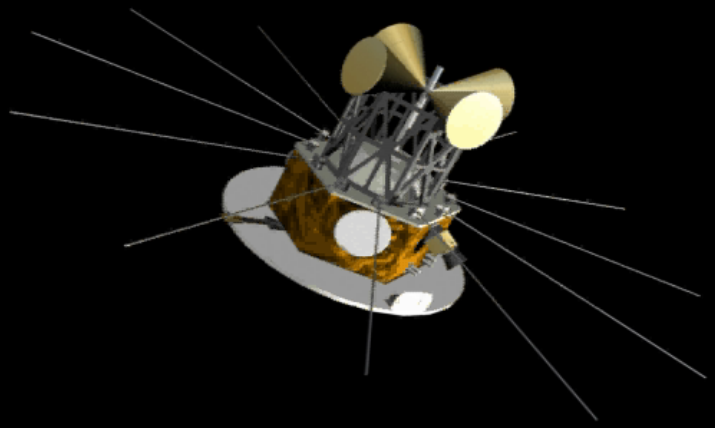


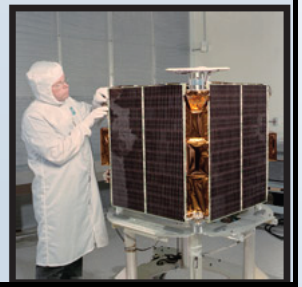
Stowed Spacecraft fits within standard 4m fairing envelope



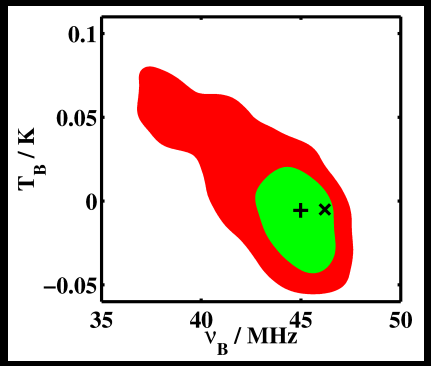
The DARE S/C, consisting of an integrated suite of flight-proven components, traces its high heritage to Kepler, Deep Impact, WISE and STPSat2. Main design features include:

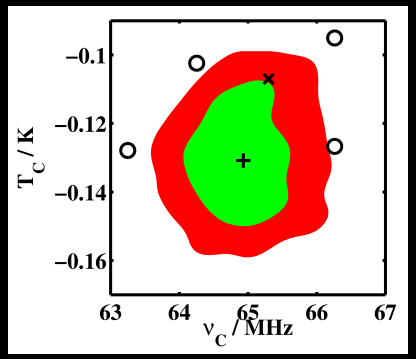
- proven RF-quiet bus
- unobscured instrument antenna FOV
- simple, light-weight, & low-risk monopropellant propulsion system
- parallel integration & reduced schedule risk using modular construction
- uninterrupted science (even with missed ground contacts) using large data storage.

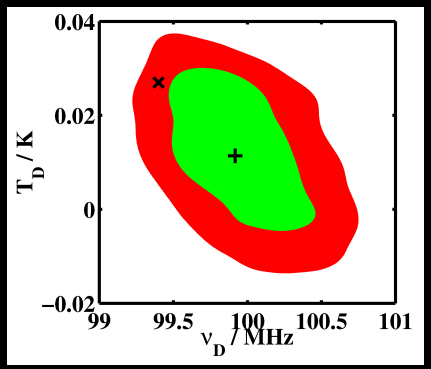
Ball has demonstrated capability in constructing RF quiet S/C as evidenced by DARPASat, which beat MIL-STD-461E standards by 44 dB. Technology advances since DARPASat will further quiet the DARE S/C by another 10 dB.



Differential Spectral Calibration



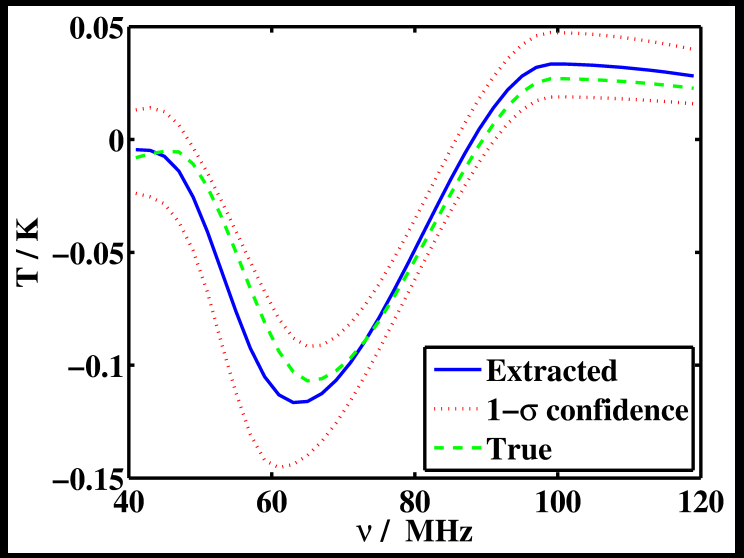




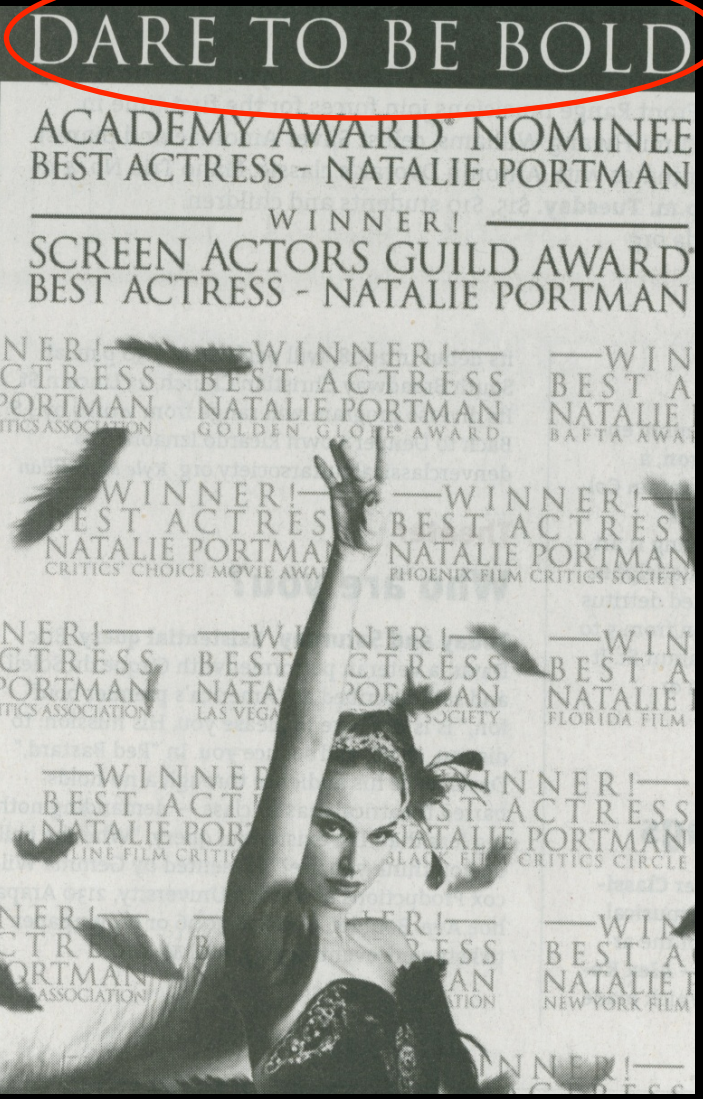
Utilize Markov Chain Monte Carlo code to fit data with model describing:

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

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

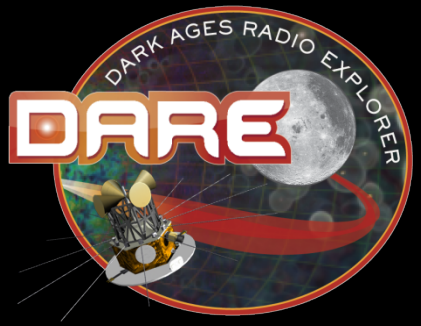


Turning Point		True Position	3000 hrs				1000 hrs
			lower (upper) bound	Best-fit	upper (lower) bound	% uncer-tainty	% un-certainty
B	z ν (MHz)	29.74 (46.20)	29.22 (47.01)	30.54 (45.03)	36.58 (37.80)	12 (10)	- -
C	z ν (MHz)	20.75 (65.30)	20.53 (65.97)	20.86 (64.99)	21.21 (63.94)	1.6 (1.6)	2.4 (2.3)
D	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)

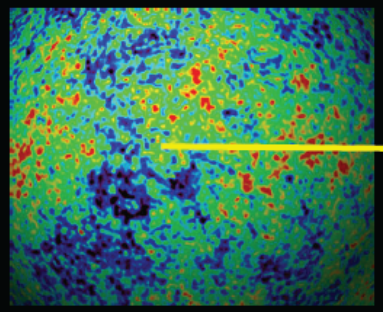


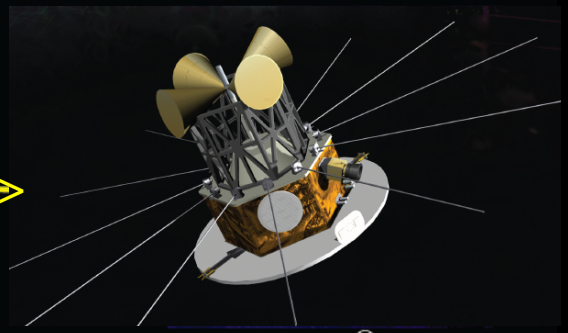
Dark Ages Radio Explorer (DARE)

- 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.



The 21-cm Line in Cosmology





T_γ T_S T_b

T_k

$z = 13$

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

$z = 0$

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

CMB acts as back light

Neutral gas imprints signal

Redshifted signal detected

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

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

neutral fraction

baryon density

spin temperature

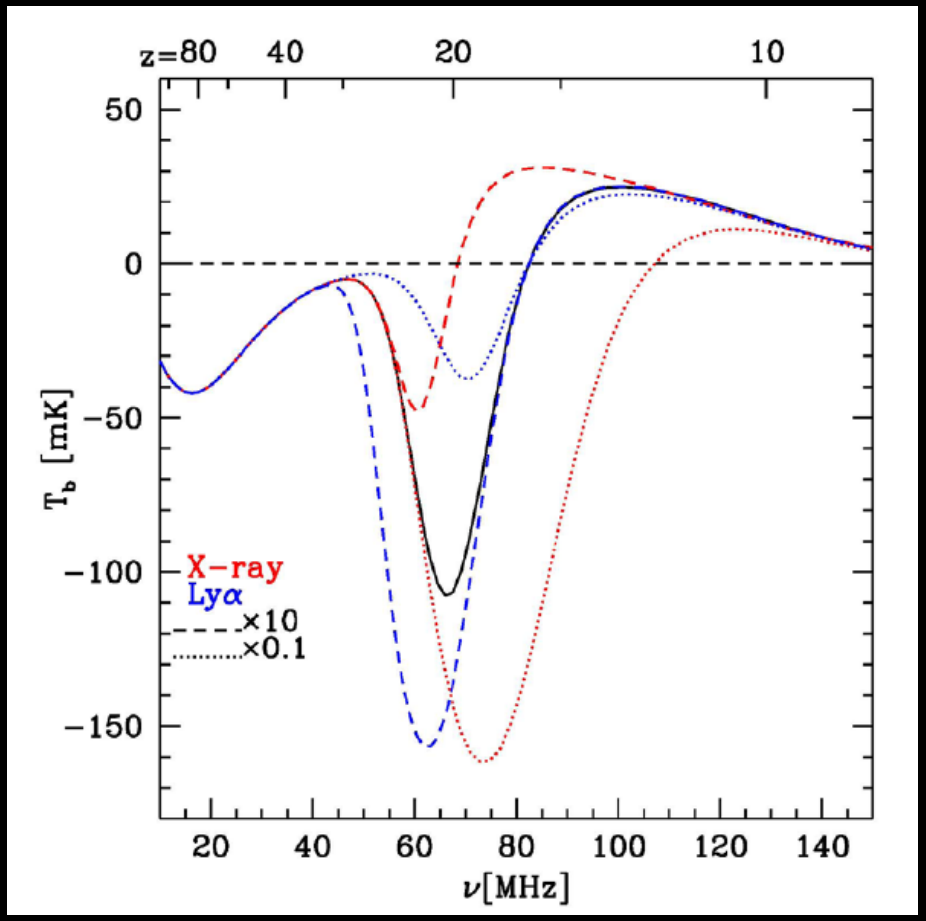
peculiar velocities

spin temperature set by different mechanisms:

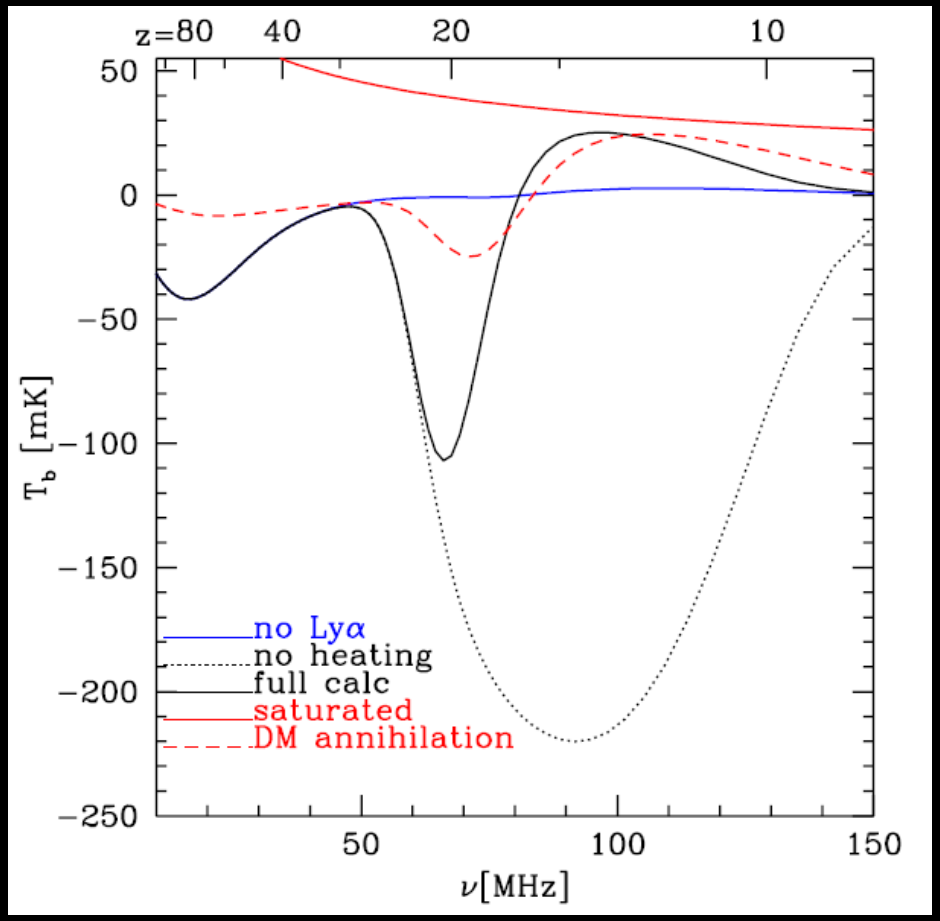
Radiative transitions (CMB)
Collisions
Wouthysen-Field effect

Adapted from J. Pritchard

But, what about other scenarios?



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



Additional physics