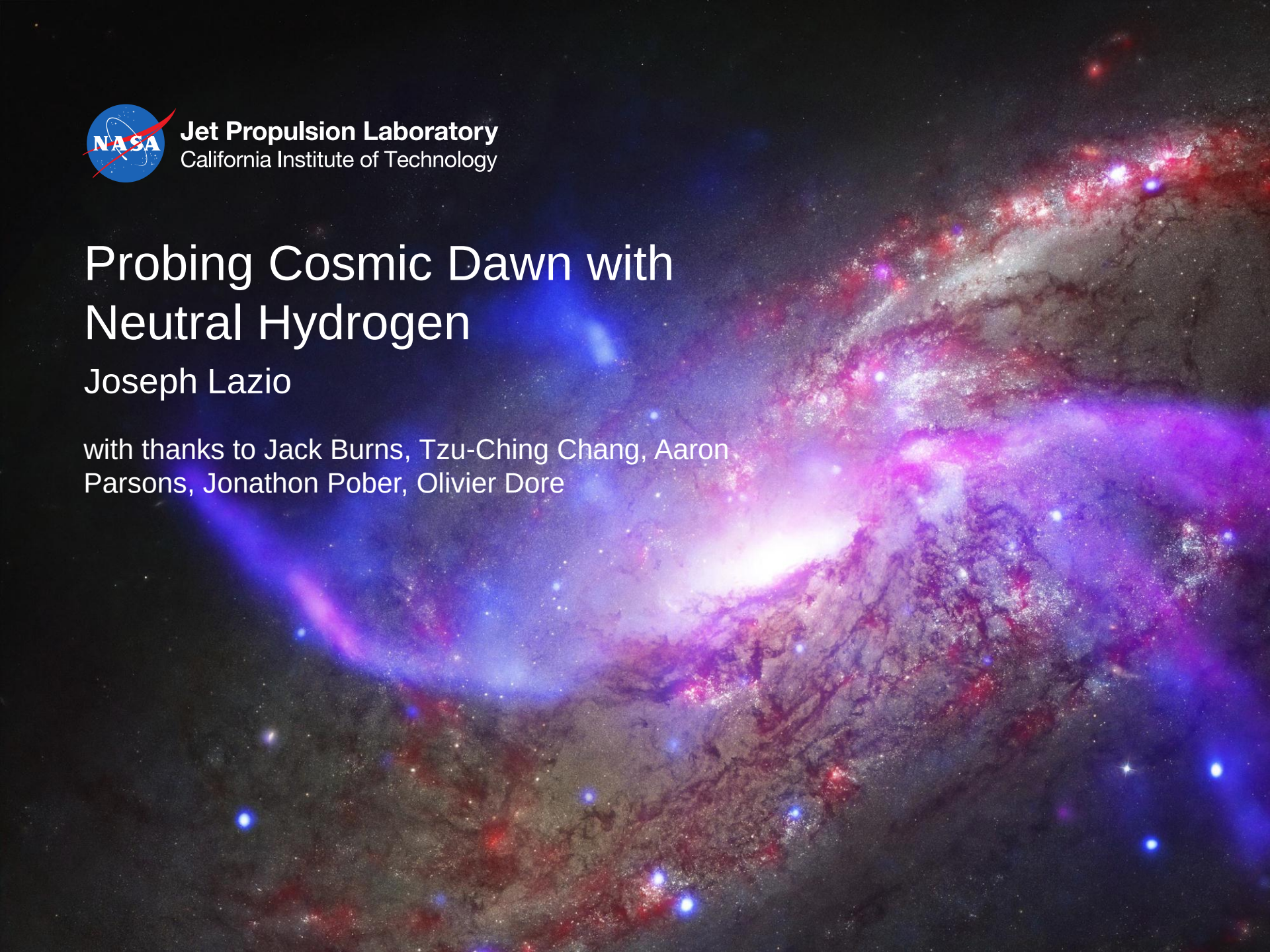


Jet Propulsion Laboratory
California Institute of Technology

Probing Cosmic Dawn with Neutral Hydrogen

Joseph Lazio

with thanks to Jack Burns, Tzu-Ching Chang, Aaron Parsons, Jonathon Pober, Olivier Dore

Brief History of the Universe

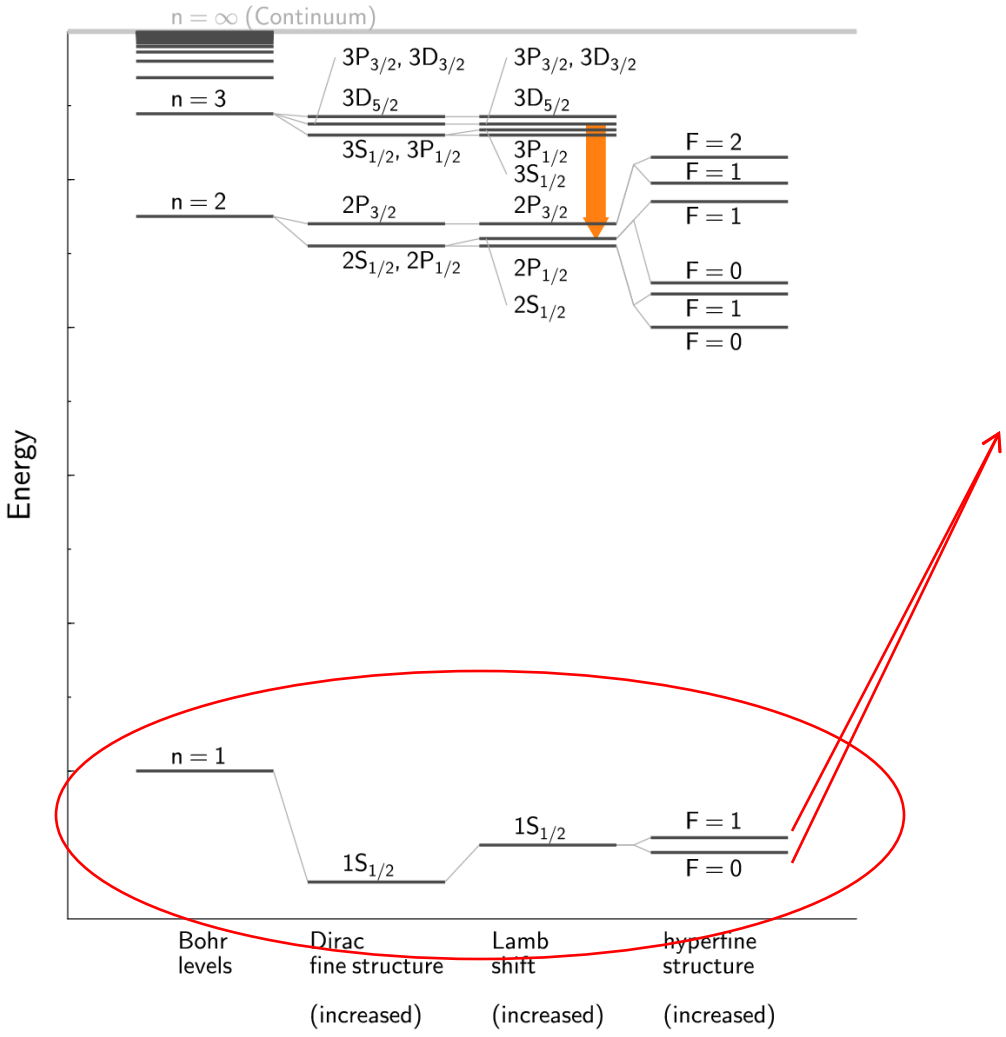
COBE

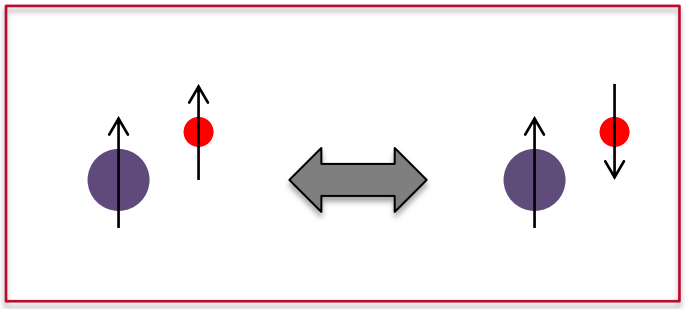
Universe starts in uniform, largely neutral state

Today, highly structure and ionized

➢ **What happened?**

Hydrogen Atom





n = 1, F = 1 → 0

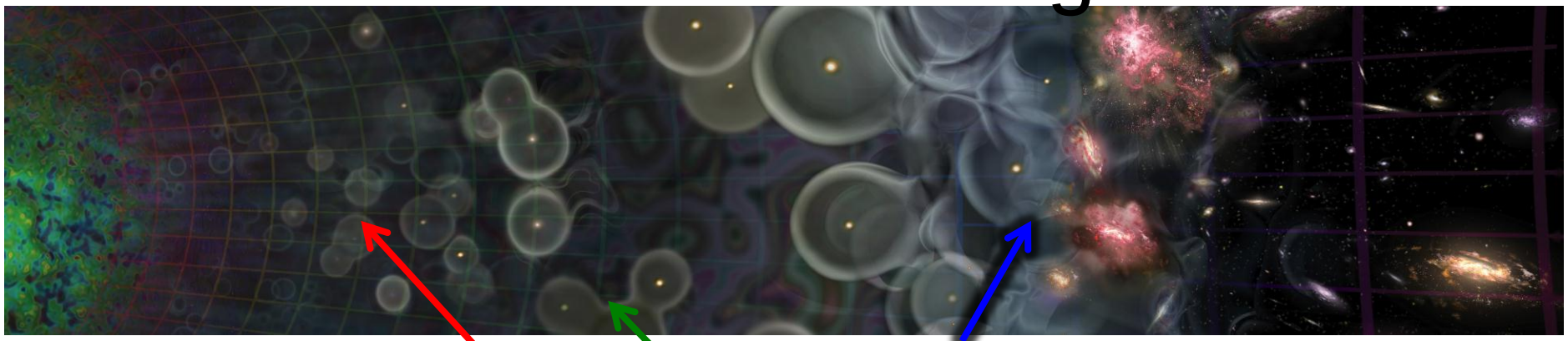
$E_{10} = h\nu$ = 5.8743253 μeV

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

ν = 1420.405752 MHz

λ = 21 cm

Hydrogen Signal from Cosmic Dawn and Dark Ages



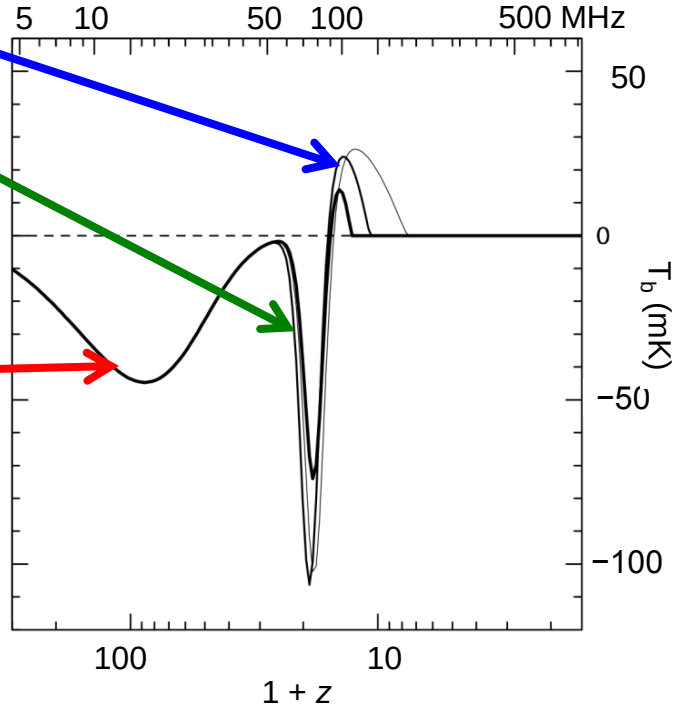
Neutral Hydrogen 21 cm

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

EoR

First Stars

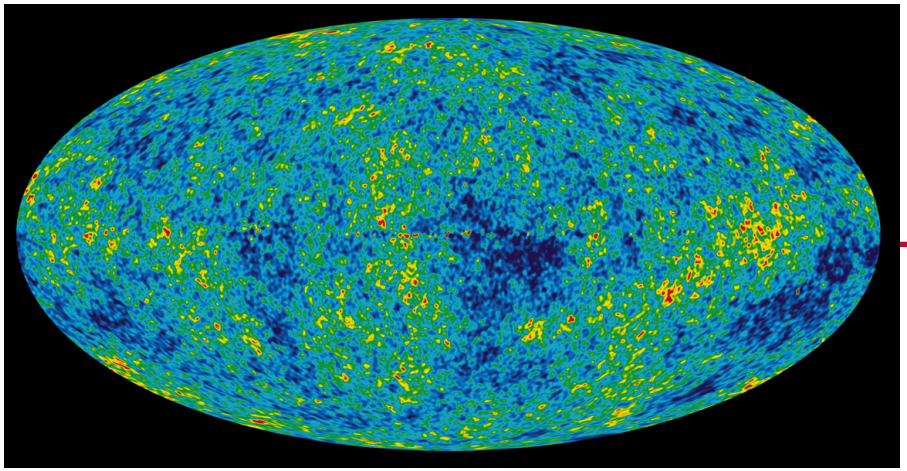
Dark Ages



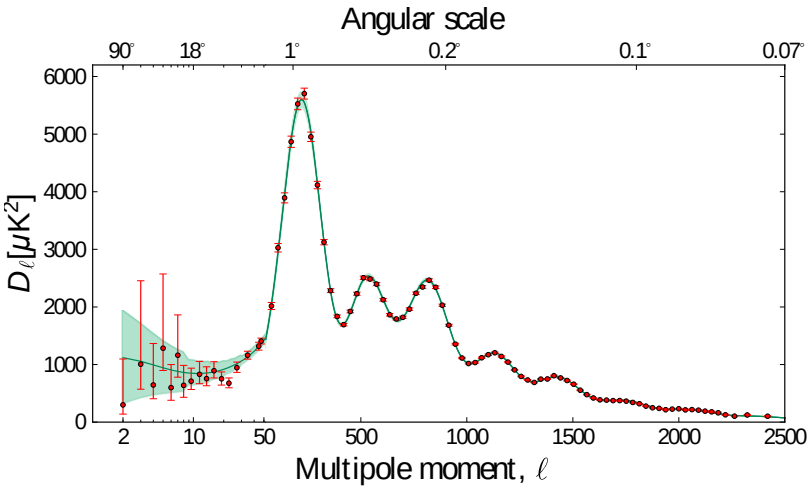
$\nu = 1420\ \text{MHz}/(1 + z)$

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

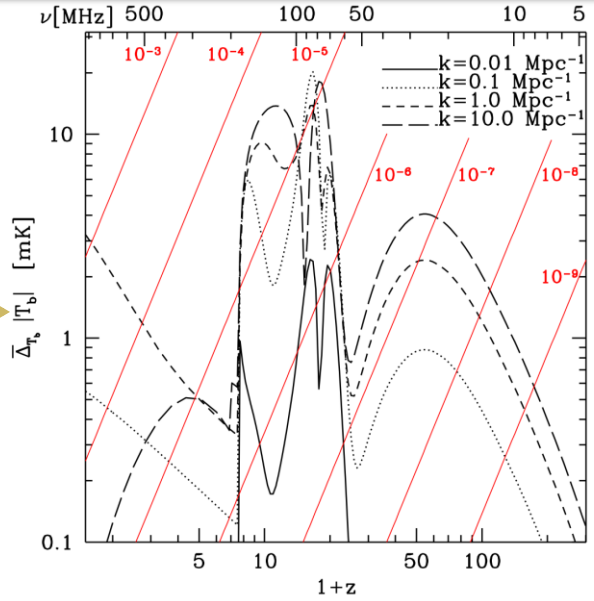
H I Fluctuation Power Spectra



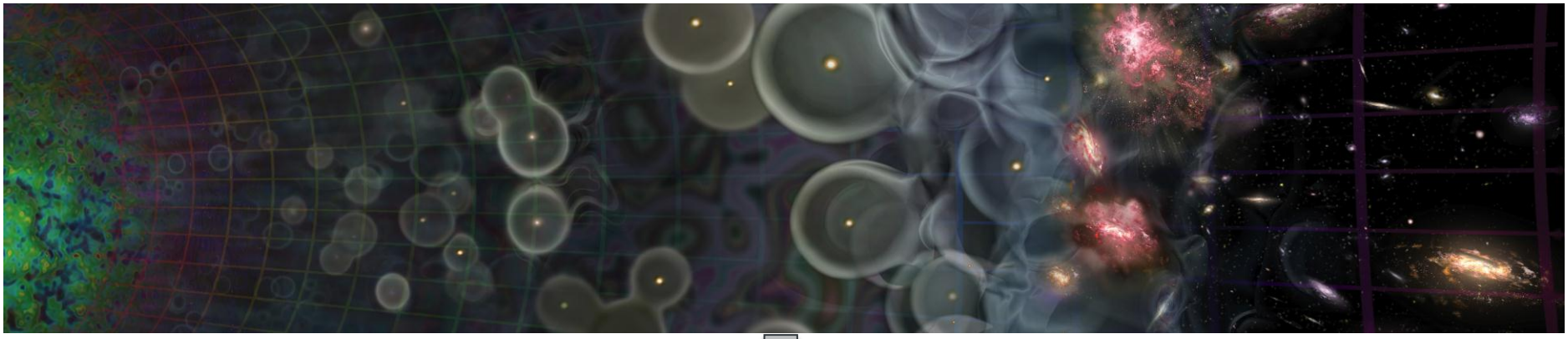
CMB

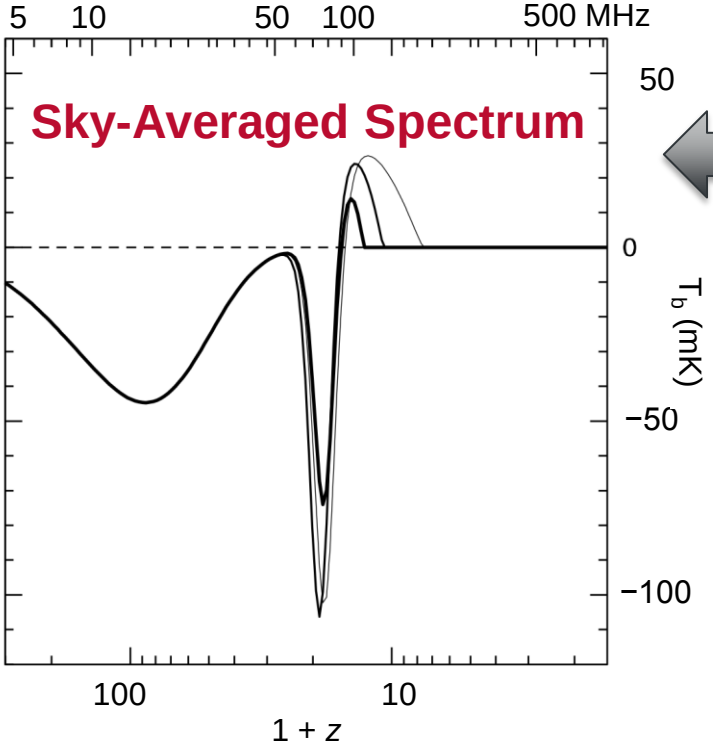


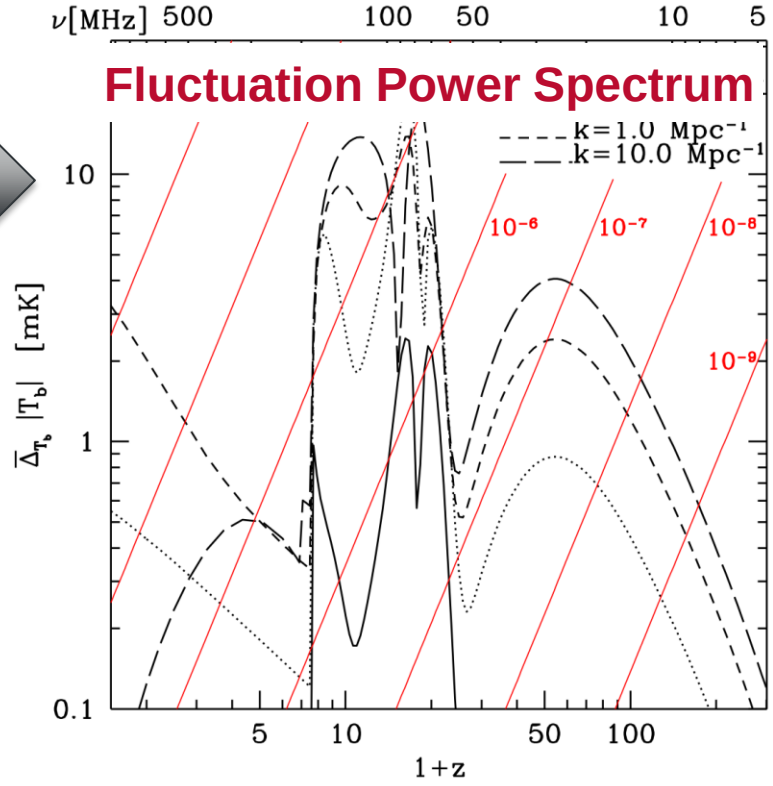
H I fluctuation power spectrum



Measurement Approaches



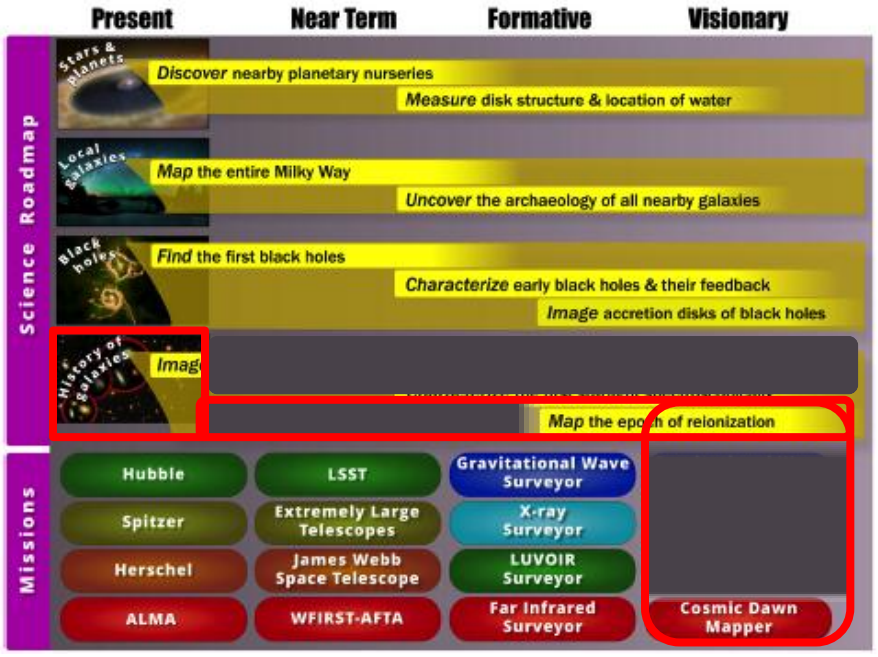




Science Goals of the Astrophysics Roadmap

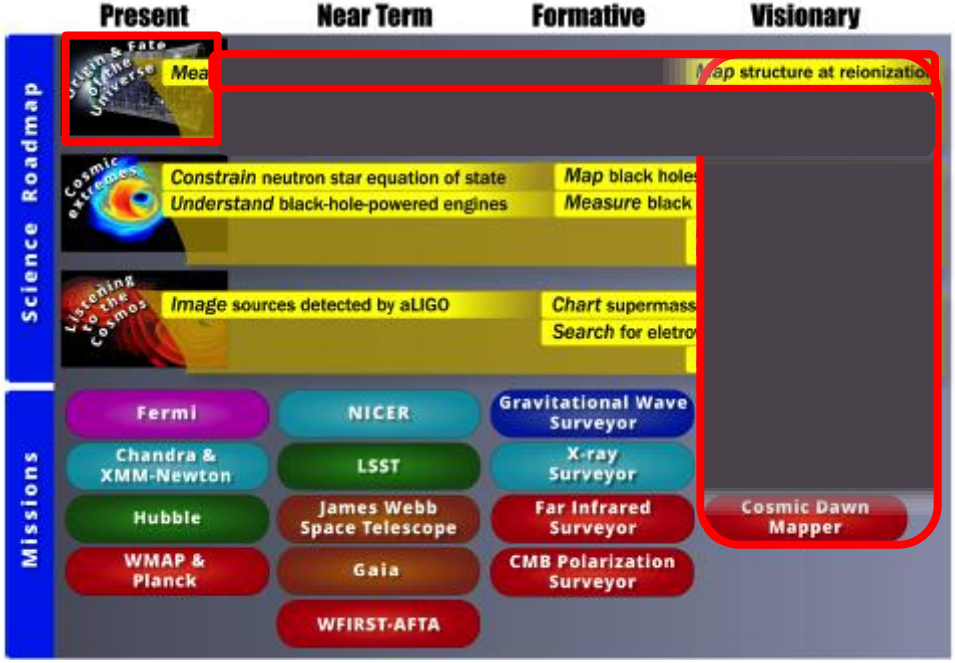
Goal 2: How Did We Get Here?

(Cosmic Origins)

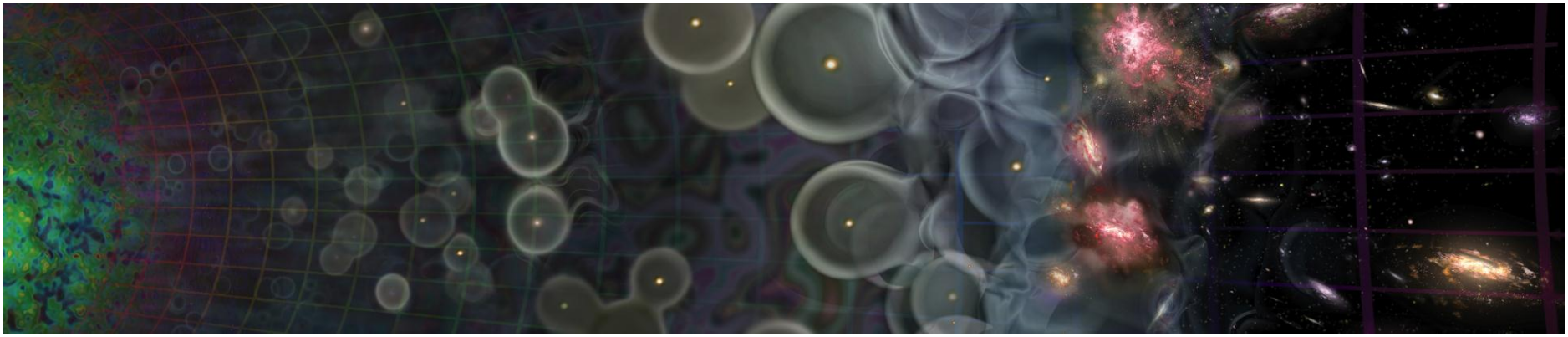


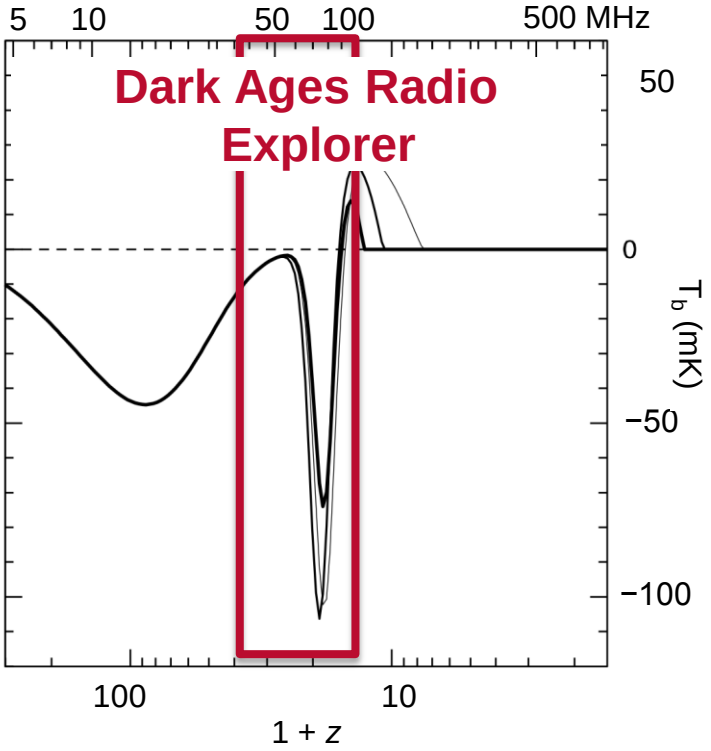
Goal 3: How Does Our Universe Work?

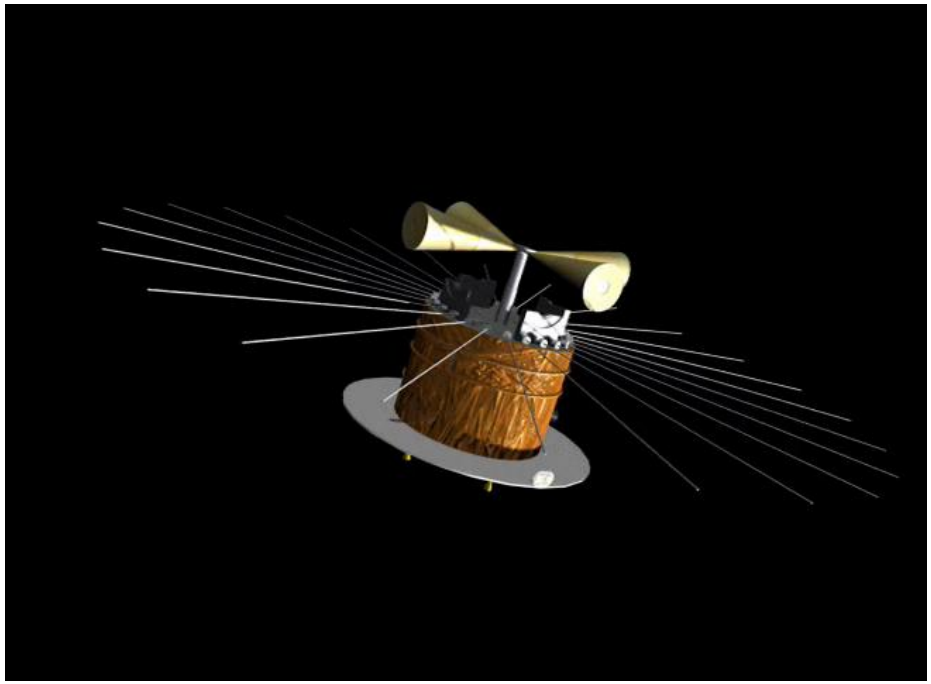
(Physics of the Cosmos)



Sky-Averaged Spectrum

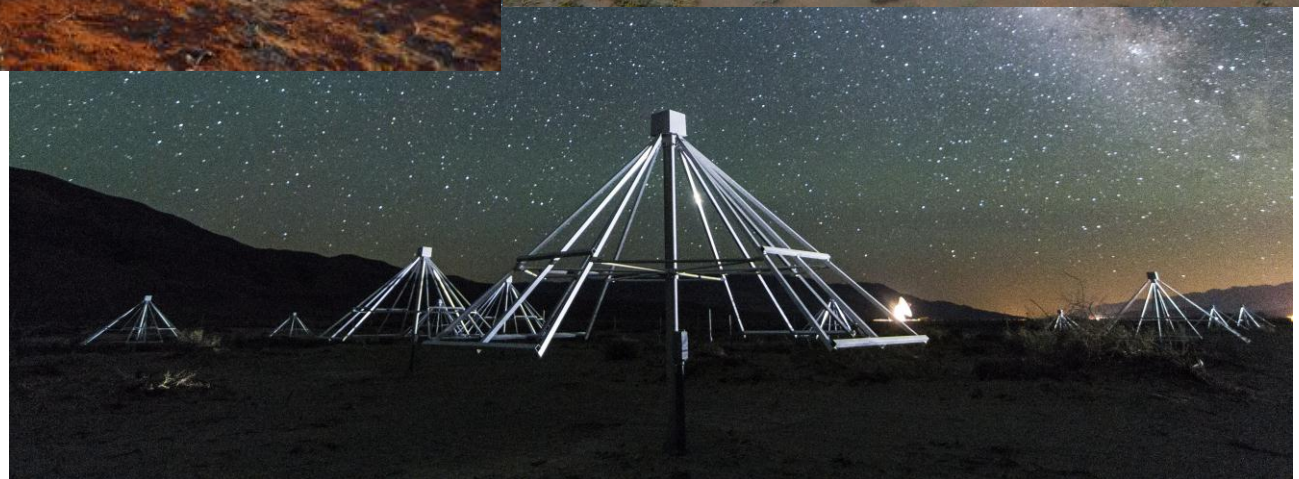






Toward a Probe-class Mission

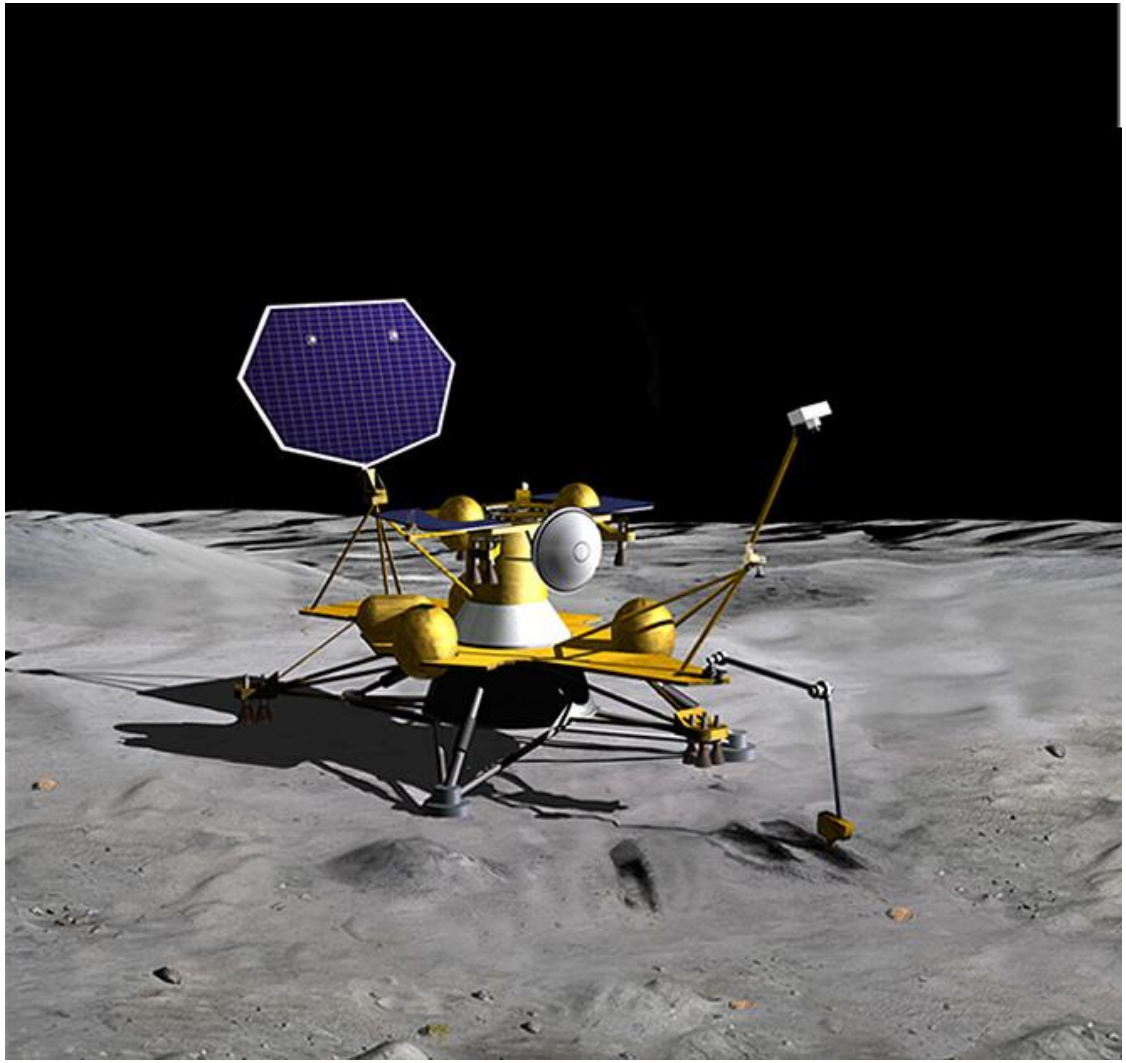
Lessons from the Ground



(Dillon et al. 2015; Ali et al. 2015)

Toward a Probe-class Mission

MoonRise Analog

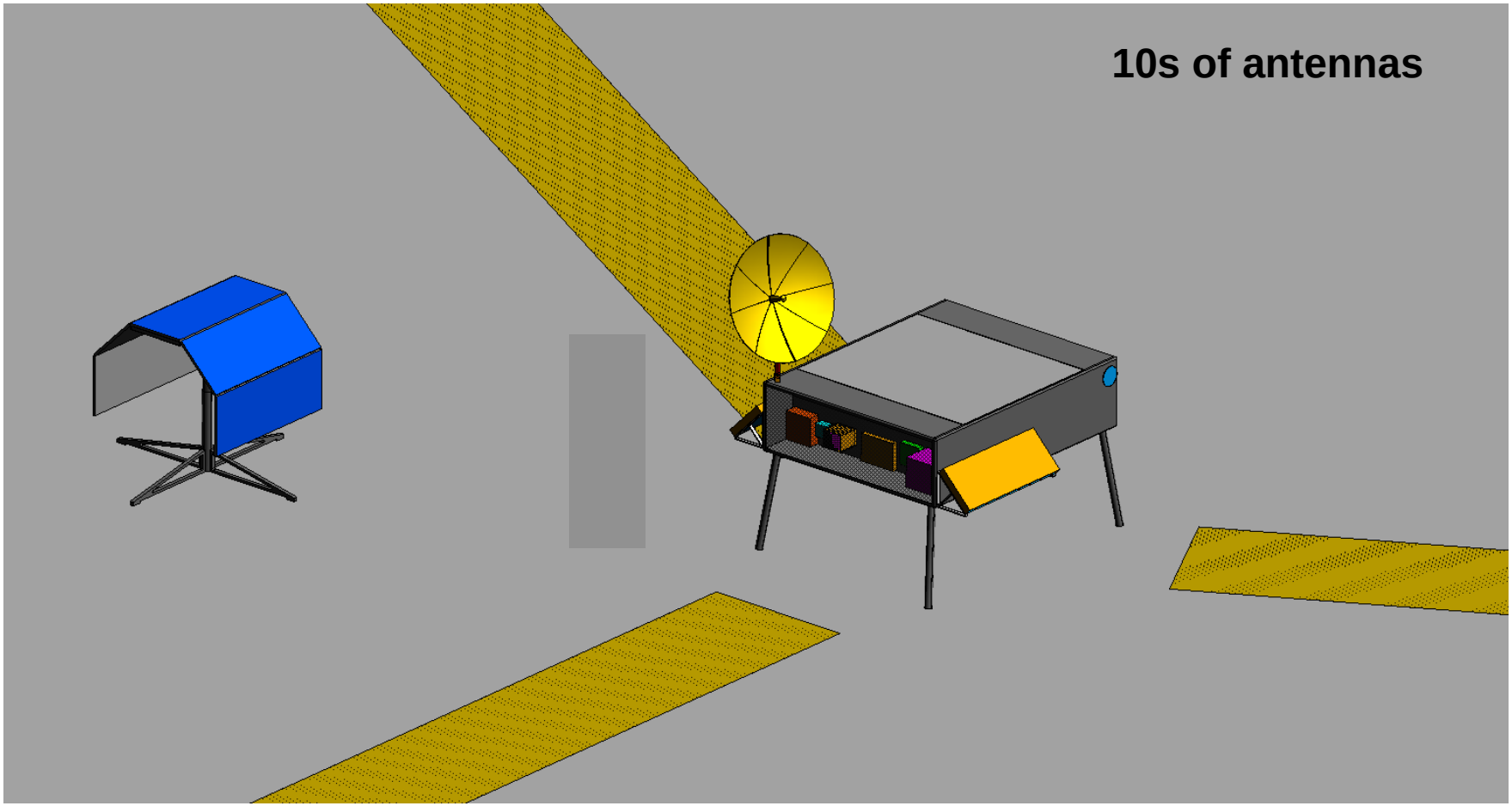


New Frontiers mission concept (Planetary Sciences)

- **Sample return from South Pole-Aitken Basin**
- **< $1B**
- **~ 1000 kg**

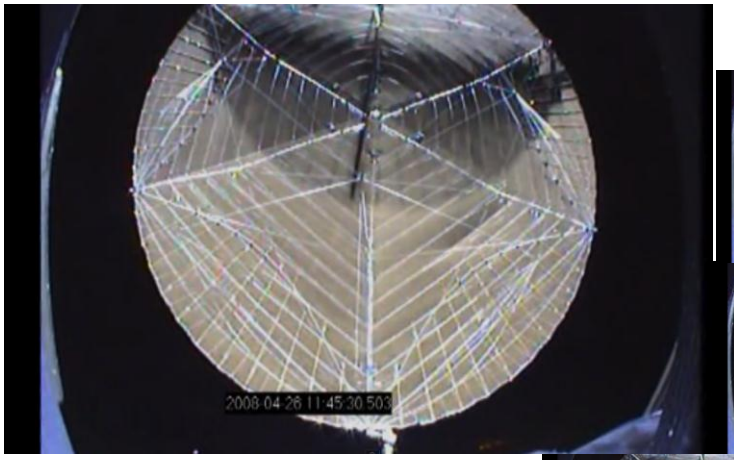
Toward a Probe-class Mission

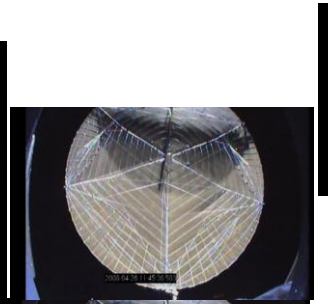
Radio Array Concept Study

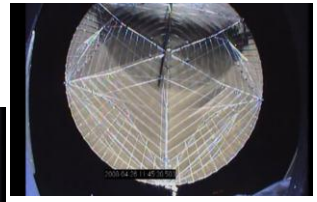


Toward a Probe-class Mission

Free-Flyer?







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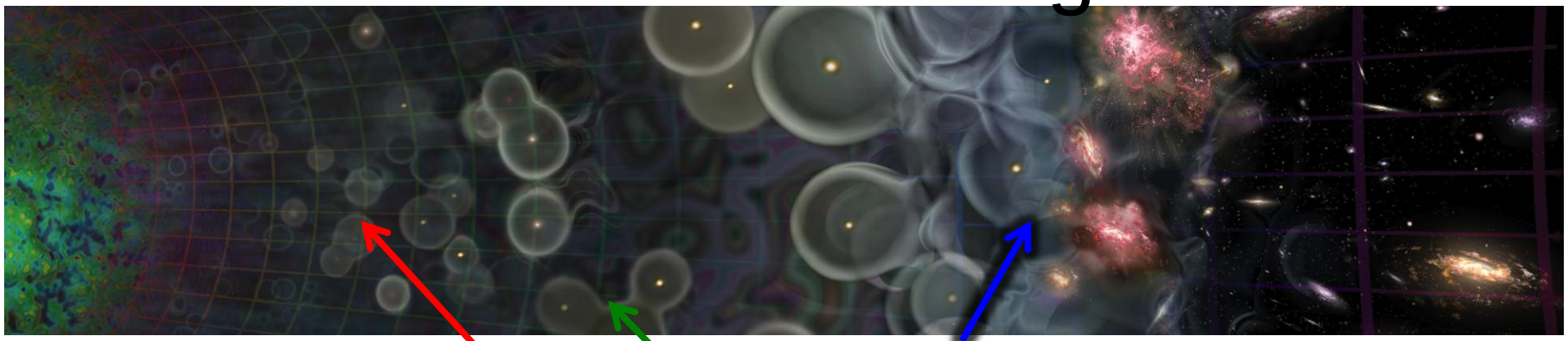
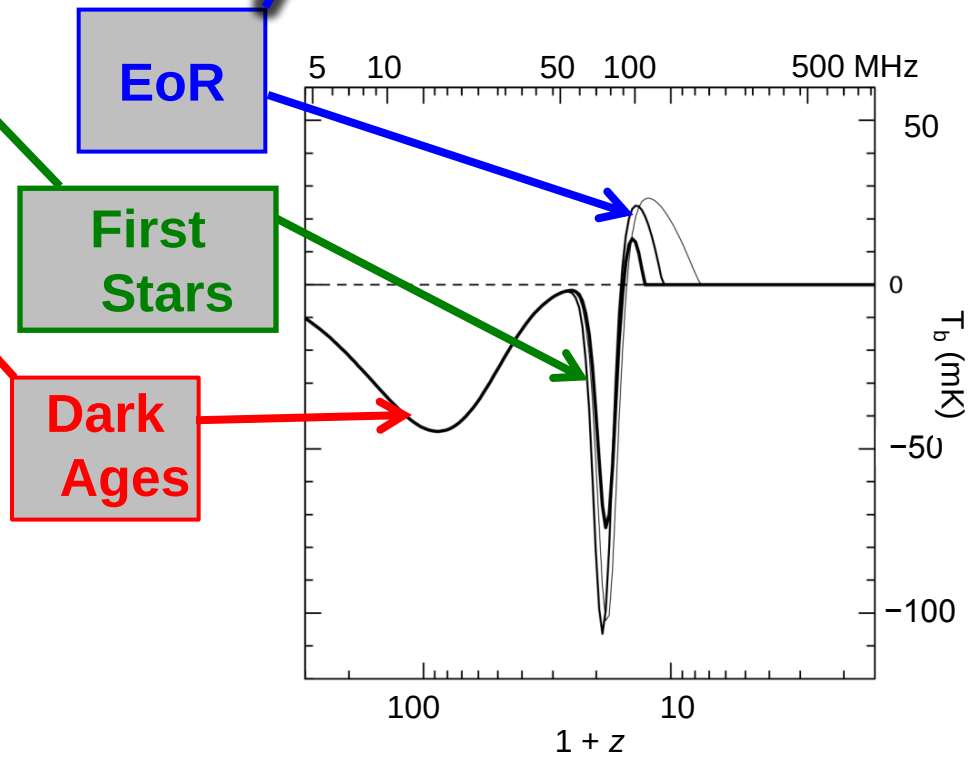
Hydrogen Signal from Cosmic Dawn and Dark Ages

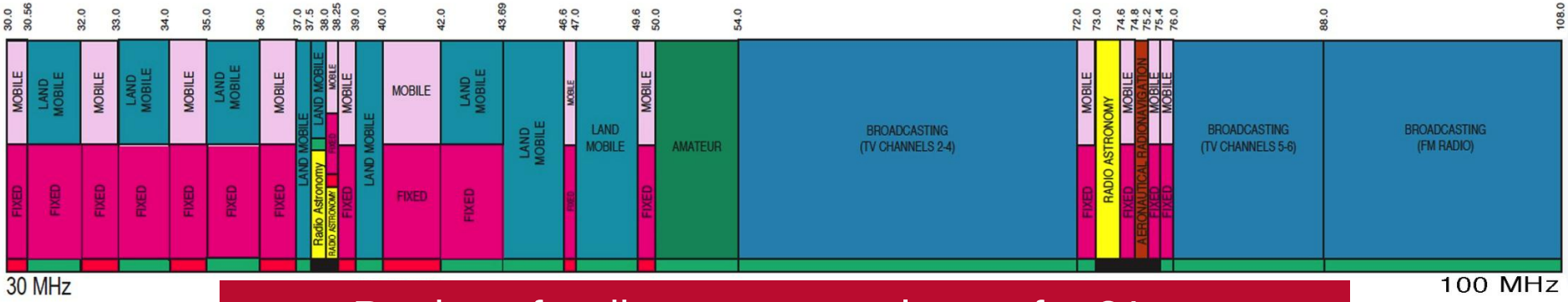


Neutral Hydrogen 21 cm spin-flip transition provides probe of neutral intergalactic medium before and during formation of first stars



Sample Chapter Divider

Radio Spectrum



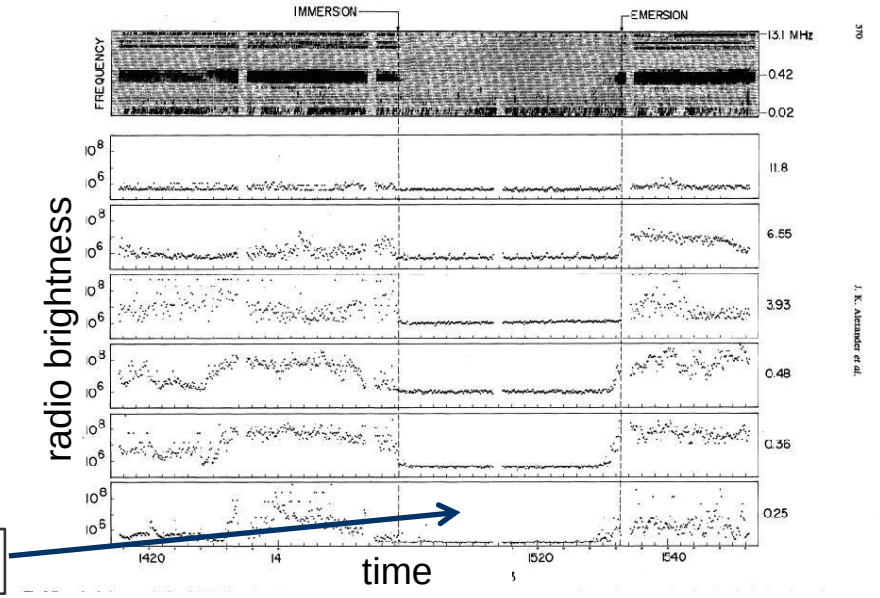
50 Myr since Big Bang

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