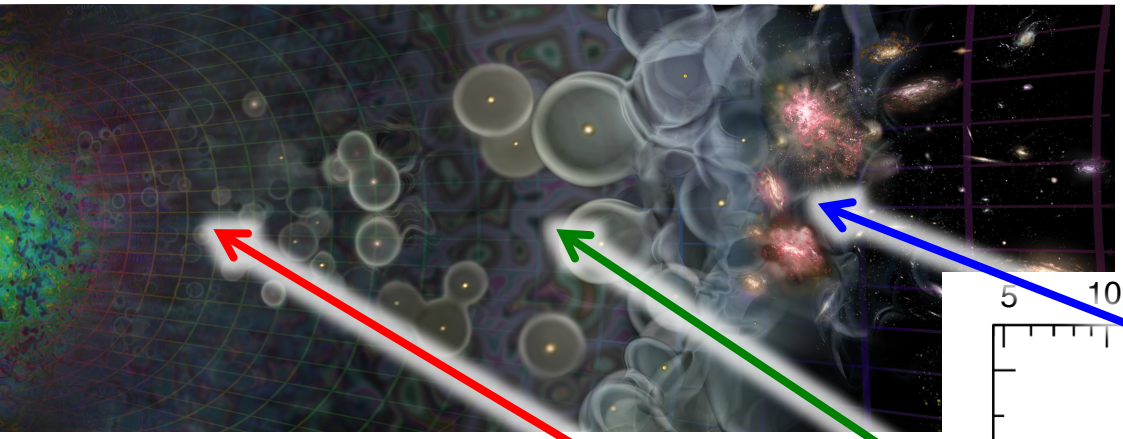
Jet Propulsion Laboratory
California Institute of Technology

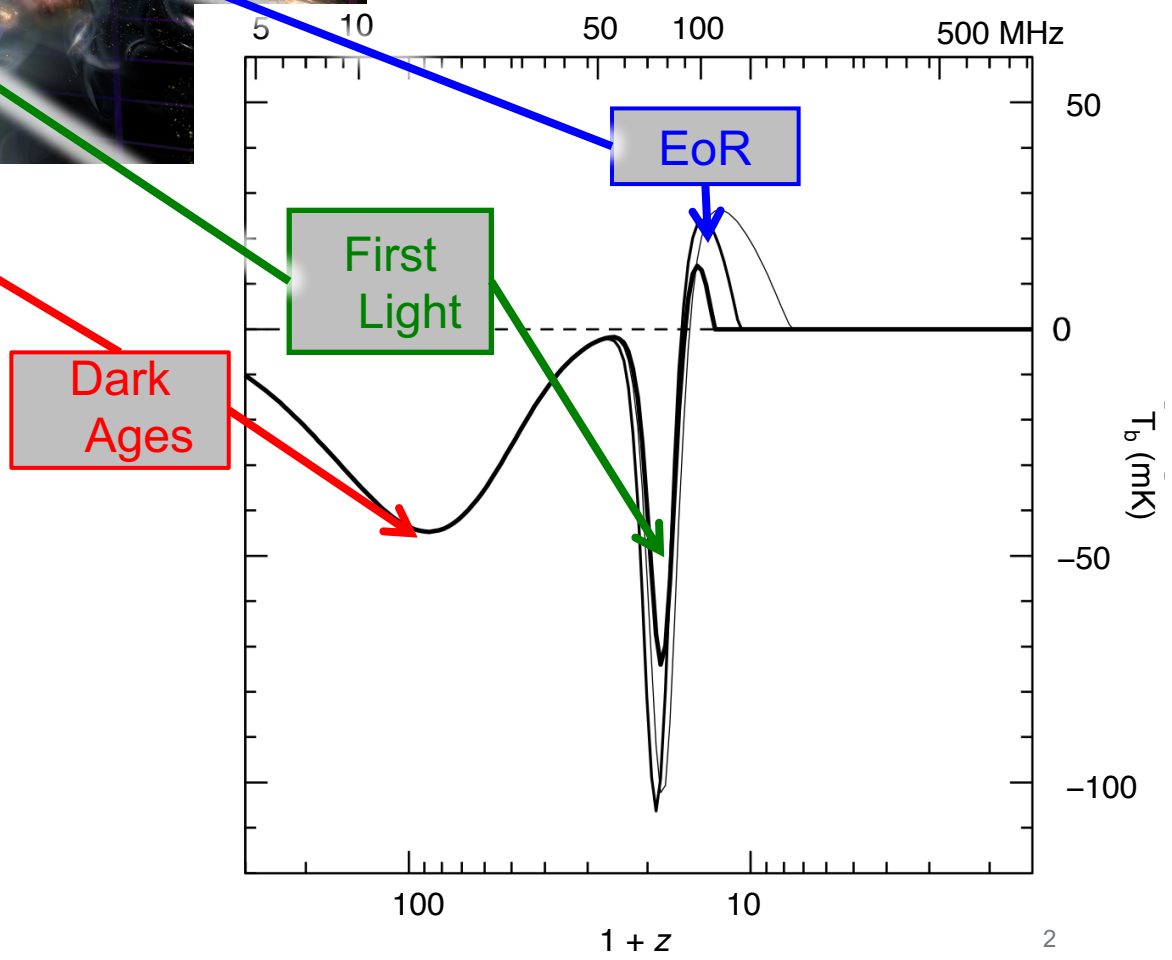
Space-based Probes for Cosmic Dawn

Joseph Lazio

Hydrogen Signal from EoR and Before



A Role for Space?

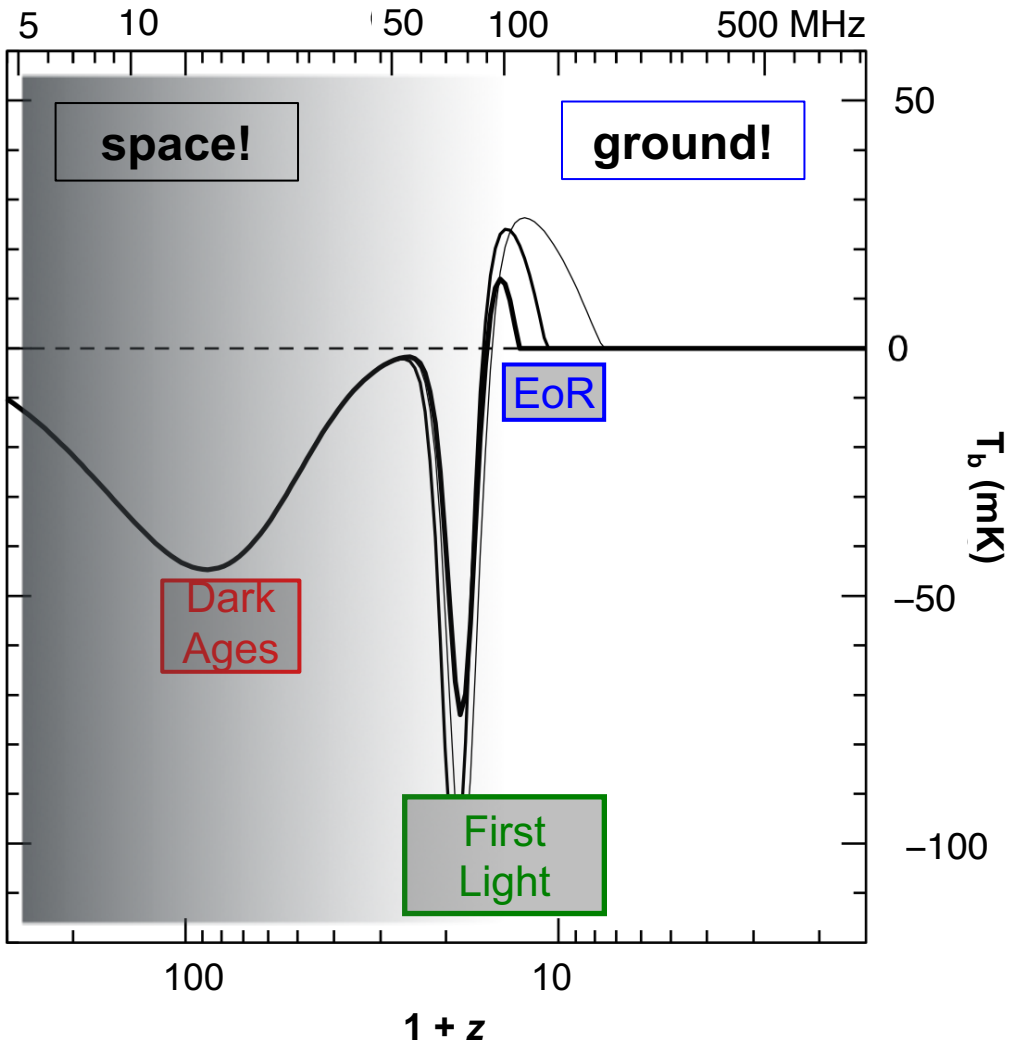


Neutral Hydrogen

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

Hydrogen Signal from EoR and Before

A Role for Space?



HERA, EDGES-Lo, SKA1-Low, LWA-LEDA, …

- **Lowest frequency ~ 50 MHz ~ redshift of 30**
- **Due to atmospheric (ionospheric) opacity**
  Caveat: RFI

Astrophysics Missions

NASA Volcabulary

Class	Budget (~ $M)	Examples	ESA equivalent
Mission of Opportunity (MoO)	65	INTEGRAL, NICER	S class
Explorer (both Small and Medium)	250	GALEX, WISE, *Swift*, WMAP, … NuSTAR, TESS	
Probe	*< 1000*	*Fermi*, *Spitzer*, *Kepler*	M class
Flagship	> 1000	*Hubble*, *JWST*, WFIRST	L class

Predicting the Future

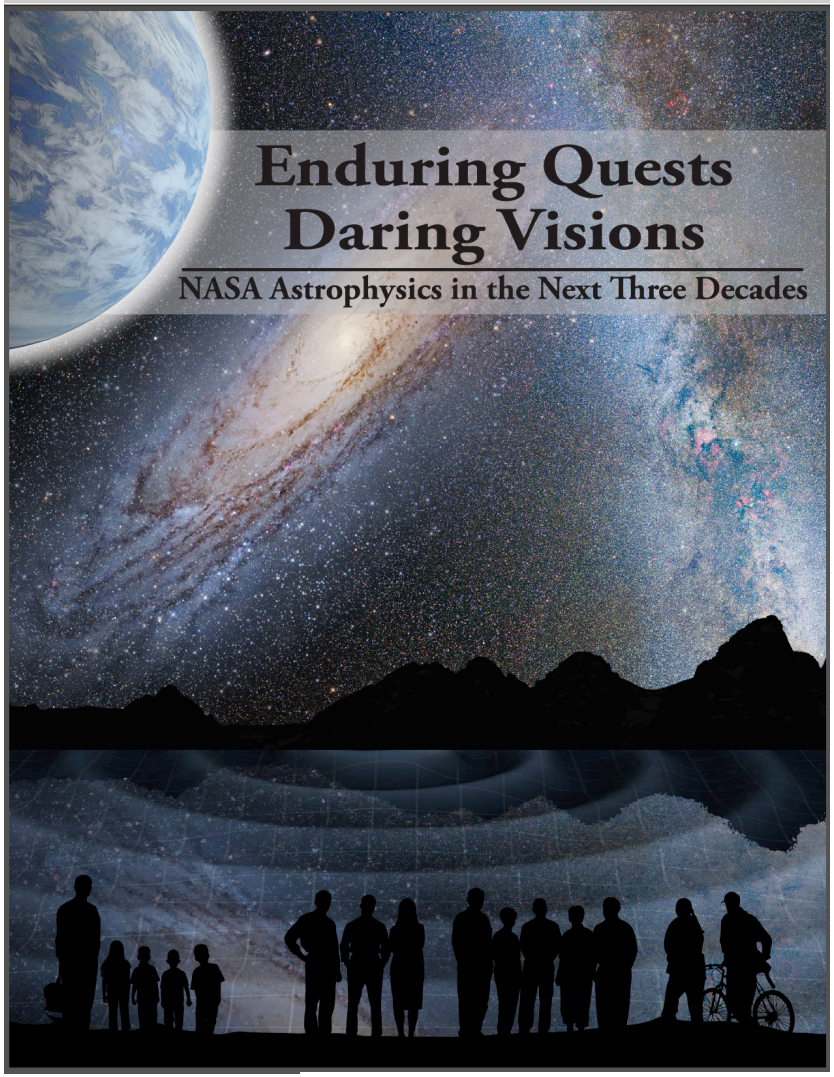
“It is difficult to make predictions, particularly about the future.”

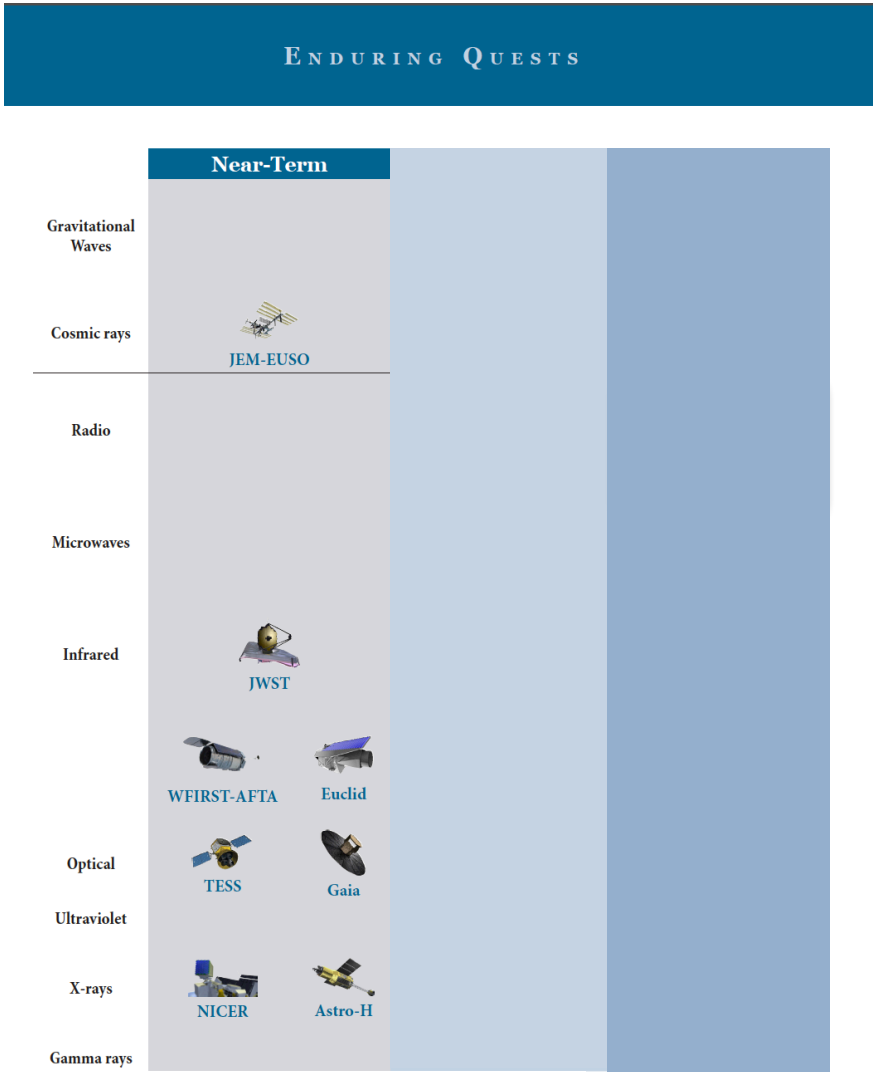
Danish proverb, and probably Yogi Berra

- **New discoveries may change trajectories.**

Predicting the Future I

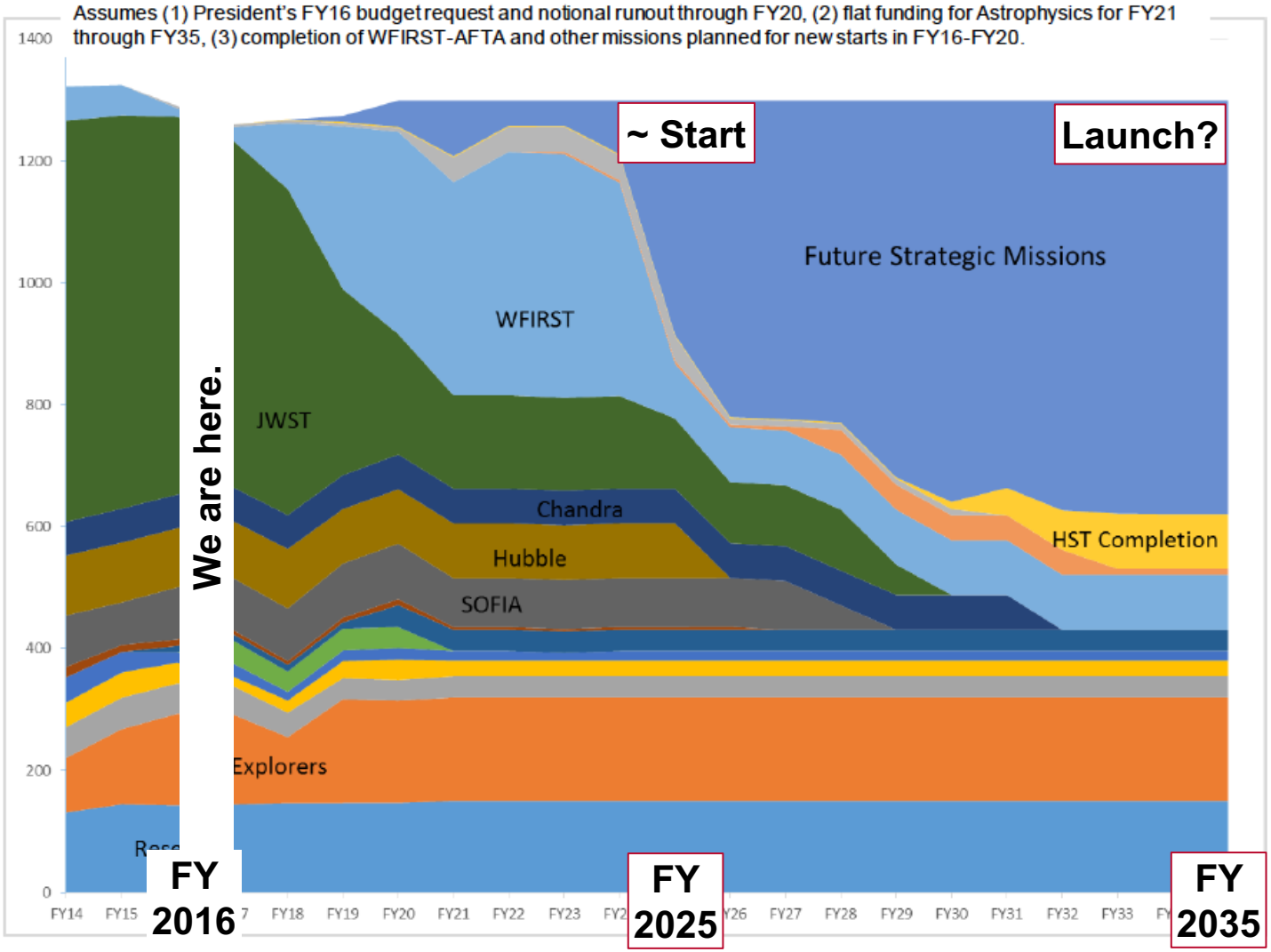
NASA Astrophysics Roadmap





Predicting the Future II

Free Energy



Courtesy P. Hertz

Preparing for the 2020 Decadal Survey
Large Mission Concepts

The initial short list (in alphabetical order):

- **FAR IR Surveyor** – The Astrophysics Visionary Roadmap identifies a Far IR Surveyor as contributing through improvements in sensitivity, spectroscopy, and angular resolution. ➡ **Origins Space Telescope**
- **Habitable-Exoplanet Imaging Mission** – The 2010 Decadal Survey recommends that a habitable-exoplanet imaging mission be studied in time for consideration by the 2020 Decadal Survey.
- **UV/Optical/IR Surveyor** –The Astrophysics Visionary Roadmap identifies a UV/Optical/IR Surveyor as contributing through improvements in sensitivity, spectroscopy, high contrast imaging, astrometry, angular resolution and/or wavelength coverage. The 2010 Decadal Survey recommends that NASA prepare for a UV mission to be considered by the 2020 Decadal Survey.
- **X-ray Surveyor** – The Astrophysics Visionary Roadmap identifies an X-ray Surveyor as contributing through improvements in sensitivity, spectroscopy, and angular resolution. ➡ **Lynx**

Courtesy P. Hertz

Predicting the Future IV

Probes?

- **Transient Astrophysics Probe**
  - **High-*z* GRBs?**
- **Cosmic Dawn Intensity Mapper**
- **Cosmic Evolution Through UV Spectroscopy (CETUS)**
- **The Galaxy Evolution Probe**
- **Inflation Probe Mission Concept Study**
- **AXIS - A High Angular Resolution X-ray Probe**
- **Concept Study of the Probe Of Extreme Multi-Messenger Astrophysics (POEMMA)**
- **EarthFinder: A Diffraction-Limited Precise Radial Velocity Observatory in Space**
- **STROBE-X: X-ray Timing and Spectroscopy on Dynamical Timescales from Microseconds to Years**
- **Starshade Rendezvous Mission**

Astrophysics Missions

NASA Vocabulary

Class	Budget (~ $M)	Examples
Mission of Opportunity (MoO)	65	competed
Explorer (both Small and Medium)	125--250	competed
Probe	*< 1000*	??
Flagship	> 1000	{ OST | HabEx | LUVOIR | Lynx }

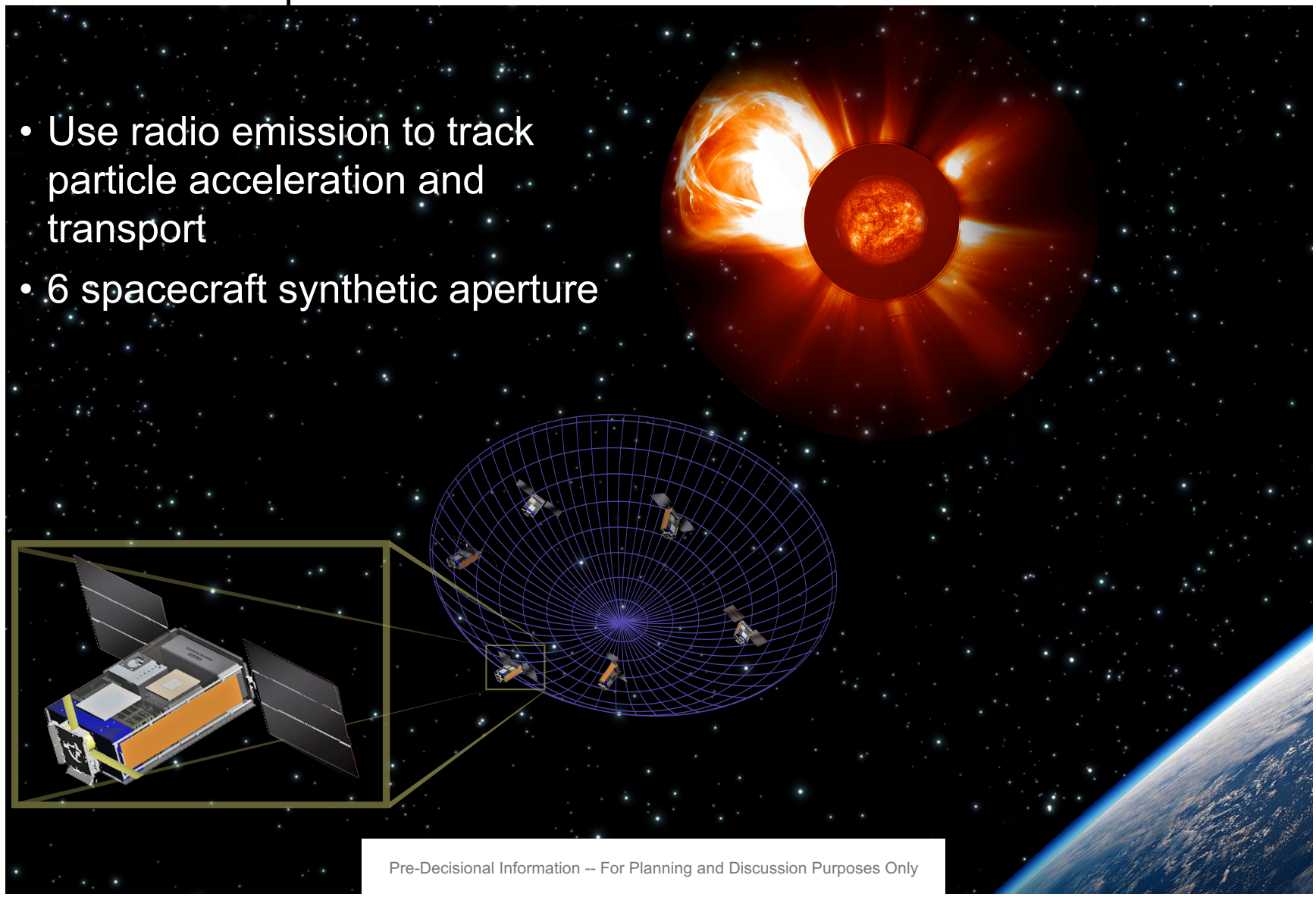
Cosmic Dawn Mapper not likely in the near future*

***pending future discoveries**

Sun Radio Imaging Space Experiment

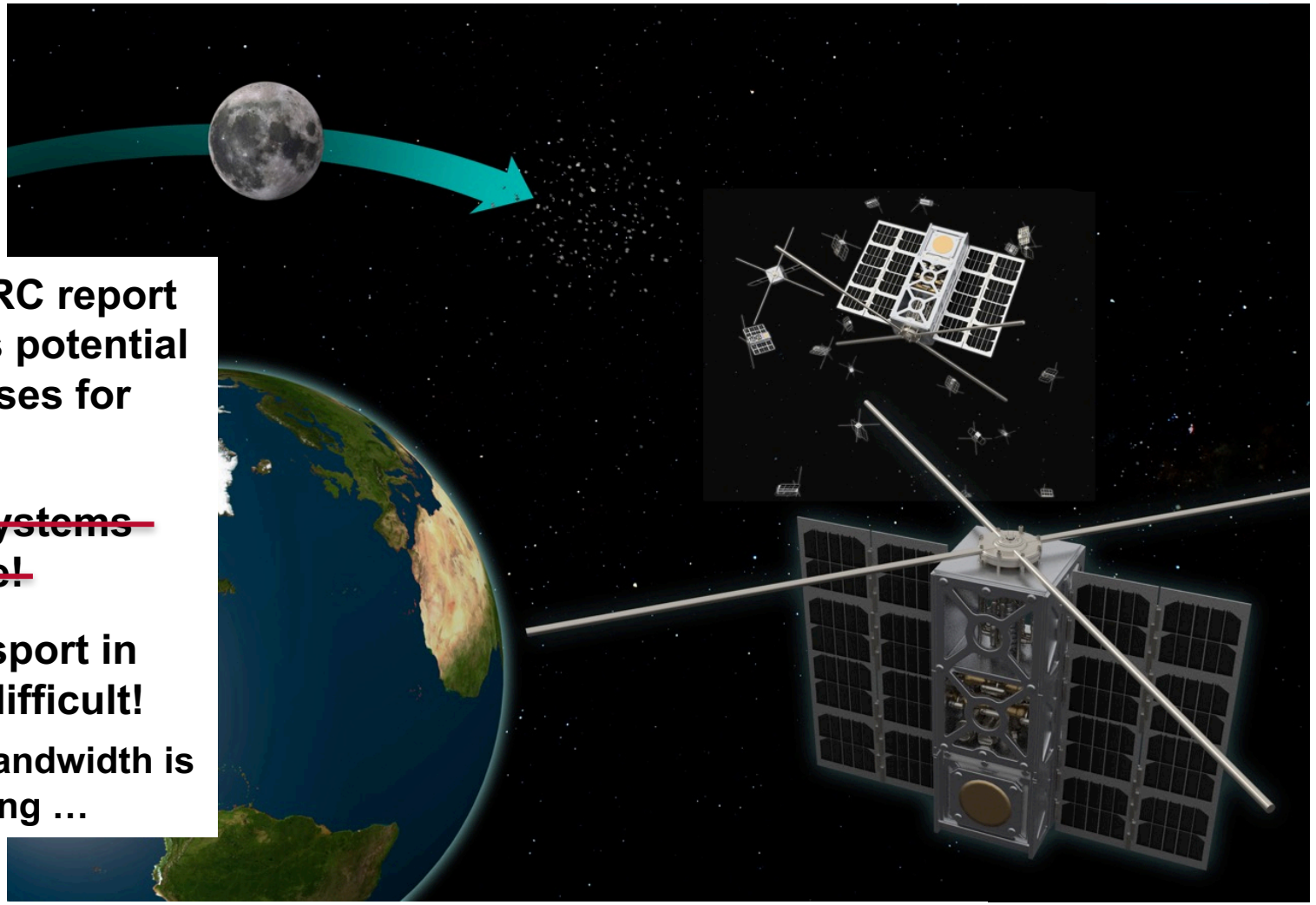
Mission Concept

- Use radio emission to track particle acceleration and transport
- 6 spacecraft synthetic aperture



Space-based Cosmic Dawn

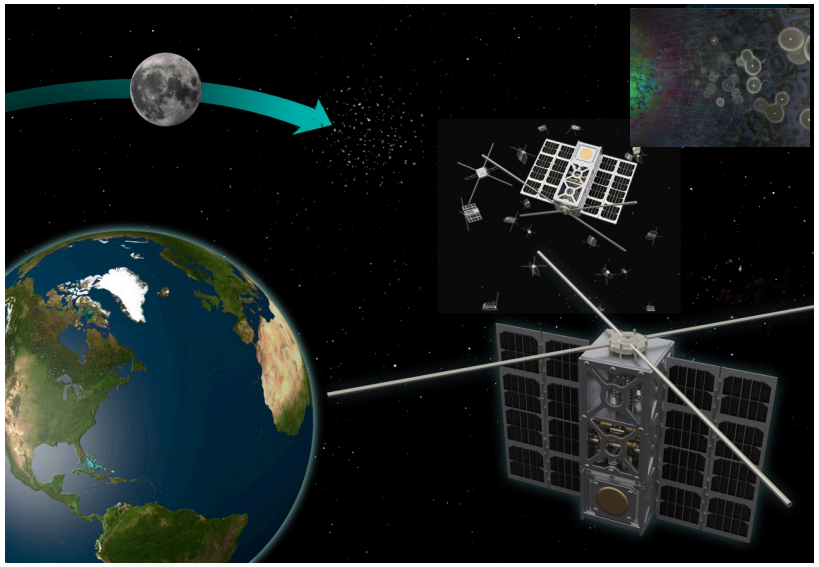
Cubesats!



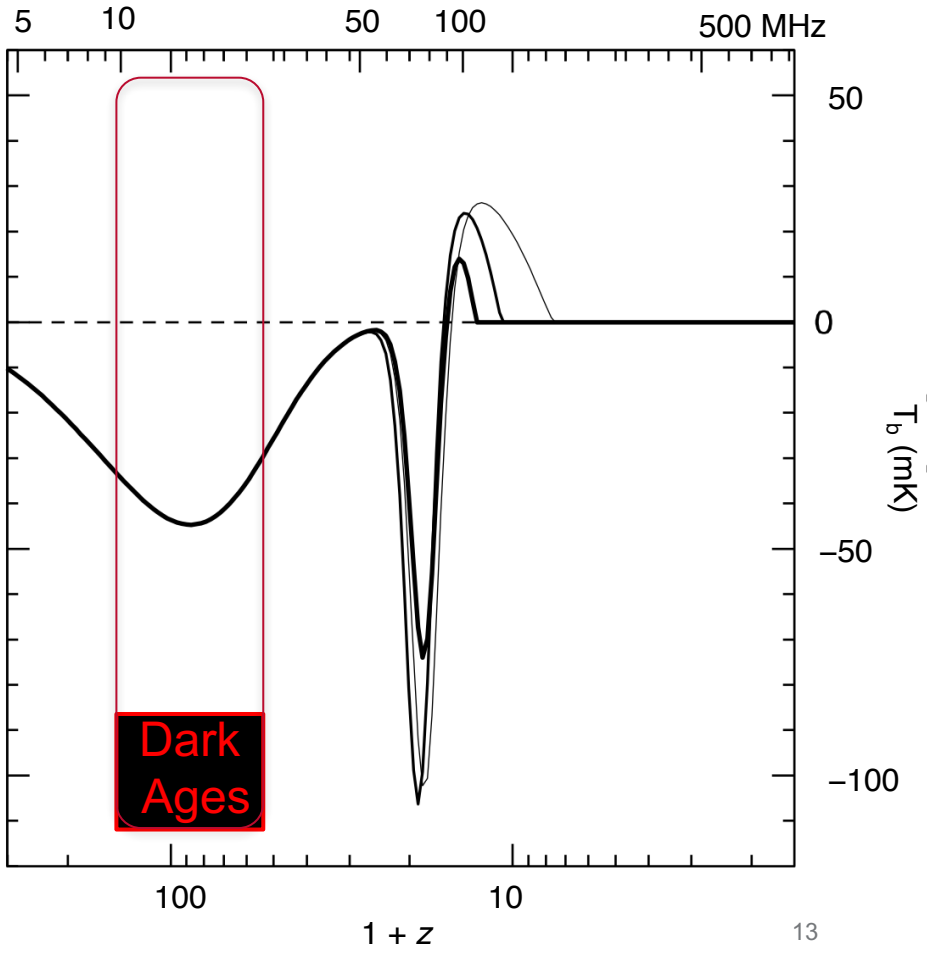
- ✓ **Recent NRC report highlights potential science uses for cubesats!**
- ✓ ~~**HF/VHF systems are simple!**~~
- – **Data transport in space is difficult!**
  - **1 MHz of bandwidth is challenging …**

Hydrogen Signal from the Dark Ages

A Role for Space



- **+ Smaller frequency range reduces requirements on antennas-receivers and data volumes**
- **− Foregrounds, foregrounds, foregrounds**



Hydrogen Signal from EoR and Before

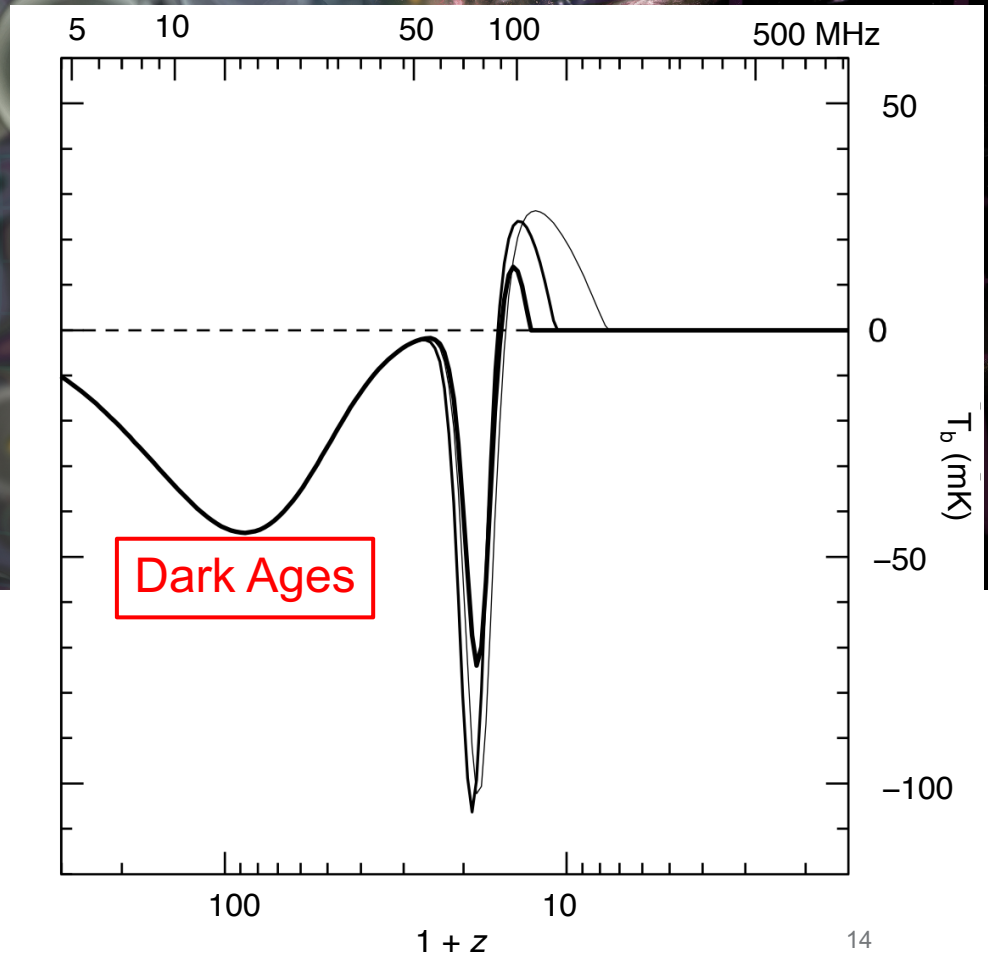
A Role for Space?

Recognition from larger space-based Astrophysics community that H I studies of Cosmic Dawn is valuable

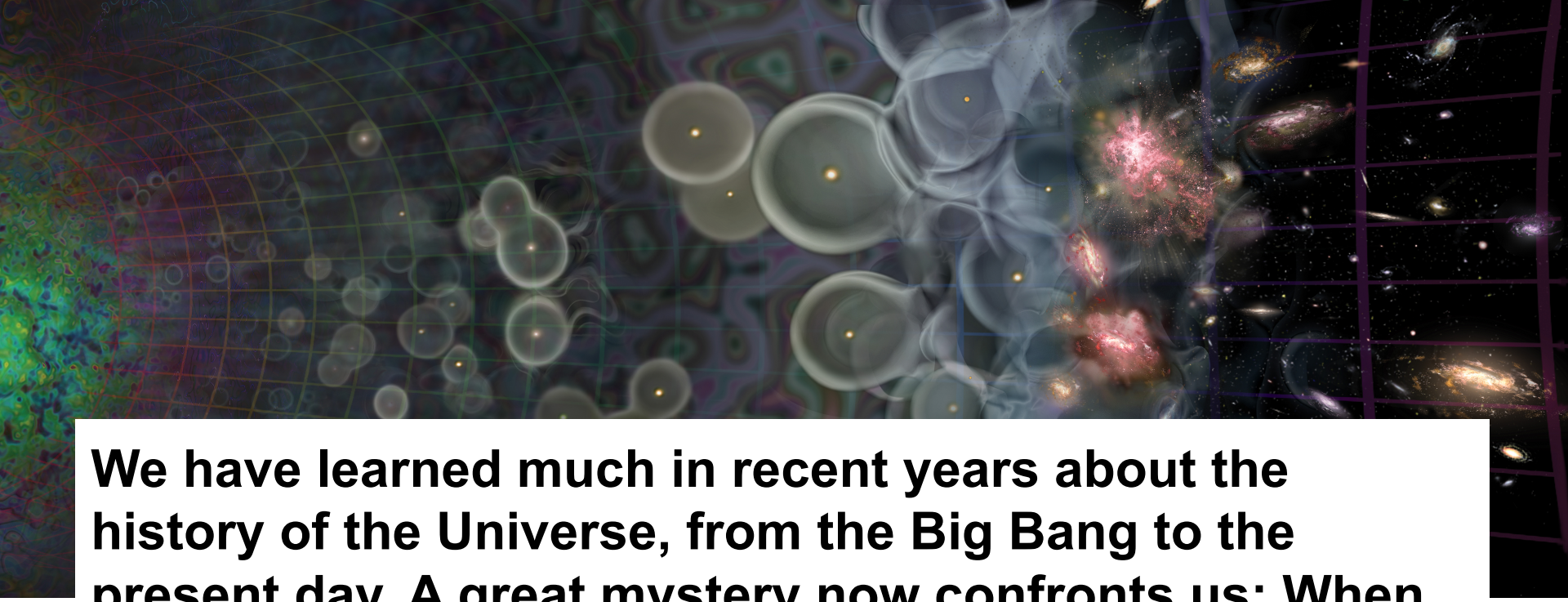
Experience from ground is essential

Large space-based radio astronomy array probably not in near-term future

Potential opportunities for innovative approaches



backup



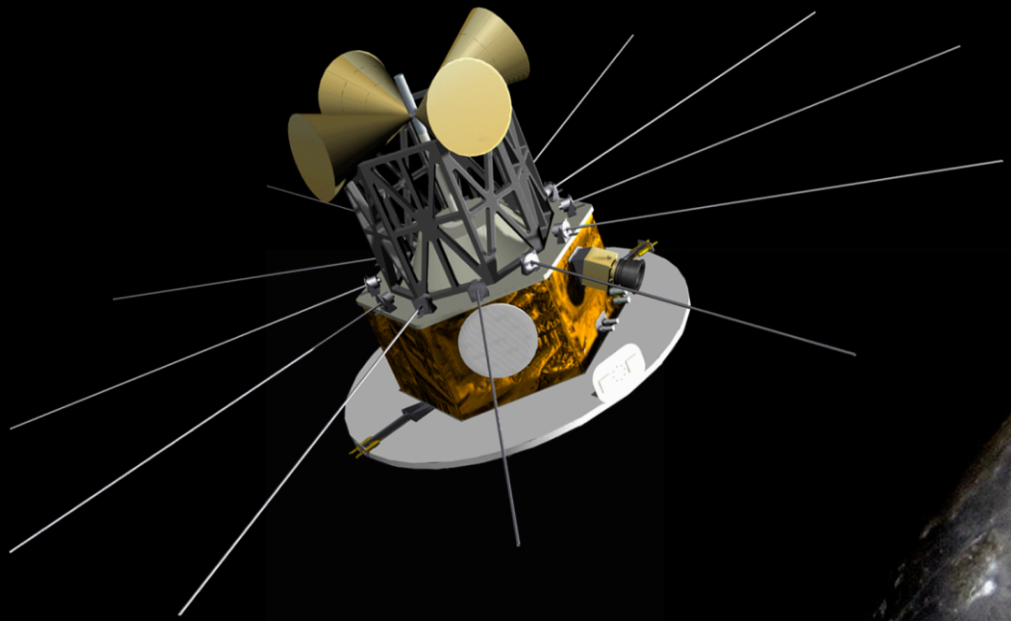
We have learned much in recent years about the history of the Universe, from the Big Bang to the present day. A great mystery now confronts us: When and how did the first galaxies form out of cold clumps of hydrogen gas and start to shine—when was our "cosmic dawn"?

New Worlds, New Horizons

Image credit: A. Loeb/Scientific American

DARE

DARK AGES RADIO EXPLORER



DARE
DARK AGES RADIO EXPLORER

Space-based Probes for Cosmic Dawn
Pre-decisional, for information and discussion purposes only

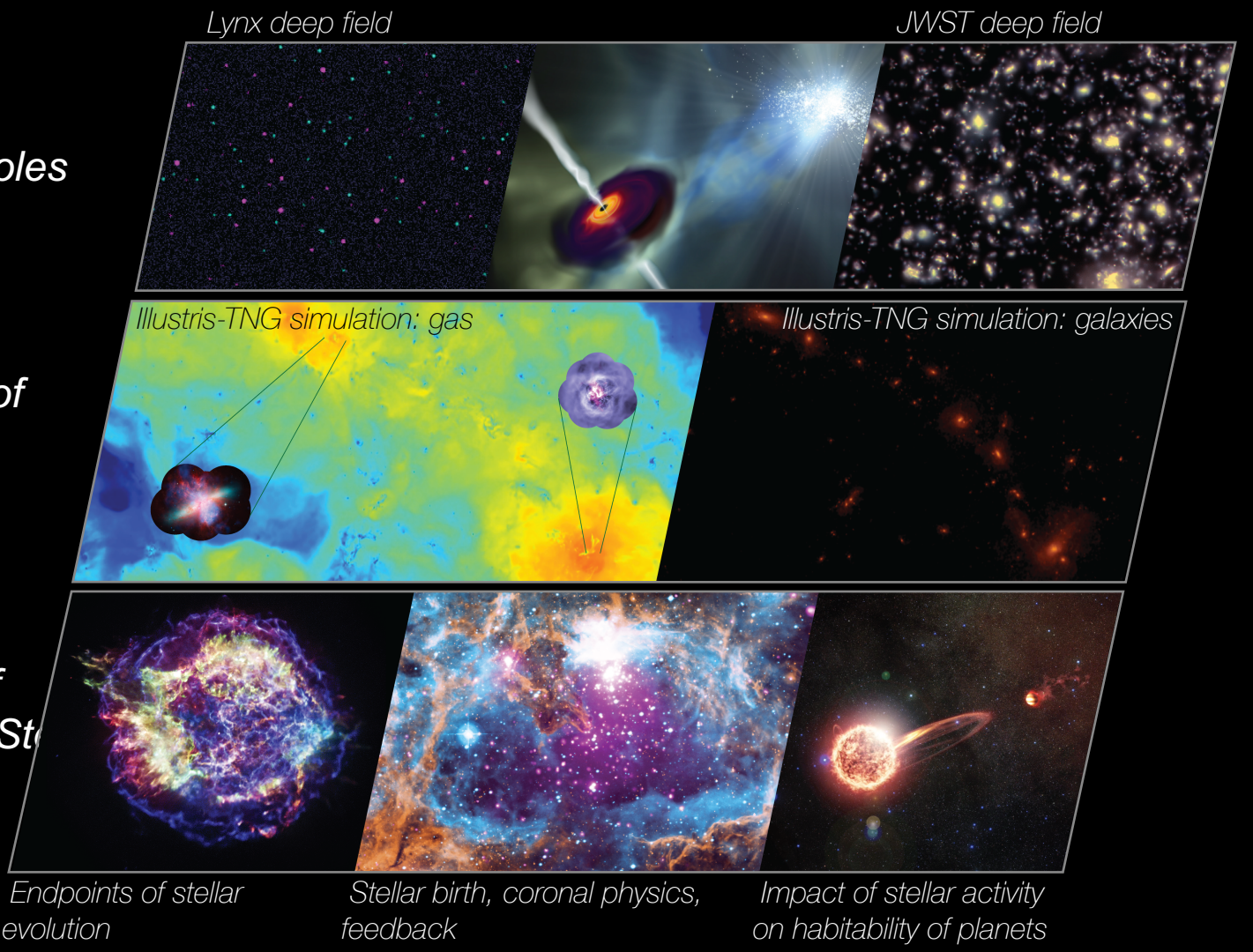
X-RAY OBSERVATORY

LYNX

The Dawn of Black Holes

The Invisible Drivers of Galaxy and Structure Formation

The Energetic Side of Stellar Evolution and St Ecosystems



Credit: A. Vikhlinin

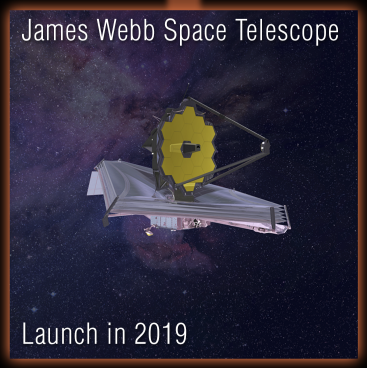
Seeing into the dark ages with Origins Space Telescope (OST)

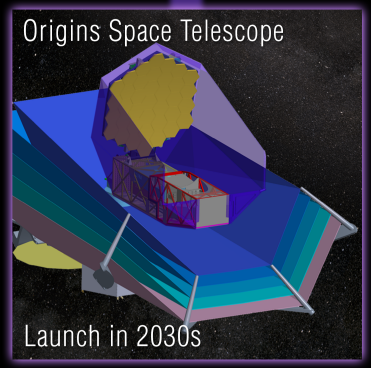
Recombination

Big Bang

Today | Reionization | First Galaxies | First Stars | Dark Ages

REDSHIFT	1	6	8	12	16	1100
BILLIONS of YEARS AGO		12.6	13.1	13.4	13.5	13.8





DIAMETER	2.4 meter	6.5 meter	9 meter
WAVELENGTH	0.1–2.4 μm	0.6–27 μm	5–660 μm
TEMPERATURE	260 K	50 K	4 K

Lunar Radio Telescope

Not a new idea!

- **First proposals pre-date *Apollo* missions**
  - **Research Program on Radio Astronomy and Plasma for Apollo Applications Program Lunar Surface Missions: Final Report 1966, North American Aviation Inc.**
  - **Greiner, J. M. 1967, "Utilization of Crater Reflectors for Lunar Radio Astronomy," Working Group on Extraterrestrial Resources**
- **Far side of Moon long recognized as unique astronomical platform**

  International Telecommunications Union radio quiet zone

➢ **EoR-Cosmic Dawn-Dark Ages may provide first compelling scientific motivation**

Cosmic Dawn beyond NASA

Chang'E 4 lunar lander

- **0.1--40 MHz system**
- ➢ **Likely to suffer significant interference from on-board ground-penetrating radar**