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?

![Graph of Hydrogen Signal](image)

- **HERA, EDGES-Lo, SKA1-Low, LWA-LEDA, …**
  - Lowest frequency ~ 50 MHz ~ redshift of 30
  - Due to atmospheric (ionospheric) opacity
  - Caveat: RFI

**Space-based Probes for Cosmic Dawn**
## Astrophysics Missions

### NASA Vocabulary

<table>
<thead>
<tr>
<th>Class</th>
<th>Budget (~ $M)</th>
<th>Examples</th>
<th>ESA equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission of Opportunity (MoO)</td>
<td>65</td>
<td>INTEGRAL, NICER</td>
<td>S class</td>
</tr>
<tr>
<td>Explorer (both Small and Medium)</td>
<td>250</td>
<td>GALEX, WISE, <em>Swift</em>, WMAP, … NuSTAR, TESS</td>
<td></td>
</tr>
<tr>
<td><em>Probe</em></td>
<td>&lt; 1000</td>
<td><em>Fermi</em>, <em>Spitzer</em>, <em>Kepler</em></td>
<td>M class</td>
</tr>
<tr>
<td>Flagship</td>
<td>&gt; 1000</td>
<td><em>Hubble</em>, <em>JWST</em>, WFIRST</td>
<td>L class</td>
</tr>
</tbody>
</table>

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

#### Enduring Quests

**Daring Visions**

**NASA Astrophysics in the Next Three Decades**

<table>
<thead>
<tr>
<th>Near-Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravitational Waves</td>
</tr>
<tr>
<td>Cosmic rays</td>
</tr>
<tr>
<td>JEM-EUSO</td>
</tr>
<tr>
<td>Radio</td>
</tr>
<tr>
<td>Microwave</td>
</tr>
<tr>
<td>Infrared</td>
</tr>
<tr>
<td>JWST</td>
</tr>
<tr>
<td>WFIRST-AFTA</td>
</tr>
<tr>
<td>Euclid</td>
</tr>
<tr>
<td>Optical</td>
</tr>
<tr>
<td>TESS</td>
</tr>
<tr>
<td>Gaia</td>
</tr>
<tr>
<td>Ultraviolet</td>
</tr>
<tr>
<td>X-rays</td>
</tr>
<tr>
<td>NICER</td>
</tr>
<tr>
<td>Astro-H</td>
</tr>
<tr>
<td>Gamma rays</td>
</tr>
</tbody>
</table>
Predicting the Future II
Free Energy

Assumes (1) President’s FY16 budget request and notional runout through FY20, (2) flat funding for Astrophysics for FY21 through FY35, (3) completion of WFIRST-AFTA and other missions planned for new starts in FY16-FY20.
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.

• **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.
Predicting the Future IV
Probes?

• Transient Astrophysics Probe
  High-z GRBs?
  ❖ Cosmic Dawn Intensity Mapper
• Cosmic Evolution Through UV Spectroscopy
• 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
• 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**

<table>
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<th>Examples</th>
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<td>Mission of Opportunity (MoO)</td>
<td>65</td>
<td>competed</td>
</tr>
<tr>
<td>Explorer (both Small and Medium)</td>
<td>125--250</td>
<td>competed</td>
</tr>
<tr>
<td><strong>Probe</strong></td>
<td>&lt; 1000</td>
<td>??</td>
</tr>
<tr>
<td>Flagship</td>
<td>&gt; 1000</td>
<td>{ OST</td>
</tr>
</tbody>
</table>

**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 ...
Smaller frequency range reduces requirements on antennas-receivers and data volumes

Foregrounds, foregrounds, foregrounds
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
The Dawn of Black Holes

The Invisible Drivers of Galaxy and Structure Formation

The Energetic Side of Stellar Evolution and Stellar Ecosystems

Endpoints of stellar evolution
Stellar birth, coronal physics, feedback
Impact of stellar activity on habitability of planets

Lynx deep field
JWST deep field
Illustris-TNG simulation: gas
Illustris-TNG simulation: galaxies

Credit: A. Vikhlinin
## Seeing into the dark ages with Origins Space Telescope (OST)

<table>
<thead>
<tr>
<th></th>
<th>Today</th>
<th>Reionization</th>
<th>First Galaxies</th>
<th>First Stars</th>
<th>Dark Ages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>REDSHIFT</strong></td>
<td>1</td>
<td>6</td>
<td>8</td>
<td>12</td>
<td>16</td>
</tr>
<tr>
<td><strong>BILLIONS of YEARS AGO</strong></td>
<td>12.6</td>
<td>13.1</td>
<td>13.4</td>
<td></td>
<td>13.5</td>
</tr>
</tbody>
</table>

### Instrument Details

<table>
<thead>
<tr>
<th></th>
<th>Hubble Space Telescope</th>
<th>James Webb Space Telescope</th>
<th>Origins Space Telescope</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Diameter</strong></td>
<td>2.4 meter</td>
<td>6.5 meter</td>
<td>9 meter</td>
</tr>
<tr>
<td><strong>Wavelength</strong></td>
<td>0.1–2.4 µm</td>
<td>0.6–27 µm</td>
<td>5–660 µm</td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td>260 K</td>
<td>50 K</td>
<td>4 K</td>
</tr>
</tbody>
</table>
Lunar Radio Telescope
Not a new idea!

• First proposals pre-date *Apollo* missions

• 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

5 m HF monopoles