Enduring Quests – Daring Visions

NASA - Astrophysics Division Roadmap

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OUR CHARTER

http://science.nasa.gov/media/medialibrary/2013/02/22/secure-Astrophysics_Roadmap_Team_Charter-final.pdf

This Road Map will:

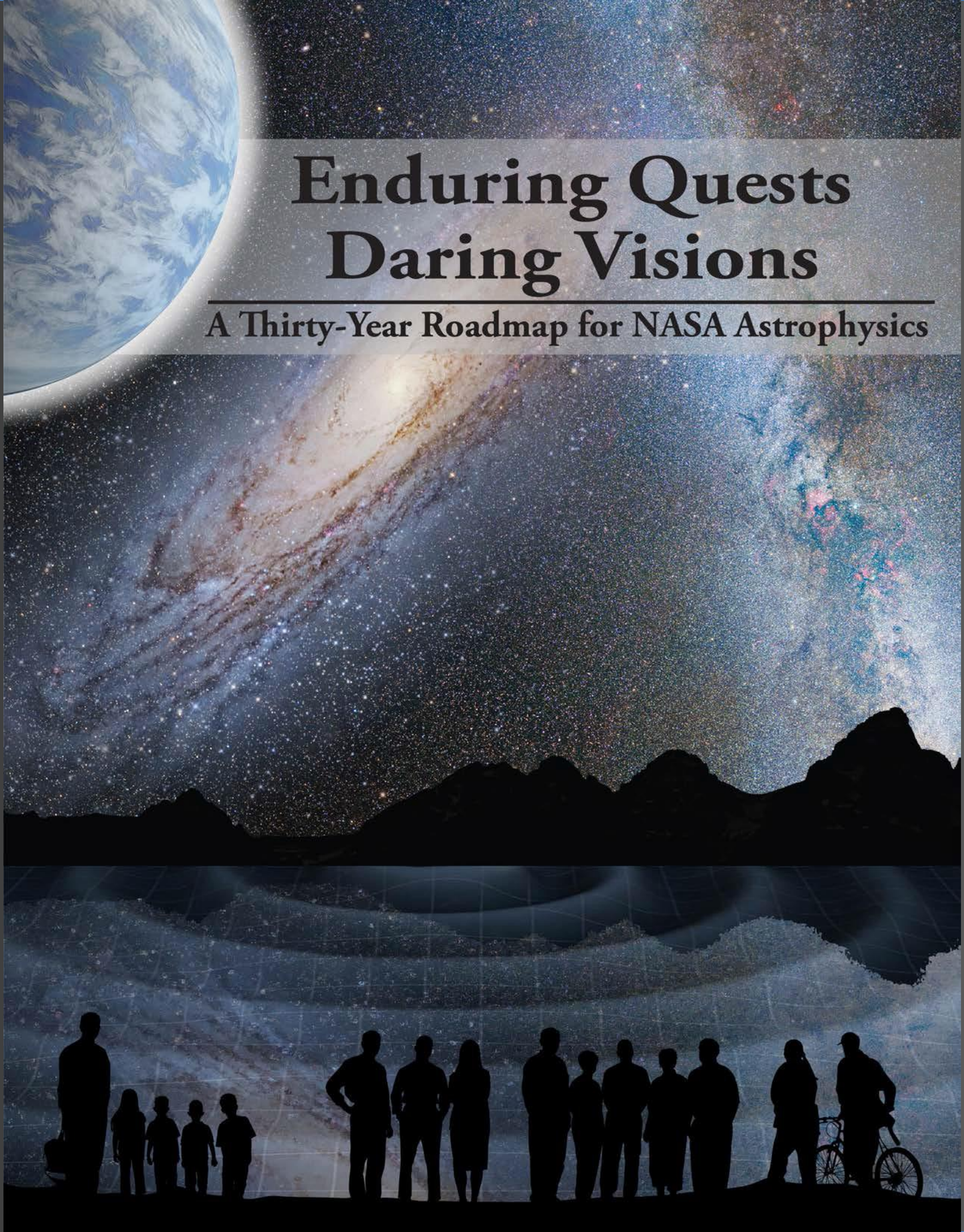
- present a compelling, 30-year vision
- take the Astro2010 decadal survey as the starting point and build upon it
- be science based, with notional missions
- be developed by a task force of the Astrophysics Subcommittee (APS)
- take into account community input solicited Town Hall meetings and other potential calls for input
- be delivered to APS

Note that the roadmap

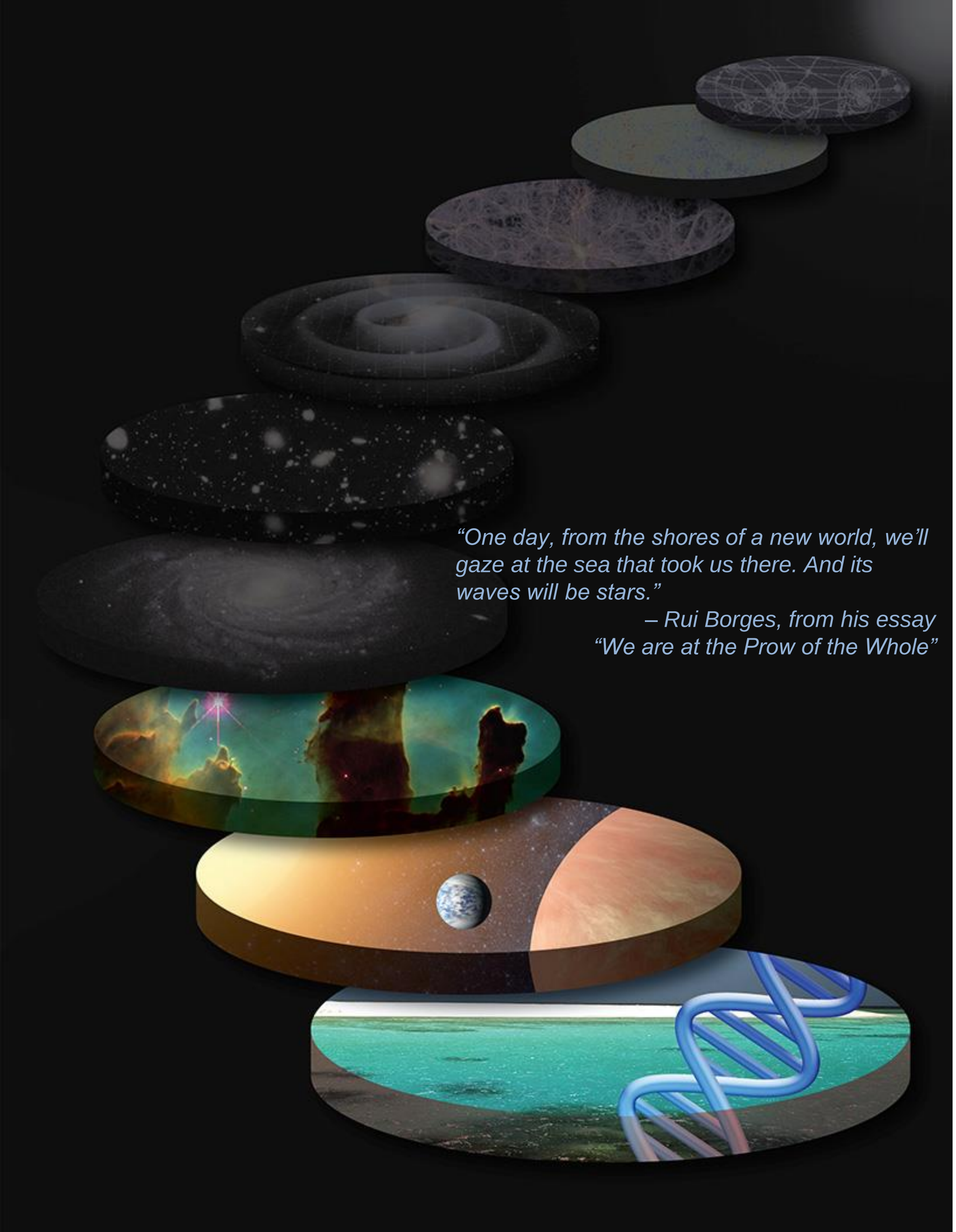
- is ***not*** a mini-decadal survey with recommendations and priorities
- is ***not*** an implementation plan
- ***is*** a long-range vision document with options, possibilities and visionary futures

Enduring Quests Daring Visions

A Thirty-Year Roadmap for NASA Astrophysics



- Probe the inflationary era
- Map Cosmic Microwave Background
- Chart Large Scale Structure
- Map extreme spacetime
- Map galaxy assembly
- Detail galactic chemo-dynamics
- Characterize planetary systems
- Find exo-Earths
- Search for life



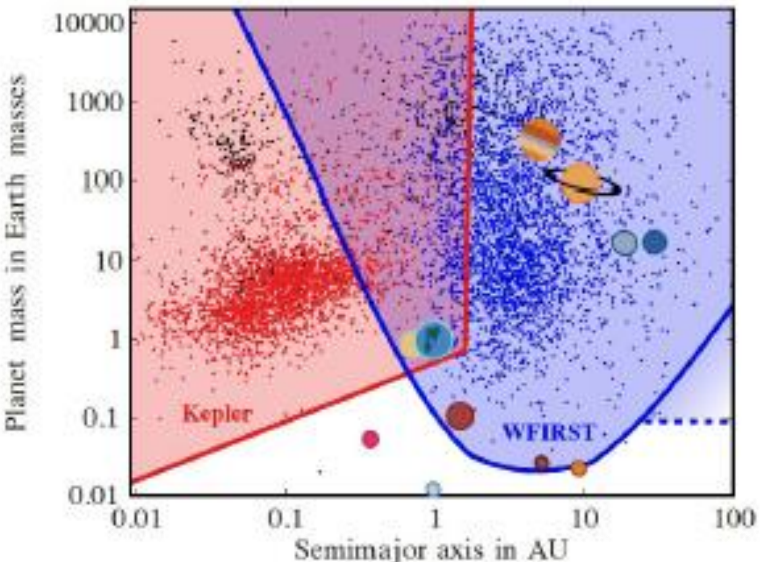
Are we alone?

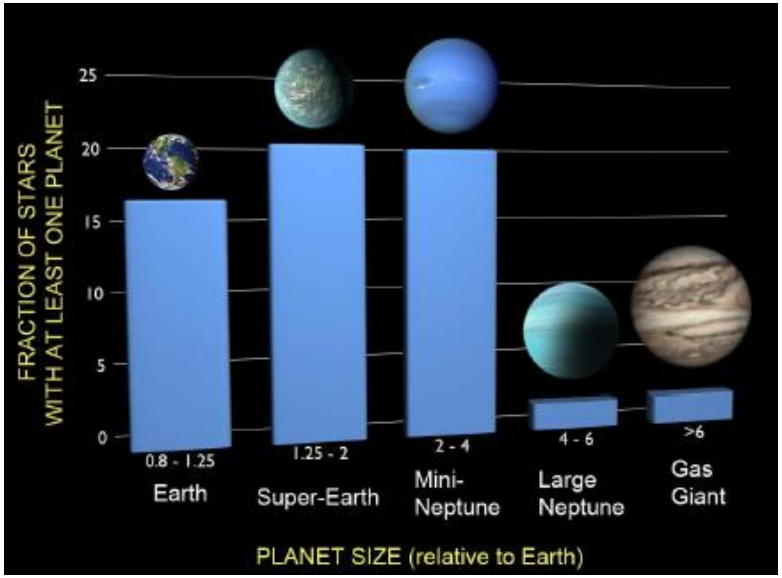
- Catalog the full diversity of planetary systems
- Perform detailed characterization of a broad sample of exoplanets
- Study nearby exoEarths in detail, and identify habitable climates and evidence for life on these worlds

The exoplanet Zoo

Complete the census of exoplanets

Ground-based surveys have revealed many exotic types of planets, including Hot Jupiters and Super-





Kepler has fully surveyed the population of "hot" and "warm" planets, and has measured the fraction of stars hosting exoEarths, η_{EARTH}=*15*-20%. *TESS* and the next generation ELTs will explore the population of exoEarths around red dwarfs.

WFIRST-AFTA will complete the *Kepler* census by measuring the frequency of "cold" outer planets using two techniques: gravitational microlensing, and high-contrast direct imaging using an internal

What are exoplanets like?

Comparative planetology

Current Exoplanet motley crew:
Super Earths
Mini-Neptunes
Hot Jupiters
Super-Jupiters
ExoEarths

Comparative planetology requires:

- *planet sizes*: in fainter, distant systems (*Kepler*), and in nearby, bright stars (*TESS*)
- *planet masses* (current and future ground-based RV)
- *planet spectra* (*HST*, *Spitzer*, *JWST, WFIRST-AFTA, LUVOIR Surveyor*)

JWST will provide high-precision time-resolved spectra for transiting planets discovered from the ground, *Kepler*, and *TESS*, possibly including planets close to exoEarth sizes orbiting low mass stars.

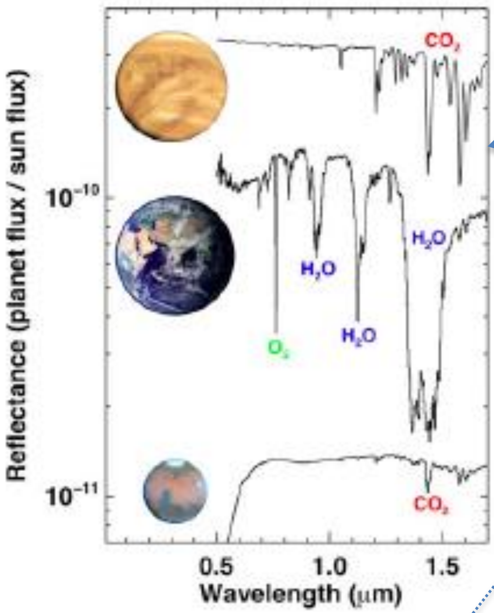
WFIRST-AFTA-coronagraph will survey dozens of the nearest stars for Jupiters and Saturns, and characterize a subset of the discoveries.

LUVOIR Surveyor will discover and characterize the atmospheres of a diversity of exoplanets orbiting nearby stars, and identify exoEarths with potentially habitable climates.

***Kepler*+ *TESS* + *JWST* + *WFIRST-AFTA* + *LUVOIR Surveyor* will enable extensive comparative planetology and identify exoEarths (η_{EARTH})**

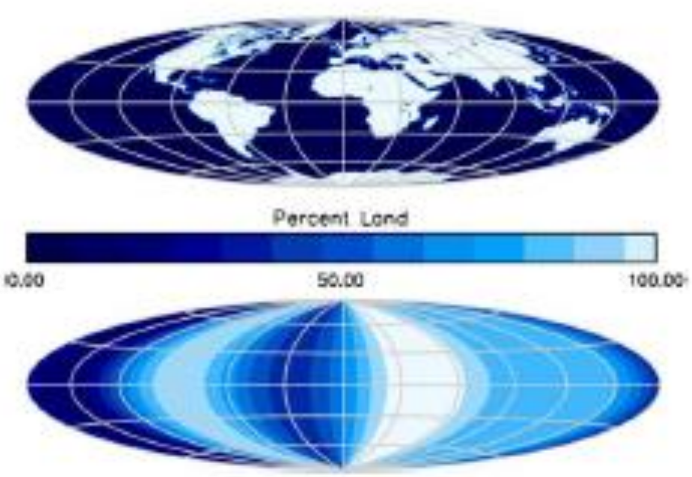
The search for life

Pale Blue Dots

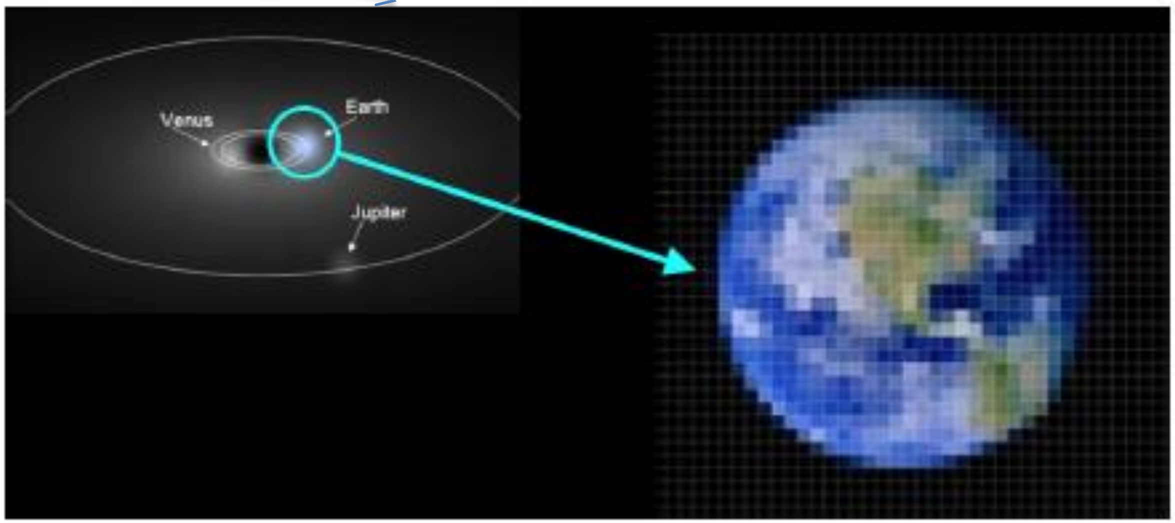


Step 1: Measure the frequency of potentially habitable planets.

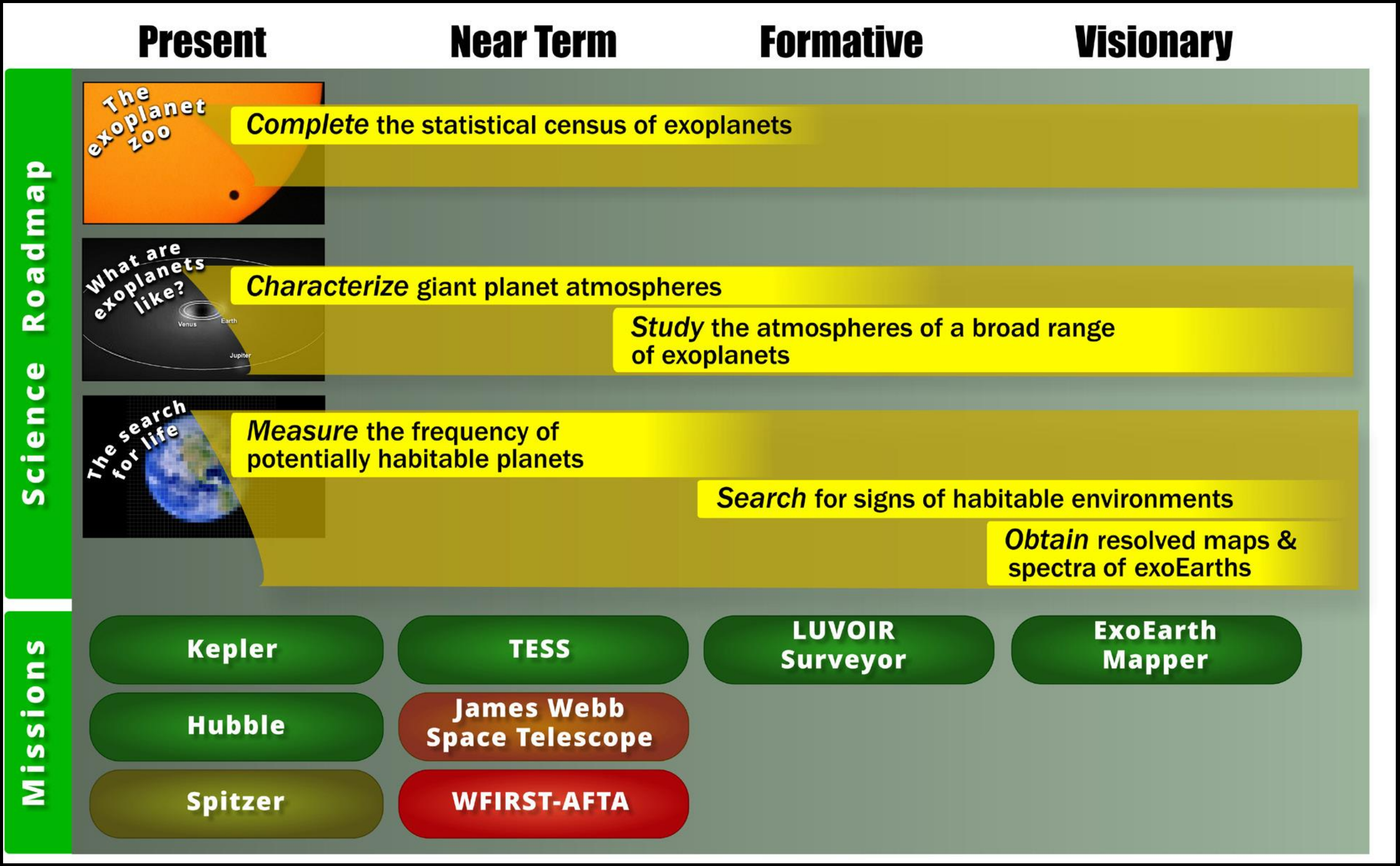
Step 2: Identify nearby potentially habitable planets and characterize these in great detail:



Step 3: Identify and map the most promising ExoEarth



Are we Alone?

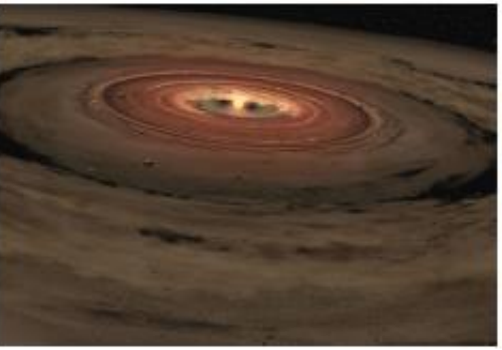

Present
Near Term
Formative
Visionary
Science Roadmap
The exoplanet zoo
Complete the statistical census of exoplanets
What are exoplanets like?
Venus
Earth
Jupiter
Characterize giant planet atmospheres
Study the atmospheres of a broad range of exoplanets
The search for life
Measure the frequency of potentially habitable planets
Search for signs of habitable environments
Obtain resolved maps & spectra of exoEarths
Missions
Kepler
TESS
LUVOIR Surveyor
ExoEarth Mapper
Hubble
James Webb Space Telescope
Spitzer
WFIRST-AFTA

How did we get here?

- Map newborn stellar and planetary systems across the Milky Way
- Decode the assembly of our Milky Way galaxy
- Characterize the detailed nature of the Universe's first galaxies and the subsequent growth of all galaxy components over cosmic

Stellar Life Cycles

Evolution of the elements



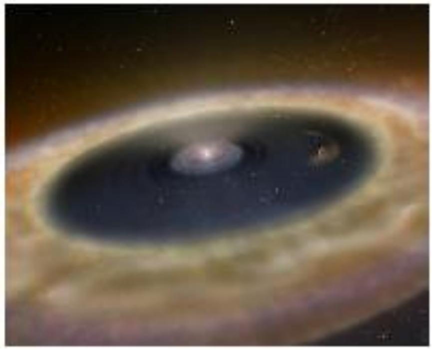
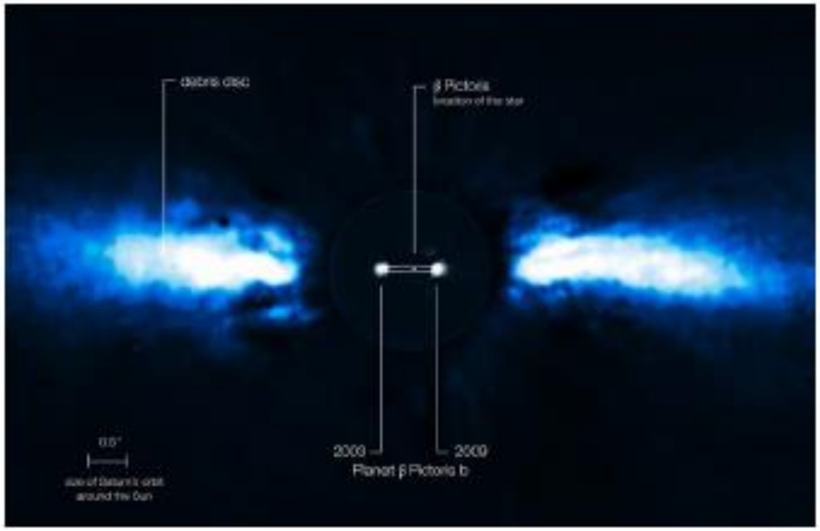


Chart 1000s of stellar nurseries

ALMA: molecular clouds and dust, planets via protoplanetary disk gaps

JWST, ELTs: search for rocky planets at inner regions

FIR Surveyor: map the distribution of water
LUVOIR Surveyor: characterize warm dust / inner regions of debris disk



Stellar Feedback

- Study SN-induced feedback with the *X-ray Surveyor*
- Establish stellar Initial Mass Function (IMF) over all mass scales & environments

Archaeology of MW & its Neighbors

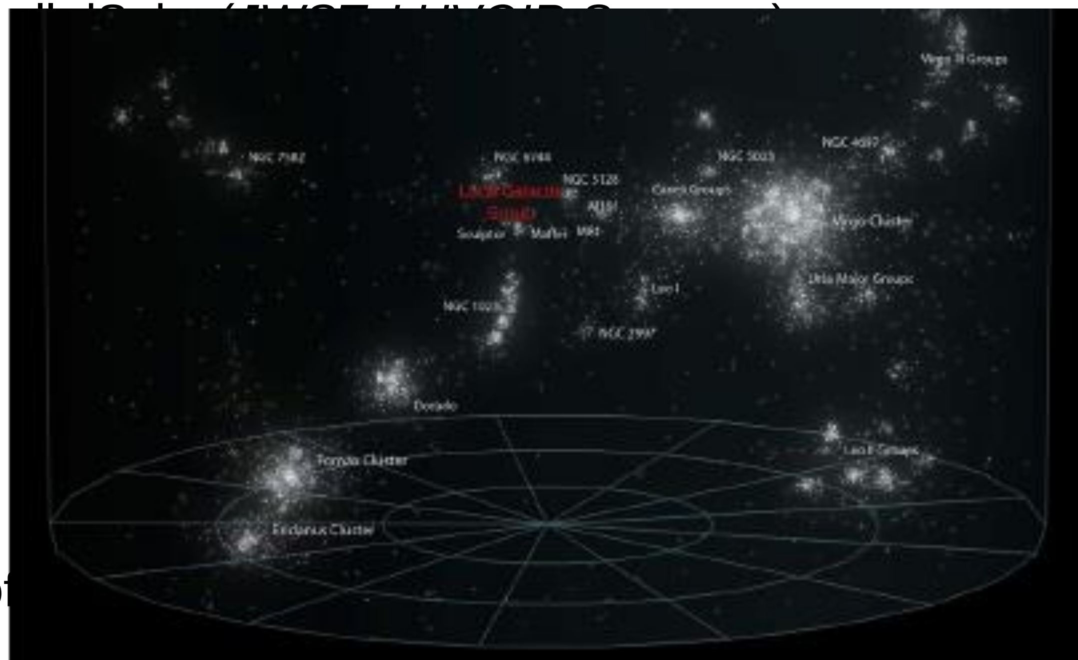
Study the fossil records

Our Milky Way

- Establish a census of the MW structure and stellar populations (*LSST, WFIRST-AFTA*)
- Fully characterize the MW relics: streams, clusters, halo stars, bulge, dwarf spheroidals (dSphs) (*LSST, WFIRST-AFTA, GAIA, ELTs, LUVOIR Surveyor*)
- Measure the MW mass from 3-D velocities of distant halo tracers
- Test DM models from 3-D velocities for stars in

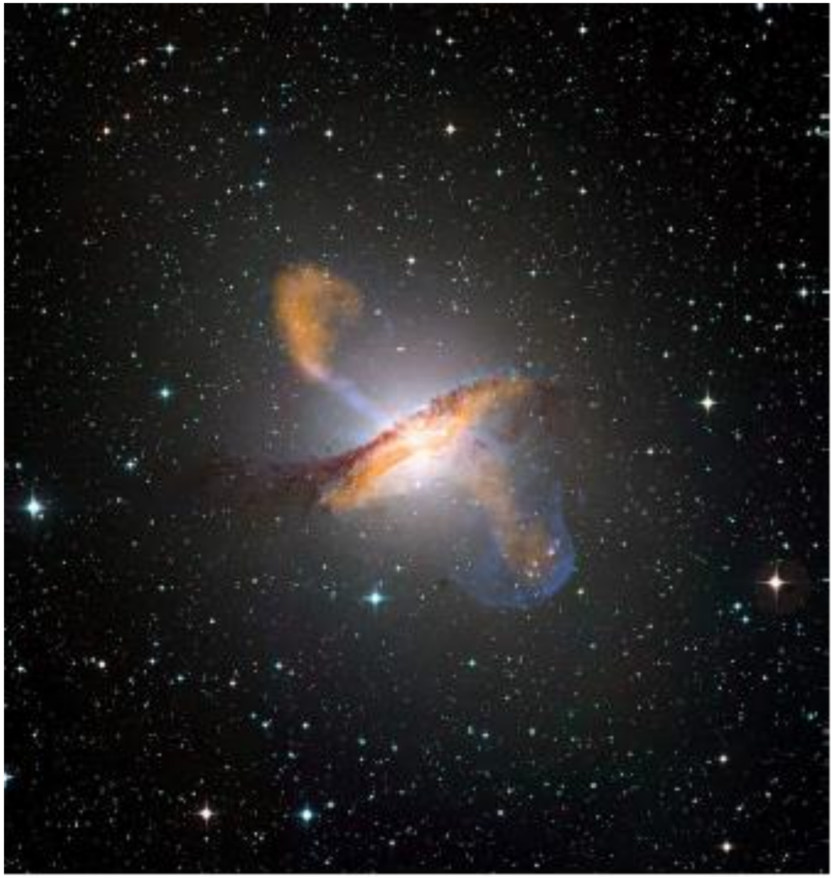
Our Neighbors

- Resolve the entire Hubble sequence & measure the surface brightness, Star Formation History, radial velocities, ages, halo shapes of hundreds of galaxies (*ELTs, JWST, WFIRST-AFTA*)
- Characterize spatial and kinematic substructure
- Measure chemical abundance gradients
- Establish tests of high-resolution simulations of galaxy formation
- Measure the line of sight absorption of cool, warm & hot gas



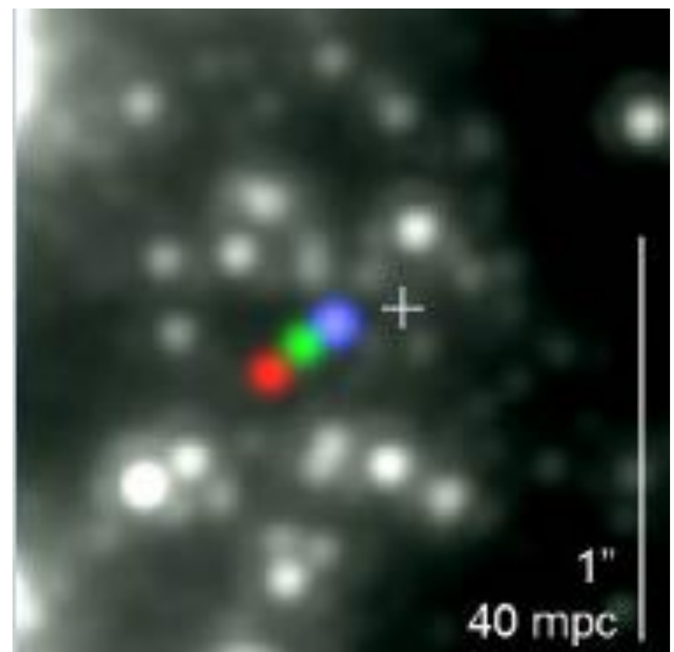
The history of galaxies

Monsters in the middle



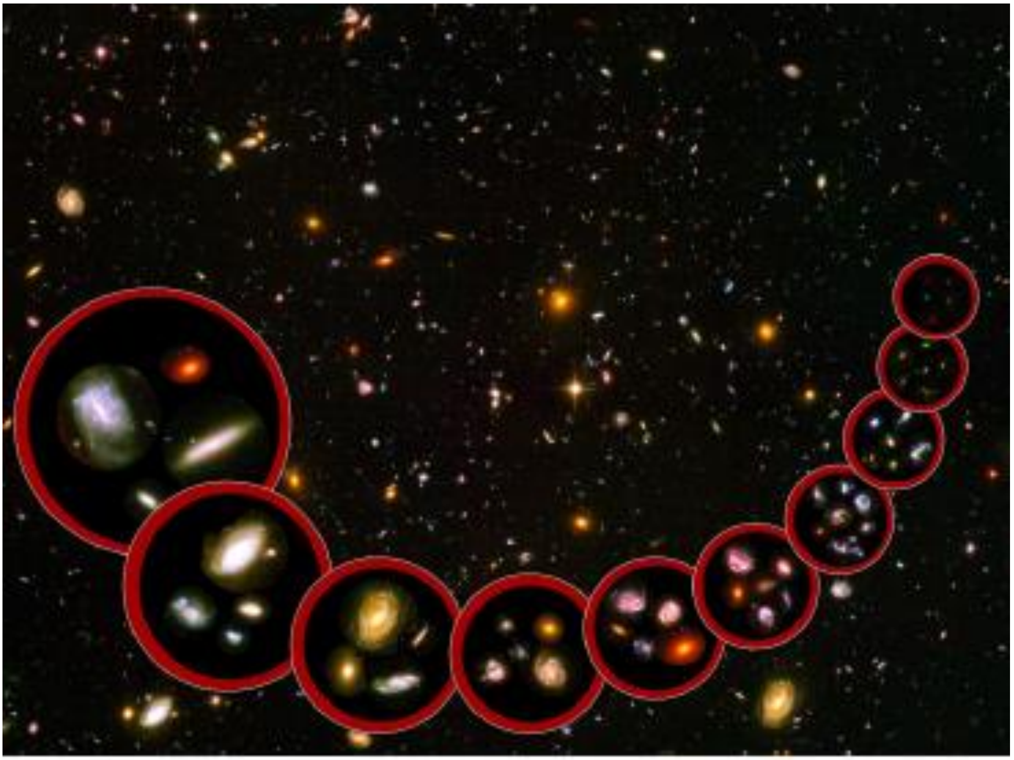
AGN Feedback

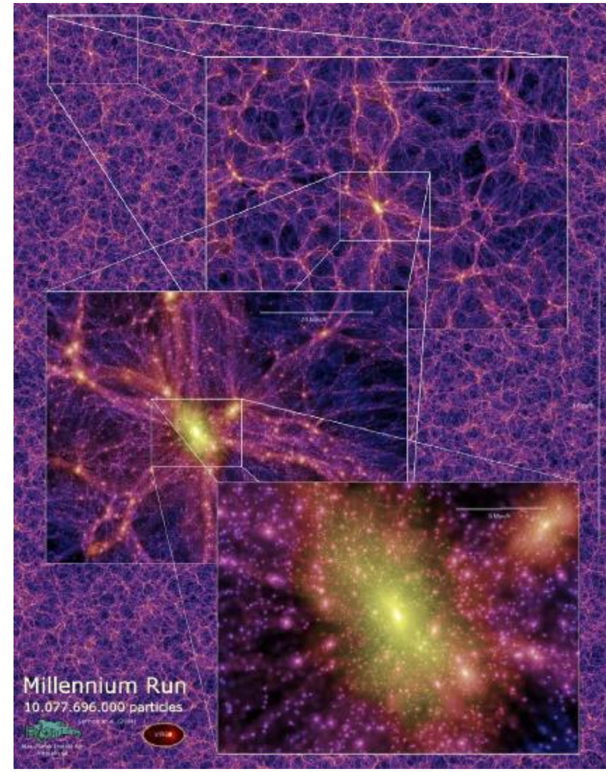
• Determine modes of galaxy-SMBH growth: “*what the monster ate*”
• Measure distribution of SMBH spins and masses in cosmic time: “*how it ate it*”
• Synergy progression: ALMA, *JWST, LUVOIR Surveyor, X-ray Surveyor* and *BH Mapper, Gravitational Wave Surveyor* and *Mapper*



The history of galaxies

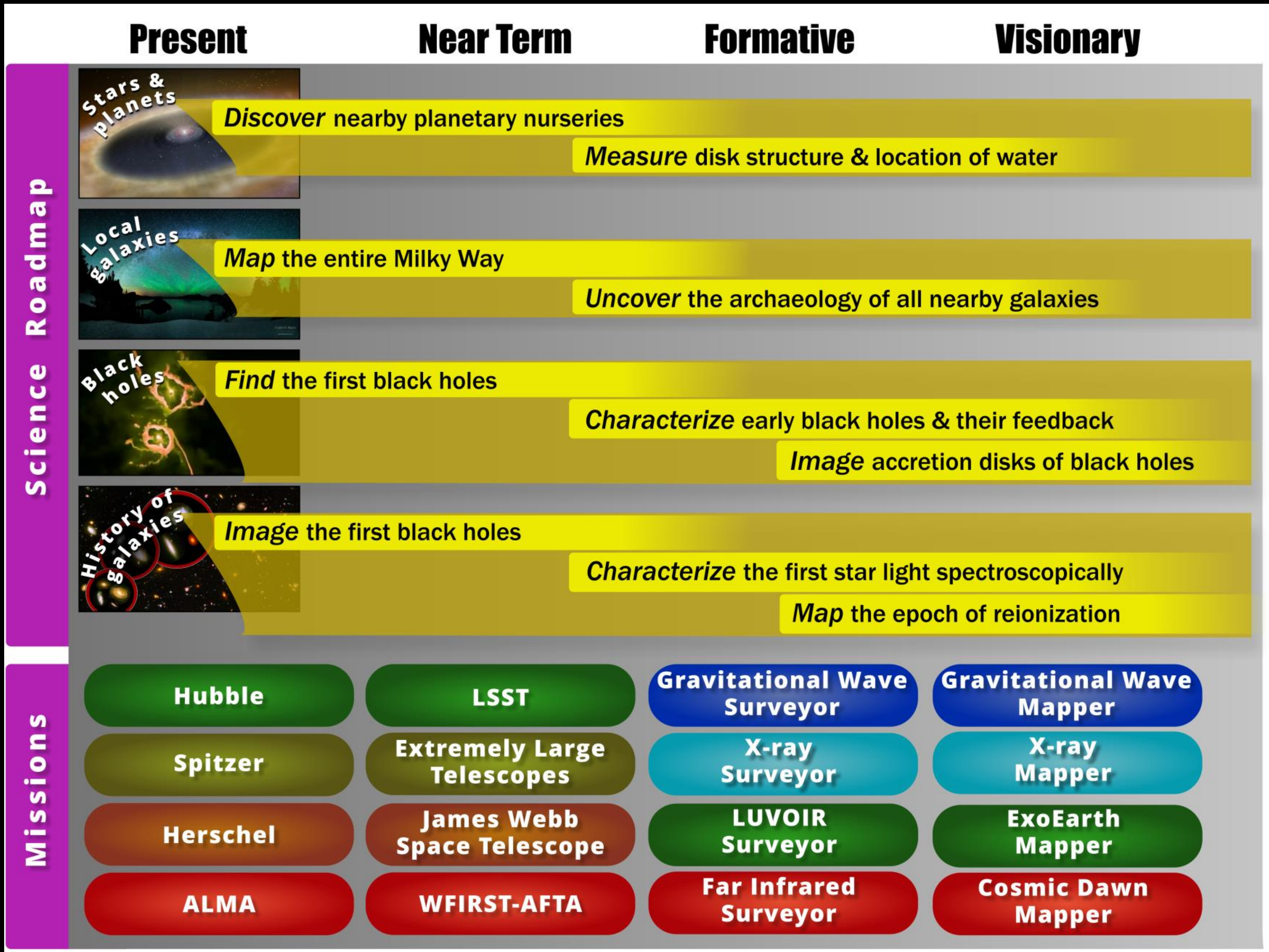
Manufacturing and Assembly

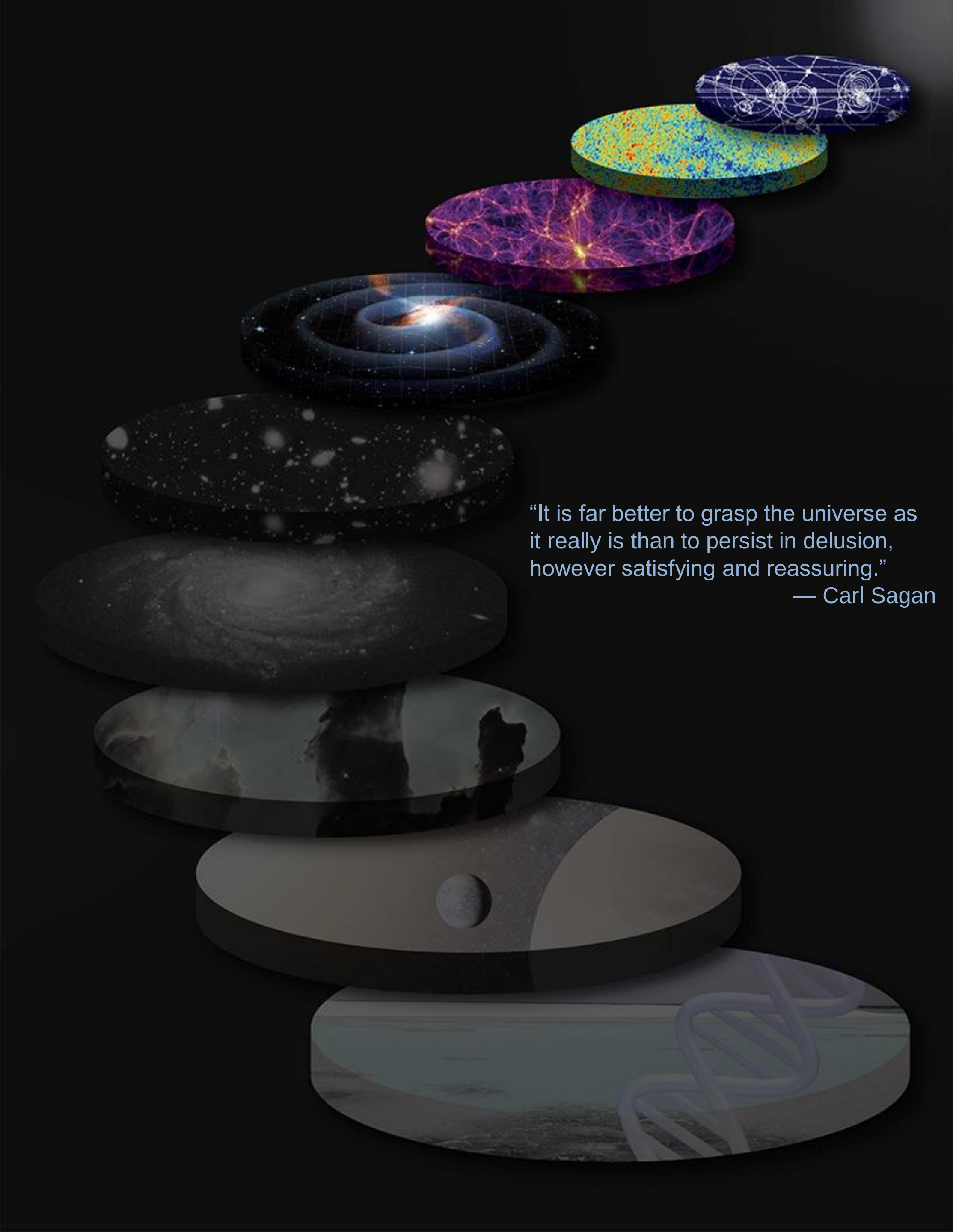




- Characterize the physical nature of the first galaxies – Measure buildup of metals since z~15
- Understand the effect of dark energy on galaxy assembly
- Map the distribution, dynamics & chemistry of gaseous galactic halos
- Map the cosmic web: measure the cold, warm and hot baryon mass budget in galaxies, galaxy clusters, and IGM
- Detect the emergence of structure during the Dark Ages (z~10-20) via 21-cm observations

How Did We Get Here?



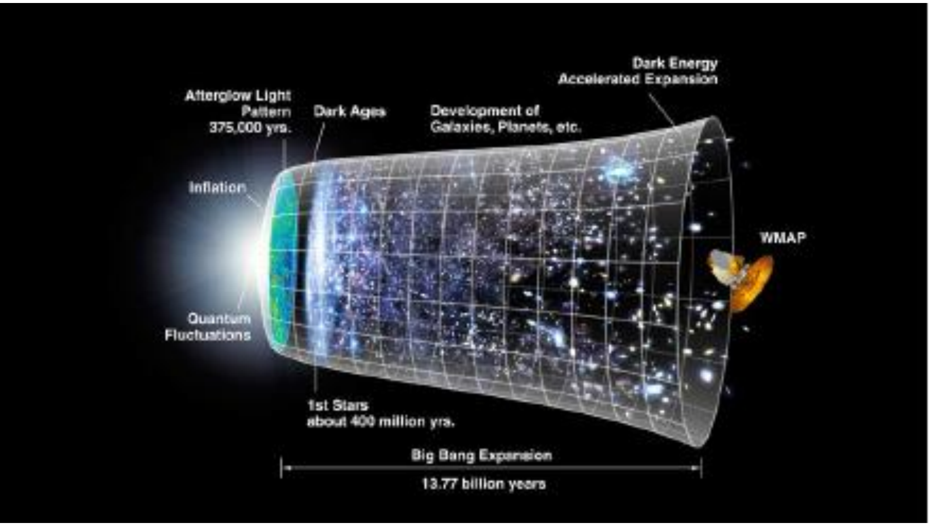


How does the Universe work?

- Probe the imprints of the Big Bang to shed light on the origin of our Universe
- Pin down the forms of matter and energy that govern the expansion and fate of our Universe
- Open a new window on the cosmos by measuring ripples of spacetime
- Explore the extremes of gravity and matter, from the horizons of black holes to the edge of the Universe, to test the limits of our fundamental physics

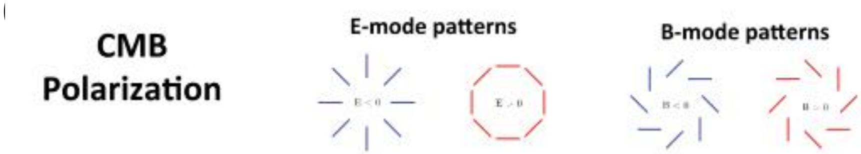
The origin and fate of the Universe

The Big Bang



• Map the CMB to cosmic variance limits using primordial GW signature (B-mode polarization) to derive powerful constraints on the inflationary epoch (*CMB Polarization Surveyor*)

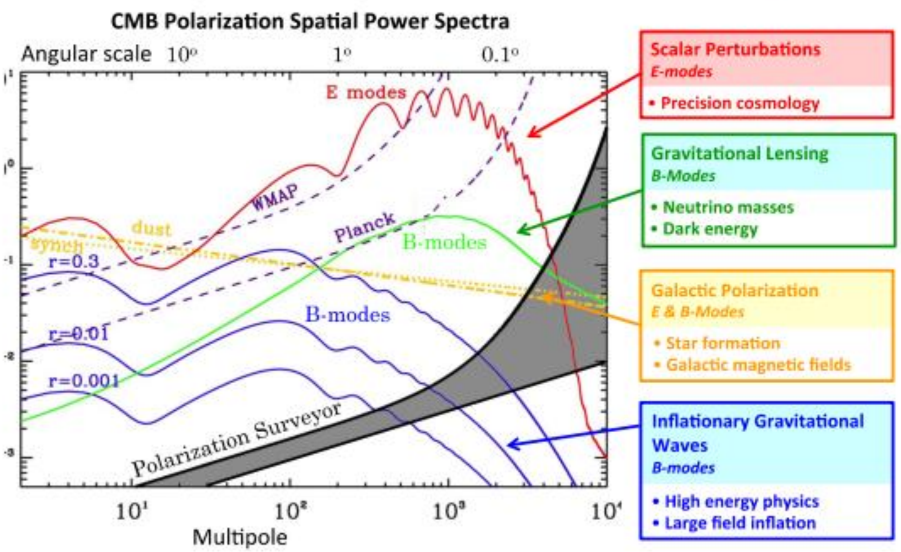
• Probe the thermal history of the Universe by measuring imprints of relics & recombination on CMB blackbody spectrum



• Constrain theories of cosmic acceleration with *WFIRST-AFTA, LSST, Euclid*

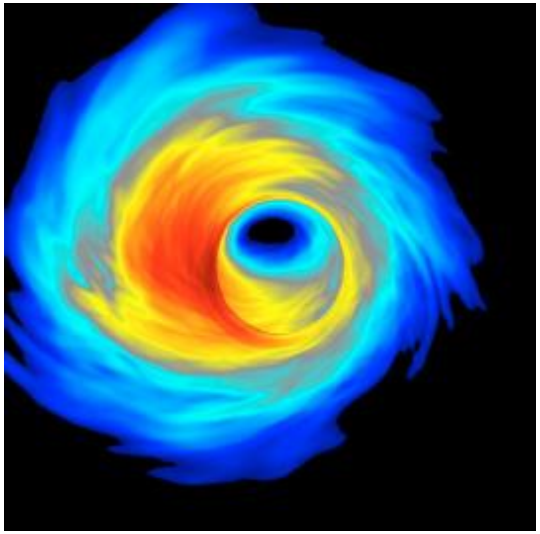
• Measure the cosmological constant to determine the fate of our Universe

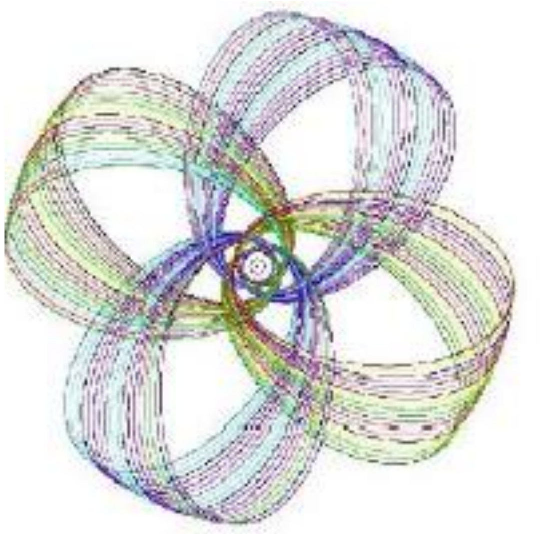
• Detect the emergence of structure during the Dark Ages (z~10-20) via 21-cm observations (*Cosmic Dawn Mapper*)



The extremes of Nature

Black Holes



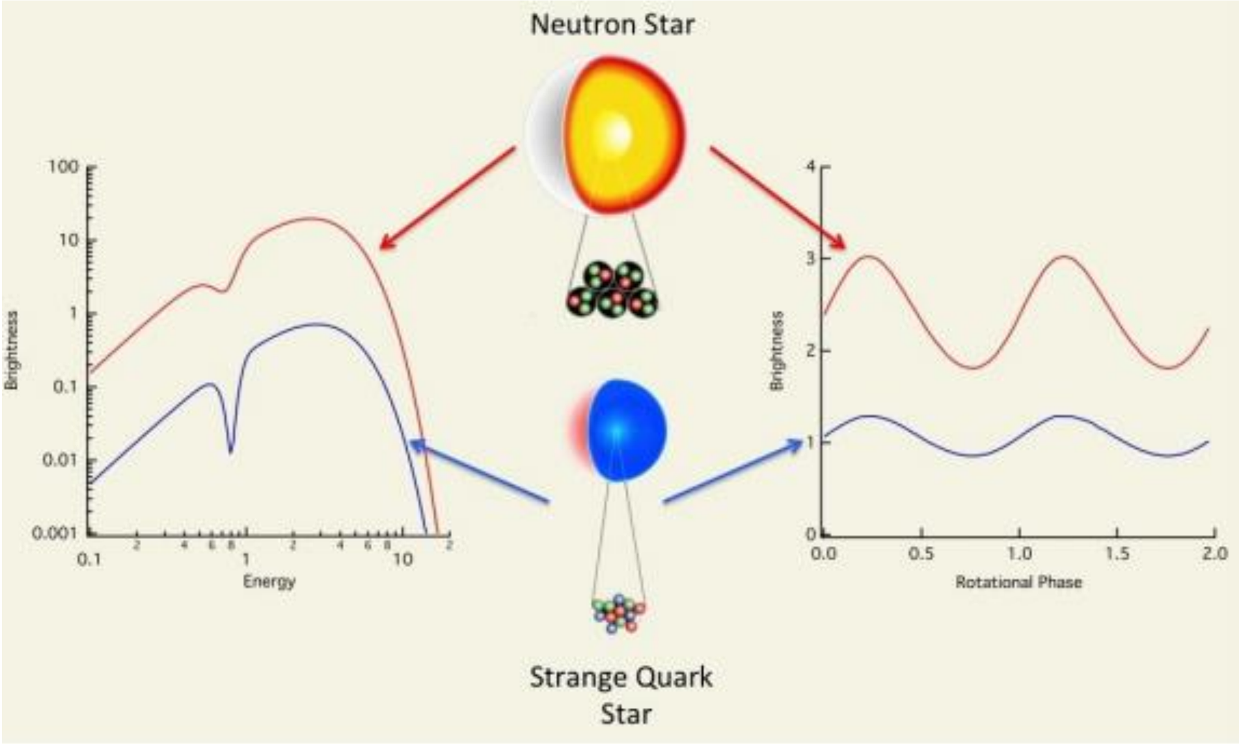


Understand the accretion-driven engines

• Measure BH masses and spins (accretion diagnostics and mergers) (*X-ray, GW Surveyors*)
• Direct imaging (sub-microarcsecond) of powerful accretion flows around SMBH and the launching regions of jets; ultimate tests of accretion models (*BH Mapper*)
• Test strong-field GR and map spacetime around SMBHs via GW from Extreme Mass Inspirals and merging SMBHs (*GW Surveyor)*

The extremes of Nature

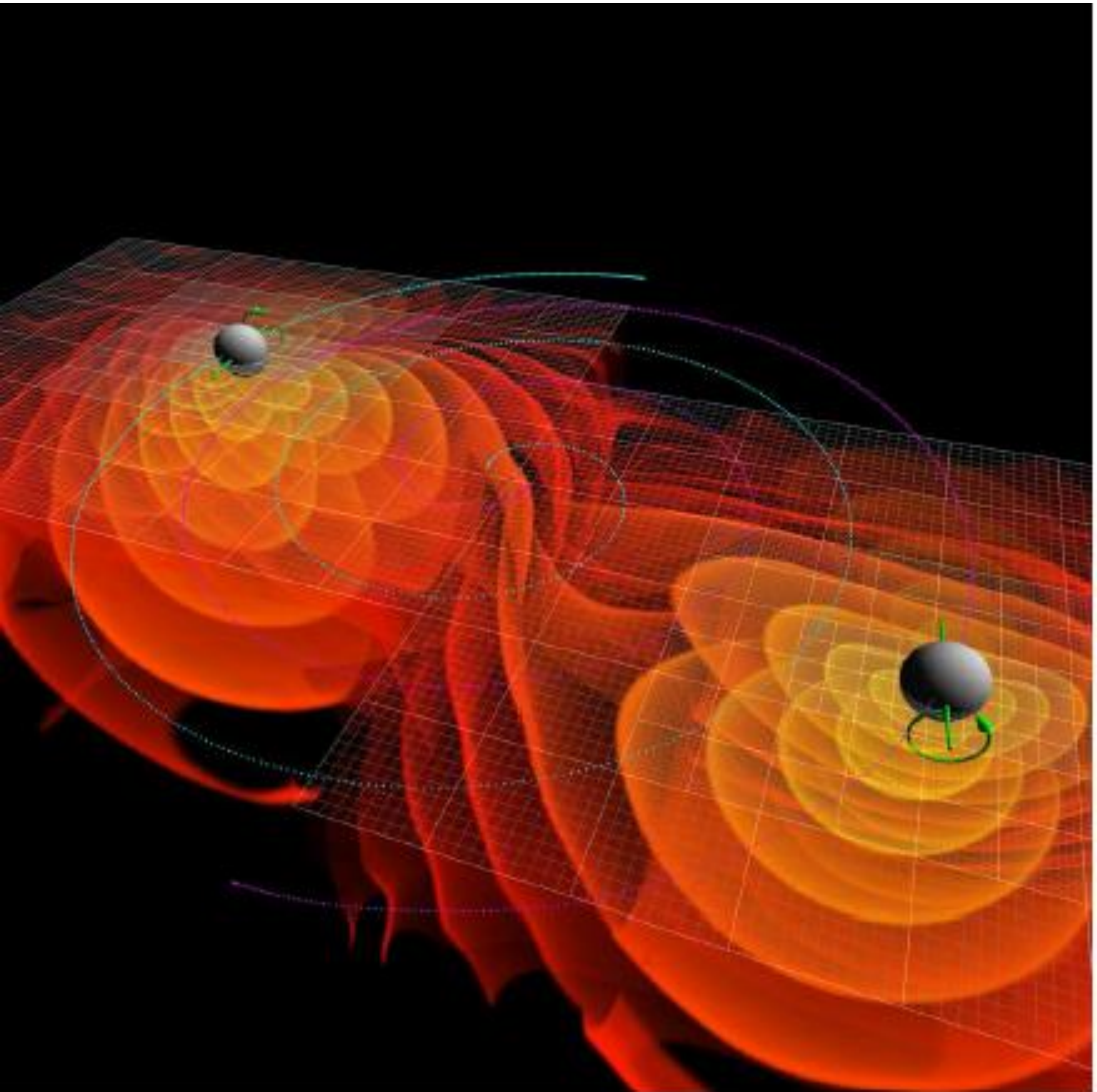
Neutron stars



• Determine the composition and interactions of particles at the NS cores - constrain the equation of state of NS (*NICER, X-ray Surveyor*)

Listening to the Cosmos

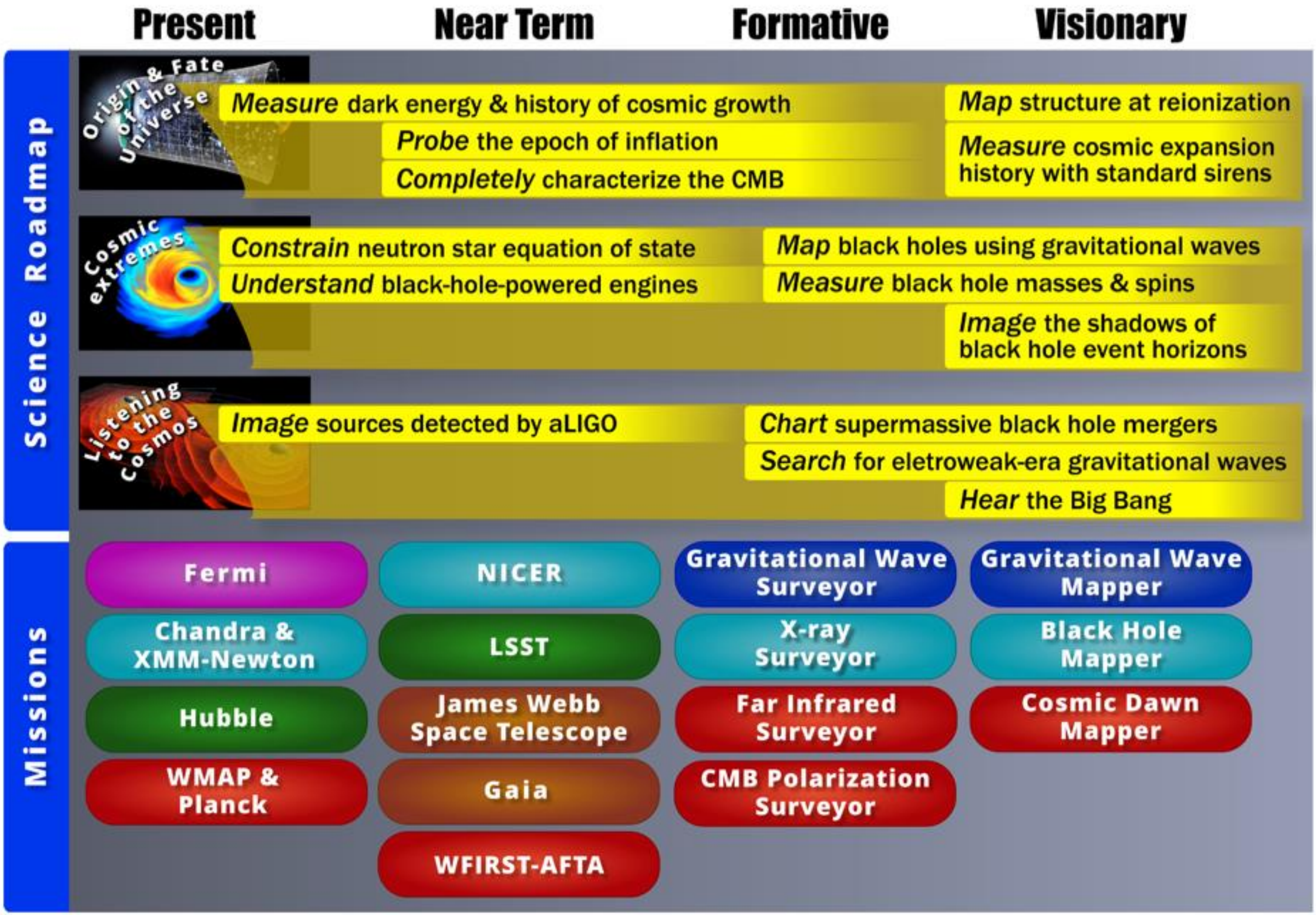
The Gravitational Wave window



- Track BH mergers across all of cosmic time
- Probe exotic phenomena – great potential for surprises
- Direct detection of primordial GWs; listening to inflation
- Chart the expansion history of Universe with GW standard sirens

(*Gravitational Wave Surveyor* and *Mapper*)

How Does the Universe Work?



Daring visions

- Sense the ripples in Gravity out to the edge of our Universe

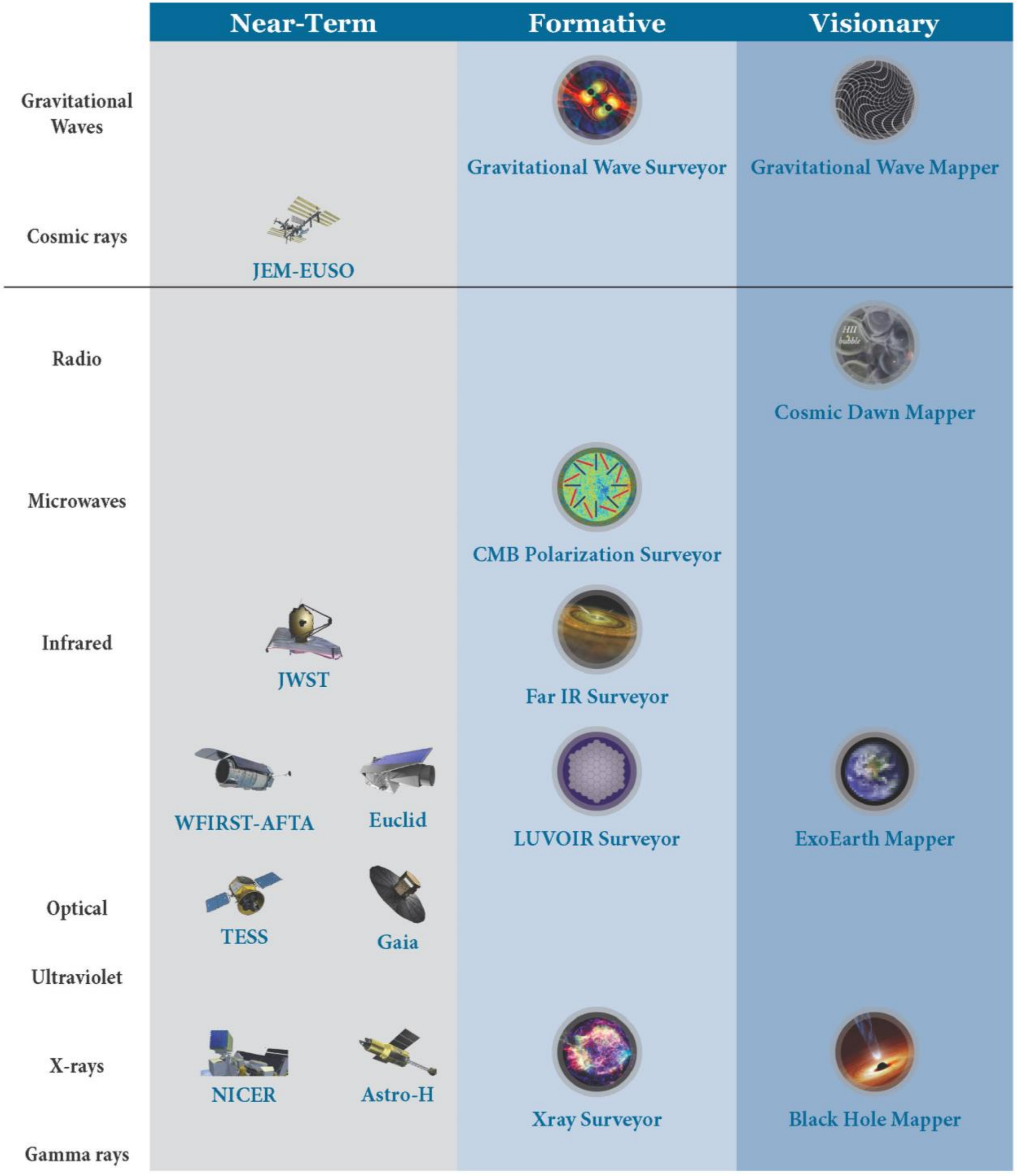
- Chart the warped space of a Black Hole and reveal how they power the greatest outflows of energy in the Cosmos

- Tell the complete the story of galaxies – from quantum fluctuations through first light to the present day

- Reconstruct the complete star formation, structural and chemical history of our Milky Way and its neighbors

- Map the Surface of an Earth-like planet

- Find evidence of life beyond the solar system



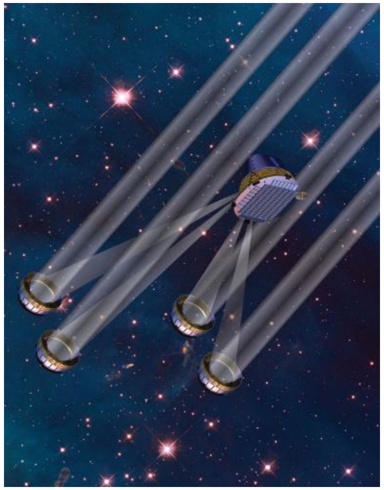
Three Eras

Near-Term

Formative

Visionary

Realizing the vision: notional missions and technologies



Formative Era: 5 **Surveyors**

Visionary Era: 4 **Mappers**

Probe-scale missions such as:

- Measure the BB spectrum distortions in the CMB
- Map the Universe's hydrogen clouds with a 21 cm lunar orbiter from the far side of the moon
- Monitor energetic transients with X- and gamma-ray telescopes
- Measure X- and gamma-ray polarization

Surveyors

Gravitational Wave Surveyor: 3 spacecraft with laser links between each, allowing for 3 independent interferometry signals (2 to measure polarization and one null). Full imaging require multiple arrays. Tech needs: precision micro-thrusters, frequency stabilized lasers, high-rigidity telescope assemblies and opt. benches, precision gravitational reference sensors.

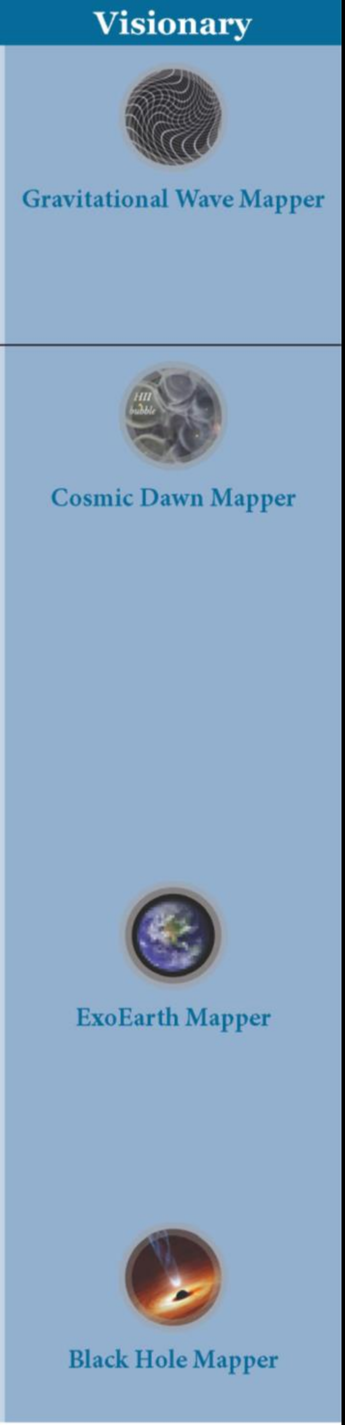
CMB Polarization Surveyor:1-4m aperture telescope with few arcmin resolution and high throughput optics. Tech needs: detector array readout electronics, large cryogenic optics systems, anti-reflection coatings, pol. Modulators, subkelvin cryo systems for large format detector arrays.

Far-IR Surveyor: Large gains to be achieved by actively cooled (4K) large dish (super-Herschel). Large aperture (4-6 m) + high res spec and ultimately interferometry to get sub-arcsec (2.5”) FIR images. Subkelvin focal plane coolers, 4K mech. Coolers, widefield spectrometers.

Surveyors

LUVOIR Surveyor: 8-16m telescope for large collecting area and high resolution. 16m would give diffraction limit of 8mas at 6000Å– with coronograph can get Earth-like planets at 3microns to 10pc.
Full wavelength coverage from 10microns to 91nm strongly constrained by technological constraints. Tech needs: optics deployment (segmented/robotic assembly), high reflectivity coating for all wavelengths, star light suppression.

Xray Surveyor: > 3m^2 collecting area with < 1” imaging and high resolution spectroscopy over 5’ FOV. 2 orders of magnitude better than Chandra. Tech needs: Large number of very thin shells and new technology to correct axial figure requirements, coatings, micro-calorimeter arrays, gratings.



Mappers

Gravitational Wave Mapper: >2 widely separated detectors significantly increases the ang. res. particularly if the peak sensitivity is moved to ~ 0.1Hz. Overall sensitivity is increased with more powerful lasers, larger telescopes and improved gravitational reference sensors.

Cosmic Dawn Mapper: 2-20m signals to study very high redshift 20cm line – array of thousands of radio antennas on the far side of the moon –3D map of neutral gas from EoR to deep into the dark ages.

Exo-Earth Mapper: Large optical-near IR space based interferometer. >370 km separation, collecting area of 500 m^2, R~100 spectroscopy.

Black Hole Mapper: Xray interferometer with (sub)microarcsec resolution to image black hole event horizon. Space array of optics kilometer in diameter with focal plane detectors 1000s of km farther away.

Cross-Cutting, game changing technologies

New technology: mirrors, on-orbit fabrication, assembly

The key to bigger and better space telescopes may rely on assembling and testing telescopes on-orbit, from subcomponents produced on Earth, and perhaps in the visionary period, from actually producing many components in space using so-called “smart materials’’ and advanced robotics and possibly astronauts.

3-D printing was invented ~30 years ago. Today 3-D printers are being used to manufacture a wide range of products from human transplants to firearms and even houses.

One could imagine, e.g., a lunar fabrication facility where giant telescope mirror support structures were printed and launched with a water reservoir and a small amount of metal.

Interferometry

Challenges:

- precision laser metrology
- formation flying
- beam combination, possibly with delay lines
- aperture synthesis techniques: beam combiner optimization, data analysis

"Somewhere, something incredible is waiting to be known"

Carl Sagan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