Enduring Quests – Daring Visions

NASA - Astrophysics Division Roadmap

The Roadmap team

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A vision, not a plan

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 Astrophysics 2011 decadal survey as the starting point and build upon it;
- be science based, with notional missions;
- be developed by 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.

We will embark on the most exciting era of NASA Astrophysics by answering the most profound and enduring questions about the beginning and nature of the Universe and our place in it.

I. Are we alone?
II. How did we get here?
III. How does our Universe work?

I. Are we alone?

We will identify and quantify the abundance and diversity of planetary systems.

We will find which of the nearest terrestrial exoplanets are habitable - and might be inhabited.

We will map habitable environments - and possibly biospheres - on nearby worlds.

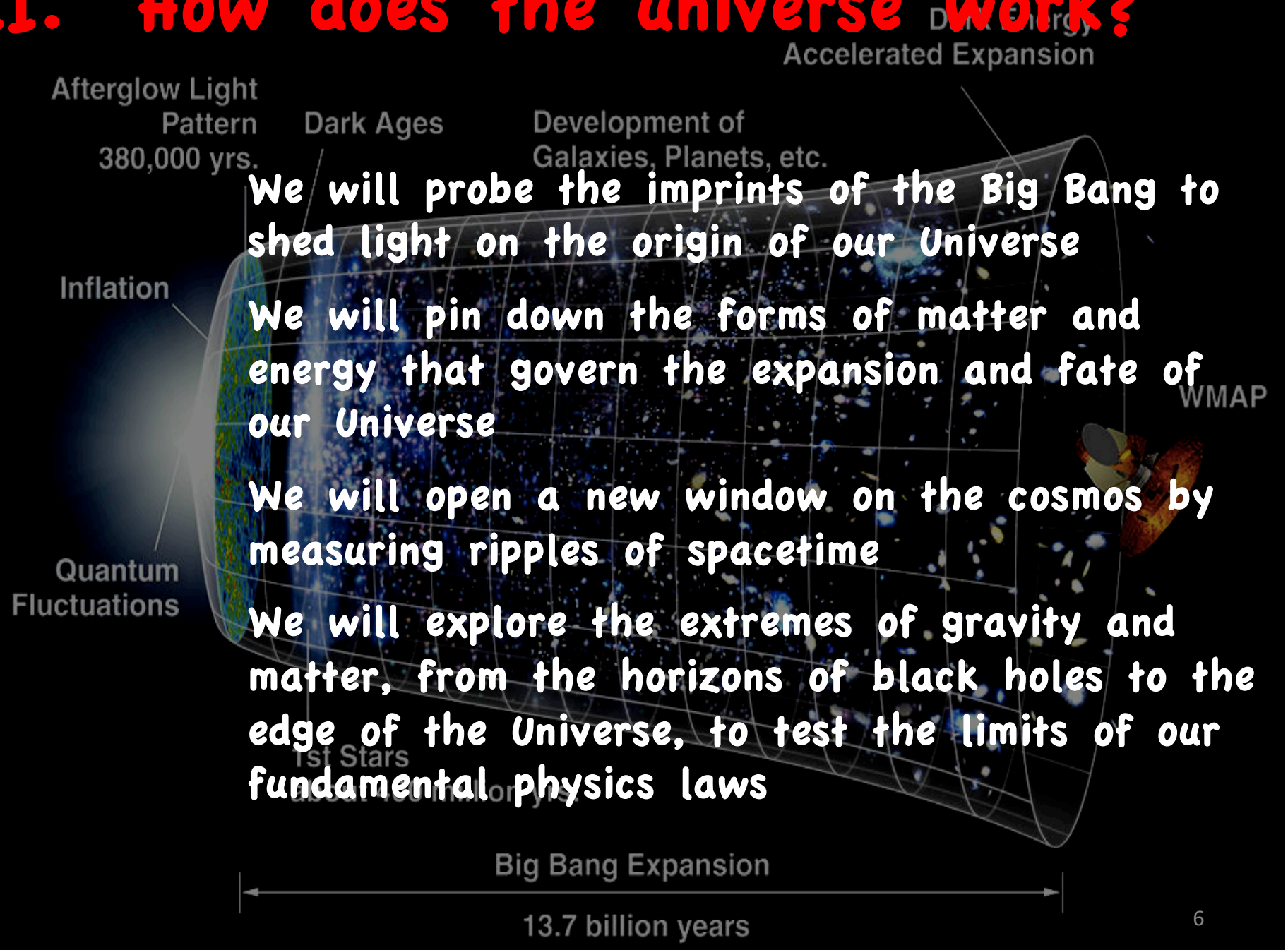
II. How did we get here?

We will map newborn stellar and planetary systems across the Milky Way

We will decode the assembly of our Milky Way galaxy

We will characterize the detailed nature of the Universe's first galaxies and the subsequent growth of all galaxy components over cosmic history

III. How does the universe work?



We will probe the imprints of the Big Bang to shed light on the origin of our Universe

We will pin down the forms of matter and energy that govern the expansion and fate of our Universe

We will open a new window on the cosmos by measuring ripples of spacetime

We will 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 laws

Daring Visions

- Map the Surface of an Earth-like planet
- Find evidence of life beyond the solar system

- Reconstruct the complete star formation, structural and chemical history of our Milky Way and its neighbors
- Tell the complete the story of galaxies – from quantum fluctuations through first light to the present day

- Chart the warped space of a Black Hole and reveal how they power the greatest outflows of energy in the cosmos
- Sense the ripples in Gravity out to the edge of our Universe

Way stations

Present - Near Future Era → 0 ~ 15 years

Formative Era → 15 - 30 years

Visionary Era → 30+ years

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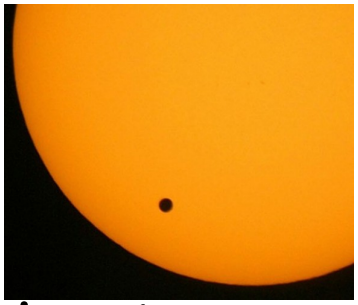
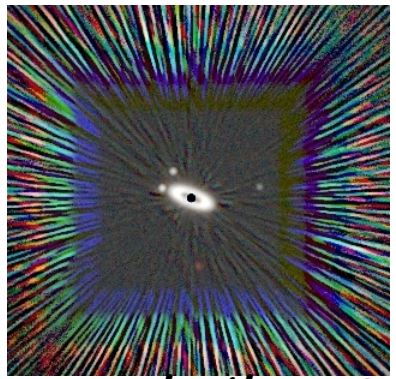
Are we alone?

Complete reconnaissance of exoplanets & find our nearest neighbors



Venus Transit

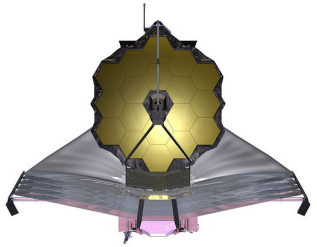
- Kepler:
  - Determine the frequency of habitable planets
- Ground-based Surveys of:
  - Nearby planets (radial velocities & high-contrast direct imaging, GMT, TMT, including future ELTs)
  - Dust in the habitable zones of nearby stars (LBTI)
- Space-based Surveys:
  - Find transiting planets around nearby stars (TESS)
  - Characterize their spectra with JWST
  - Determine exoplanet frequencies in outer parts of star systems using micro-lensing and high-contrast direct imaging (WFIRST + coronagraph)



Karl Stapelfeldt, private communication

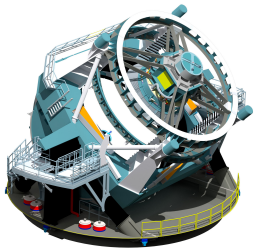
How did we get here?

Star and Planet Formation



- Characterize nearby protoplanetary disks (ALMA, JWST)

Milky Way

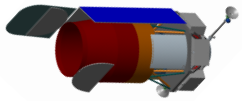


- Map & Inventory Galactic substructure & small satellite galaxies (LSST, WFIRST, GAIA)

Galactic Neighborhood - Local group of galaxies

- Stellar Feedback: e.g., Supernova Remnants (Chandra…)
- Surface brightness, radial velocities, ages, and halo shapes (30-m, WFIRST, JWST)
- LOS absorption of cool, warm & hot gas (HST, Chandra…)

Galaxy Assembly - First light



- Earliest galaxies (HST, JWST, WFIRST, 30-m)

How does our Universe work?

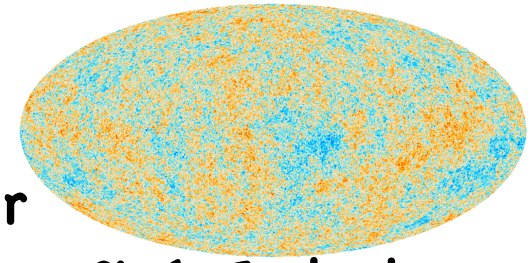
Co-evolution/Feedback of SMBHs and their Galaxies

- Characterize buildup of SMBH mass back to z~6
- Physics of AGN feedback in nearby galaxy clusters

Fundamental Physics and the Extremes of Nature

- Search for Primordial BHs and Intermediate Mass BHs
- Determine the NS EOS; probe nuclear matter physics in the cold/ultra-dense limit (NICER…)
- Detect Gravitational Waves; *multi-messenger* Explorations (aLIGO + EM counterparts)

Cosmology



- Measure CMB polarization and search for inflationary signatures; characterize the z ~ 1-5 dark structure via CMB lensing (Planck, ground-based, balloons)
- GRBs as cosmological probes (early star formation, QG)
- EOS of the dark energy in our Universe (WFIRST)

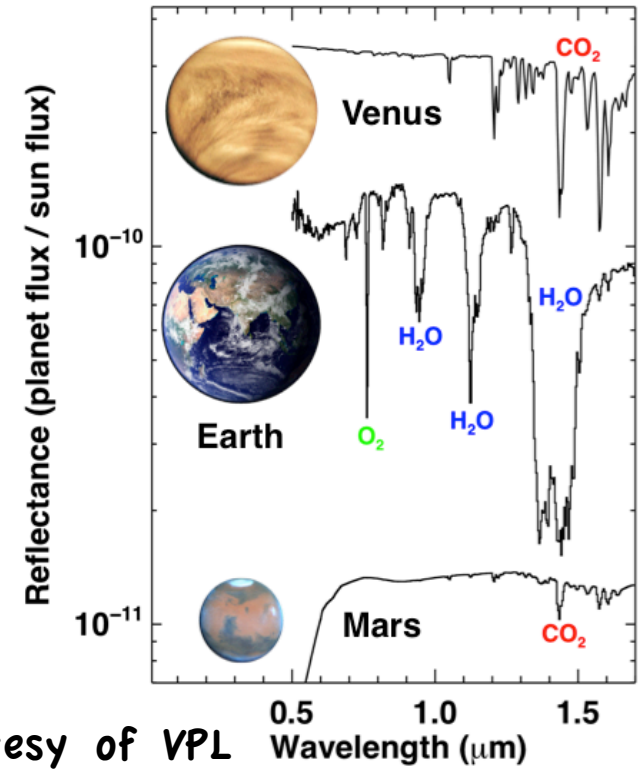
Present - Near Future Era → 0 ~ 15 years

Formative Era → 15 - 30 years

Visionary Era → 30+ years

Are we alone?

Probe the atmospheres of habitable zone terrestrial planets around nearby suns



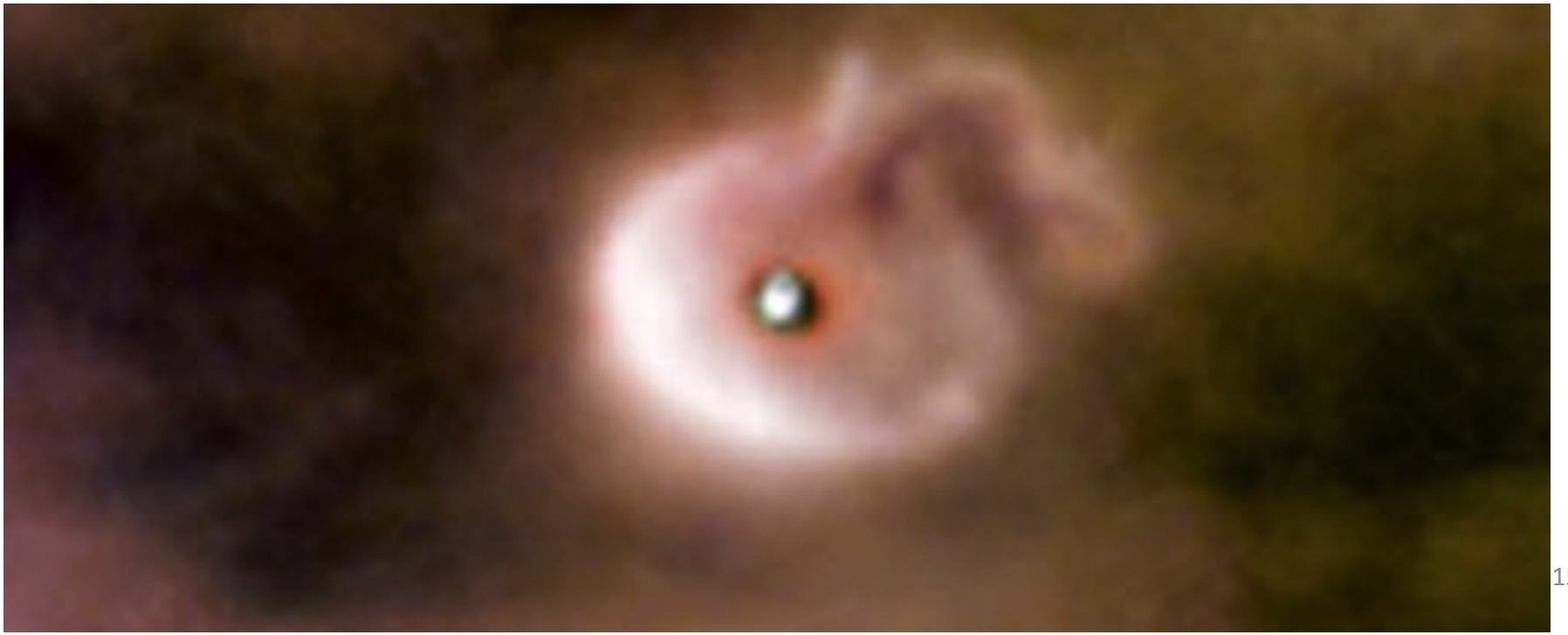
Spectra courtesy of VPL

- Measure primary atmospheric constituents (disc-averaged direct spectra)
- Measure planet orbits and identify surface features (repeated direct imaging)
- Detect atmospheric biomarkers to establish evidence of surface life (select set of habitable planets)

How did we get here?

Star and Planet Formation

- Map the chemical composition & understand the physics of *planet formation environments*
  - Determine distribution of water in ~ 100 young star and protoplanetary systems (10 – 500 pc)
  - Probe the structure and composition of nearby (10s of pc) debris disks in the terrestrial planet forming phase



How did we get here?

Our Milky Way

– Fully characterize the surviving and disrupted MW relics: streams, clusters, halo stars, bulge, dwarf spheroidals (dSphs)

- Measure the stellar Initial Mass Function (IMF) over all mass scales and in different environments
- Understand conditions for efficient particle acceleration
- Measure the MW mass from 3-D velocities of distant halo tracers
- Test DM models by establishing 3-D velocities for stars in all dSphs

How did we get here?

Our Galactic Neighborhood

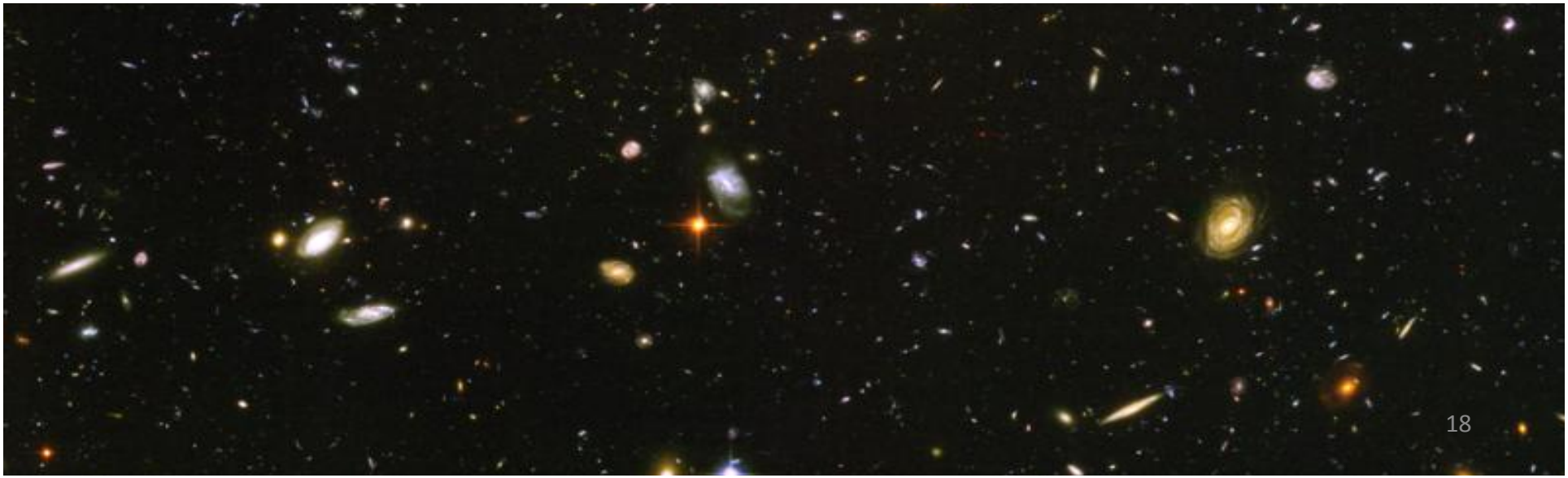
– Resolve the entire Hubble sequence with ~ 100 galaxies of all Hubble types

- Measure Star Formation History
- Characterize spatial and kinematic substructure
- Measure chemical abundance gradients
- Establish tests of high-resolution simulations of galaxy formation

How did we get here?

First light & Galaxy Assembly

- Characterize the physical nature of the first galaxies
  - Determine modes of galaxy + SMBH growth (mergers & accretion)
  - Measure the buildup of metals in galaxies since z ~ 15
  - Understand the effect of dark energy on galaxy assembly
- Understand the interplay of gas and evolving galaxies
  - Map the distribution, dynamics & chemistry of gaseous galactic halos
  - Measure the cold, warm and hot baryon mass budget in galaxies, galaxy clusters, and IGM



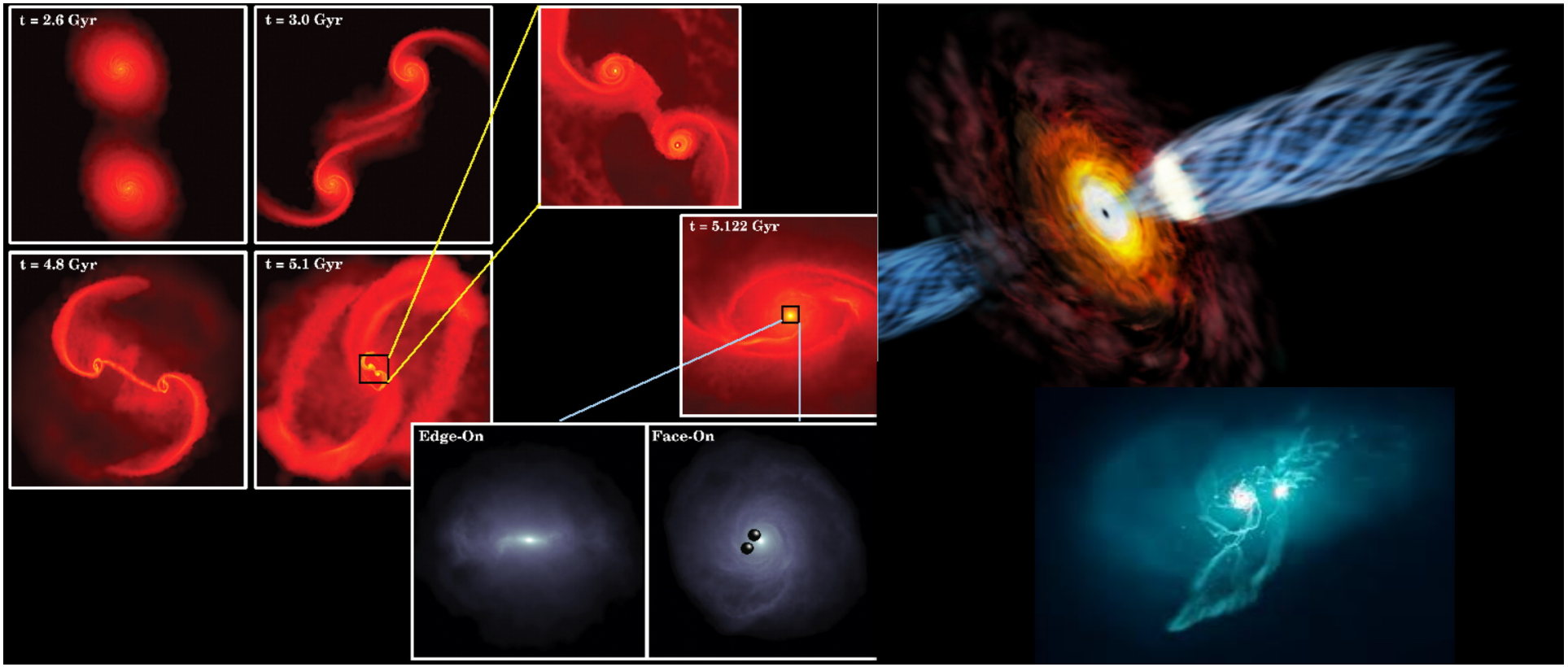
How does our Universe work?

Co-evolution/Feedback of SMBHs and their Host Galaxies

"Monsters in the Middle"

– Obtain the full history of SMBH growth through determination of the mass- and spin-distributions back to the formation epoch

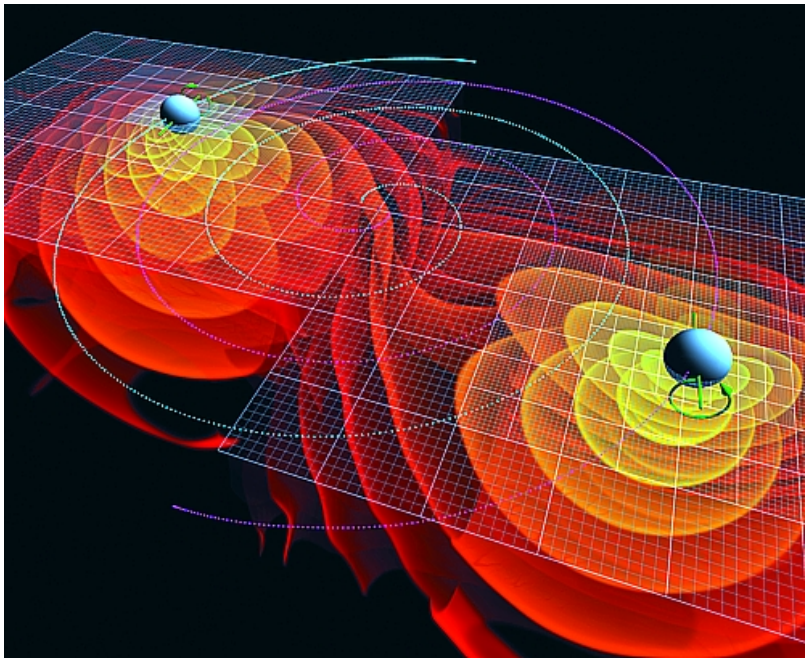
- Spatially resolve the accretion disks of AGNs in the nearby Universe
- Measure BH masses and spins (accretion diagnostics and mergers)

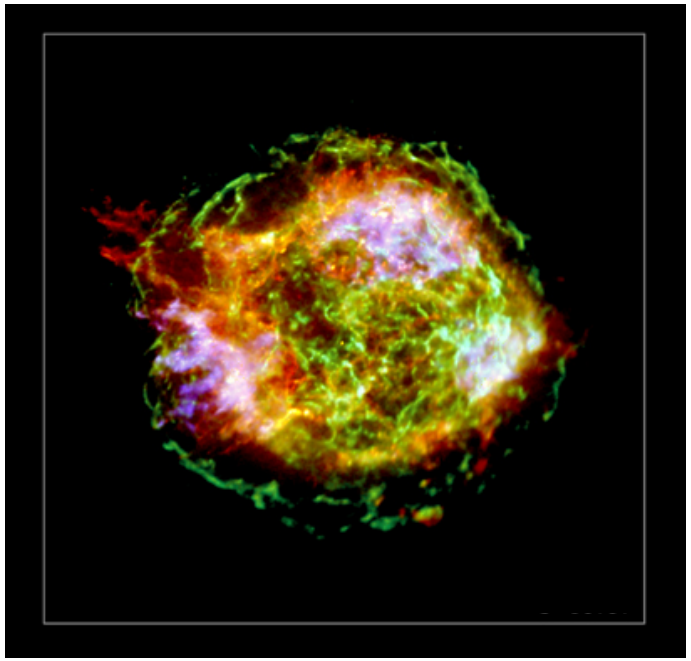


How does our Universe work?

Fundamental Physics and the Extremes of Nature: gravity, density, energy

- Test strong-field GR and map spacetime around SMBHs via GW from Extreme Mass Inspiral and merging SMBHs
- Understand the accretion-driven engines of BHs and NSs
- Probe the dynamics, mixing, and CR acceleration in SNRs

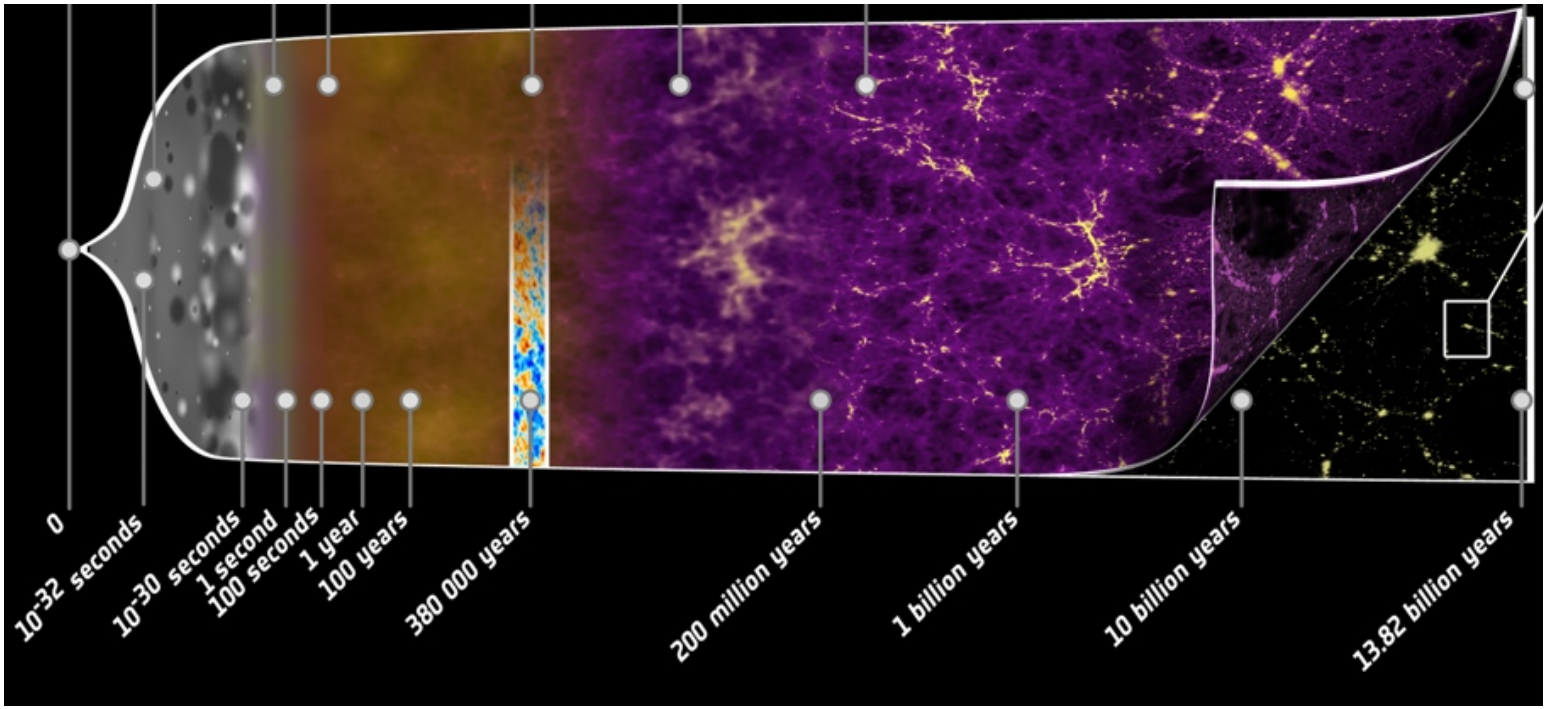




How does our Universe work?

Cosmology

- Map the CMB to cosmic variance limits using primordial GW signature (B-mode polarization) to derive powerful constraints on the inflationary epoch
- Probe thermal history of Universe by measuring imprints of relics & recombination on CMB blackbody spectrum
- Detect the emergence of structure during the Dark Ages (z~10-20) via 21-cm observations



CAPABILITIES REQUIRED

X-ray missions (high throughput and high resolution Spectroscopy – very high resolution timing) - large collecting area (A>3m^2) modest imaging ability (sub to a few arcsec)

Large UVOIR 16m with <10 mas resolution
30+m MIR-FIR (10-400 microns) space-based interferometer

CMB polarization mission to search for GW signal from inflation with ~100 times the Planck mapping speed

GW mission with peak frequency sensitivity ~1 mHz, and sensitivity to measure SMBH mergers throughout the observable Universe and extreme mass inspirals out to z ~ 1

Possible probe or explorer class missions:
CMB - blackbody spectrum distortion measurements
21-cm lunar orbiter observing from the far side of the moon
X- and gamma-ray transient monitor + polarimeter

Present - Near Future Era → 0 ~ 15 years

Formative Era → 15 - 30 years

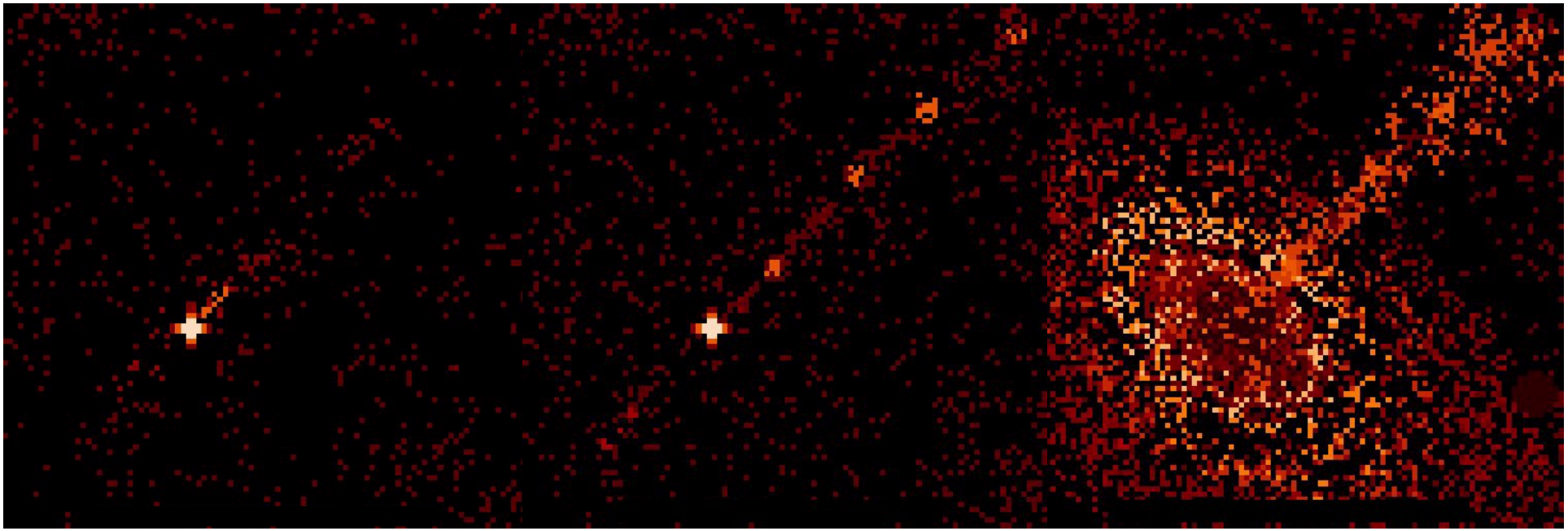
Visionary Era → 30+ years

Map surfaces of habitable worlds

Observe the habitable set of planets to distinguish land, water, clouds, ice -> distinguish different kinds of biomarkers such as vegetation (High Resolution imaging and spectroscopy).

Fundamental Physics and the Extremes of Nature

- Direct imaging (sub-microarcsecond) of powerful accretion flows around SMBH and the launching regions of jets; ultimate tests of accretion models
- Direct detection of primordial GW; listening to inflation



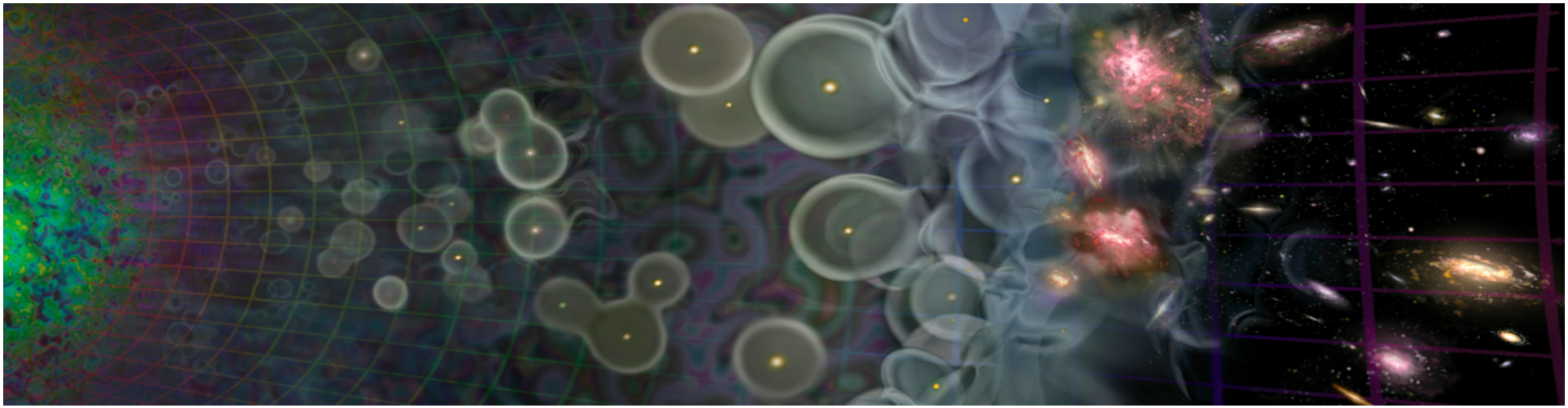
100 milliarcsec 1 milliarcsec 1 μarcsec

W. Cash: http://casa.colorado.edu/~wcash/interf/Qso/qso.htm

Cosmology

- Precise and accurate expansion history of Universe from GW standard sirens
- Detailed map of structure formation in the Dark Ages via 21cm observations

Surprises - New Phenomena ???



CAPABILITIES REQUIRED

- Microarcsecond X-ray imager employing X-ray interferometry
- OIR space interferometer: At least an array of ten 10m telescopes
- High sensitivity, multi-element, imaging GW array with peak sensitivity ~0.1 Hz. Sensitivity to inflationary background and neutron star and black hole binaries *at all redshifts*
- 21 - cm lunar surface radio telescope array

Visionary Astrophysics Outreach

Astronomy has a unique ability to capture the imagination of the public and inspire the next generation of explorers. Ensuring that NASA data are easily accessible and scientific discoveries are effectively communicated is our highest priority.

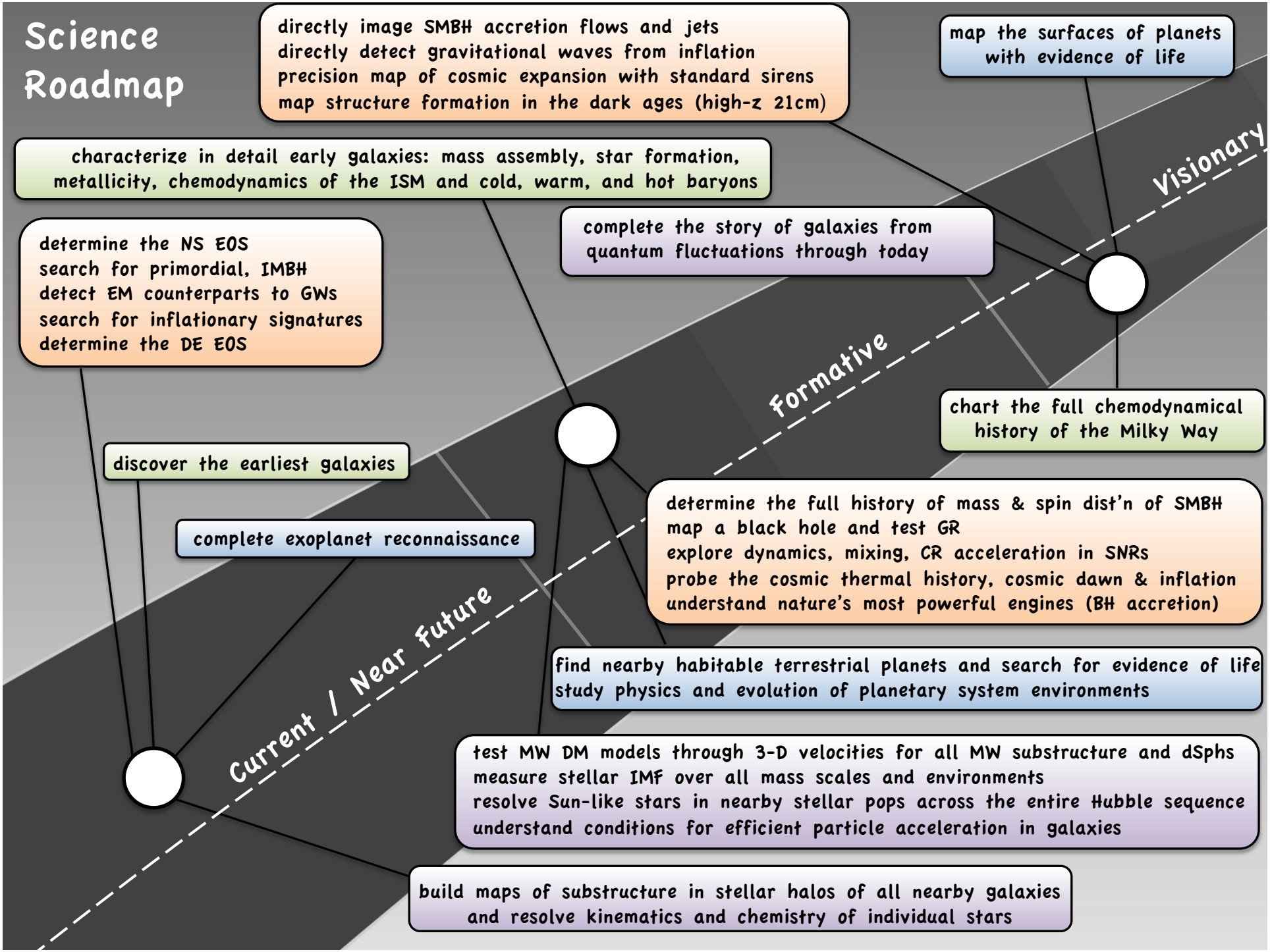
We recommend:

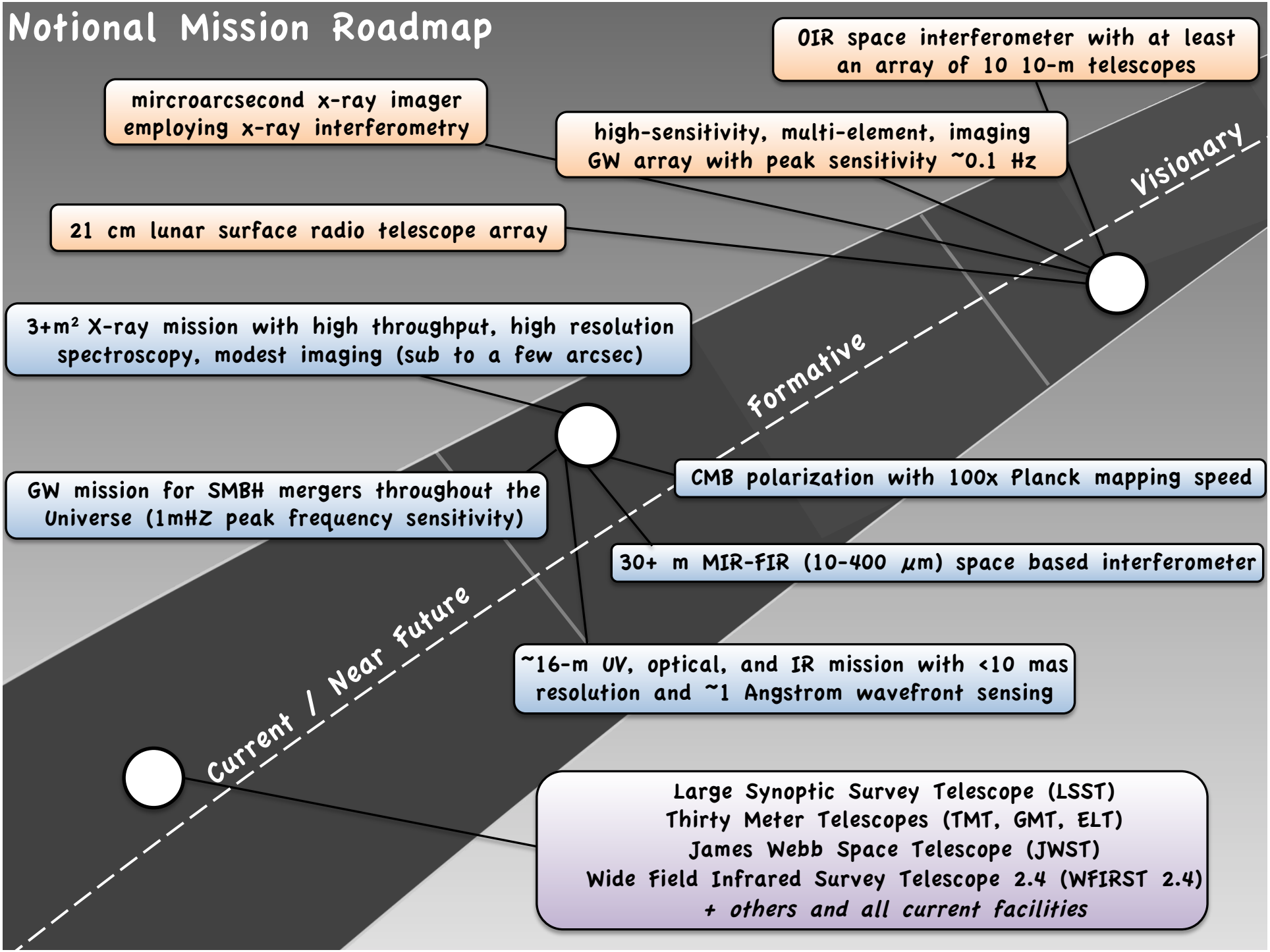
Adapting to quickly-changing technologies to reach the public effectively

Fostering learning in formal and informal settings through networked collaborations and partnerships

Engaging the widest audience possible using technologies and methods conducive to learning in a variety of settings

Summary


Science Roadmap
directly image SMBH accretion flows and jets
directly detect gravitational waves from inflation
precision map of cosmic expansion with standard sirens
map structure formation in the dark ages (high-z 21cm)
map the surfaces of planets with evidence of life
characterize in detail early galaxies: mass assembly, star formation, metallicity, chemodynamics of the ISM and cold, warm, and hot baryons
Visionary
determine the NS EOS
search for primordial, IMBH
detect EM counterparts to GWs
search for inflationary signatures
determine the DE EOS
complete the story of galaxies from quantum fluctuations through today
Formative
chart the full chemodynamical history of the Milky Way
discover the earliest galaxies
determine the full history of mass & spin dist'n of SMBH
map a black hole and test GR
explore dynamics, mixing, CR acceleration in SNRs
probe the cosmic thermal history, cosmic dawn & inflation
understand nature's most powerful engines (BH accretion)
complete exoplanet reconnaissance
Current / Near Future
find nearby habitable terrestrial planets and search for evidence of life
study physics and evolution of planetary system environments
test MW DM models through 3-D velocities for all MW substructure and dSphs
measure stellar IMF over all mass scales and environments
resolve Sun-like stars in nearby stellar pops across the entire Hubble sequence
understand conditions for efficient particle acceleration in galaxies
build maps of substructure in stellar halos of all nearby galaxies and resolve kinematics and chemistry of individual stars


Notional Mission Roadmap
OIR space interferometer with at least an array of 10 10-m telescopes
mircroarcsecond x-ray imager employing x-ray interferometry
high-sensitivity, multi-element, imaging GW array with peak sensitivity ~0.1 Hz
Visionary
21 cm lunar surface radio telescope array
3+m² X-ray mission with high throughput, high resolution spectroscopy, modest imaging (sub to a few arcsec)
Formative
GW mission for SMBH mergers throughout the Universe (1mHZ peak frequency sensitivity)
CMB polarization with 100x Planck mapping speed
30+ m MIR-FIR (10-400 μm) space based interferometer
~16-m UV, optical, and IR mission with <10 mas resolution and ~1 Angstrom wavefront sensing
Current / Near Future
Large Synoptic Survey Telescope (LSST)
Thirty Meter Telescopes (TMT, GMT, ELT)
James Webb Space Telescope (JWST)
Wide Field Infrared Survey Telescope 2.4 (WFIRST 2.4)
+ others and all current facilities

Enduring Quests – Daring Visions

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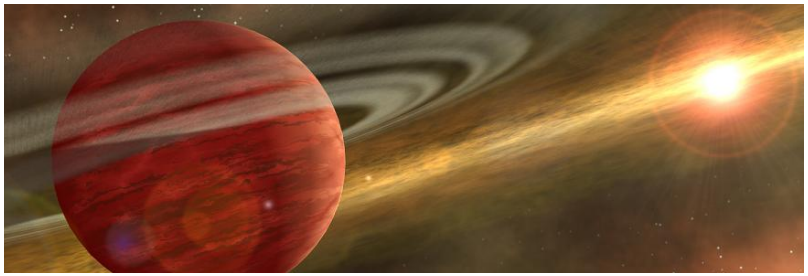

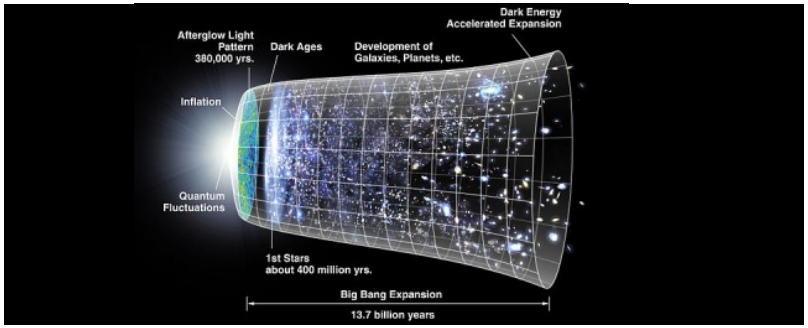

Are we alone?

1) Discover the diversity of planetary systems
2) Seek nearby habitable planets
3) Map and explore habitable environments

How did we get here?

1) Learn how star systems evolve and make planets
2) Decode the assembly of the Milky Way
3) Characterize the Universe's first galaxies and their growth over cosmic history

How does the Universe work?

1) Probe the imprints of the Big Bang
2) Pin down the forms of matter and energy that govern the expansion and fate of the Universe
3) Measure the ripples of spacetime
4) Explore the extremes of gravity and matter