Optical Technology Needs for Future Space Telescopes

H. Philip Stahl, Ph.D.
Prelude – Scientific Democracy

Process that Drives Policy:
- National Academy Decadal Survey – Defines Science
- NASA Strategic Plans – Defines Missions
- NASA Budget – Defines Spending

How to Influence Policy:
- Get invited as a Contributor/Reviewer for Decadal Survey or NASA Strategic Plan
- Also NASA Science Advisory Panels

How to Influence Funding
- Get involved in the political process.
  - President Proposes
  - Congress Disposes
Executive Summary

Optical Technology enables the next generation of advanced space telescopes and their scientific instruments & sensors.

Future Space Telescopes will operate over broad spectrum:
- Gamma Rays, X-Rays, XUV, Visible, Near-IR, Far-IR, Sub-MM, Microwave, Radio Wave, Gravity Waves, etc.
- See Advanced Telescope and Observatory (ATO) Capability Roadmap

Instruments for these observatories include:
- Multi-Spectral Imaging / Spectroscopy (Vis-IR-FIR)
- Multi-Spectral Sensing (UV-Gamma)
- Laser / LIDAR Remote Sensing
- Microwave Instruments and Sensors
- Direct Sensing of Particles, Fields and Waves
- See Scientific Instruments and Sensors (SIS) Capability Roadmap
NASA’s Science Missions Directorate Themes:

Earth Science
Sun-Solar System Connection
Solar System Exploration
Search for Habitable Planets
Origin, Structure, Evolution & Destiny of Universe
Earth Science Objectives

Predictive understanding of Earth as a system of interacting natural and human systems.

Synergistic integration of Earth observations & models.
Sun-Solar System Connection Objectives

Develop the capability to predict space weather.
Understand the nature of our home.
Safeguard our outward journey.
How does a planetary system become habitable?

Origin and Evolution of the Earth’s Biosphere
Habitability of other Planetary Environments
Habitability in the architectures of planetary systems

What is the fate of our planetary system?
Universe Exploration Objectives

*Origin and Destiny: Beyond Einstein Program*
How did the Universe Begin - what powered the Big Bang.
Understand properties of space, time, and matter at edge of black hole.
How will the Universe End - investigate dark energy

*Structure and Evolution: Pathways to Life Program*
How Did we Get Here - follow evolution of universe, galaxies, stars, elements, planets and ultimately life itself.
Search for Earth Like Planets Objectives

*Are We Alone?*

Find planets and nearby Earth-like worlds.
Profile planetary characteristics and biomarkers.
Understand planet formation and habitability.
Universe Exploration Objectives

**Origin and Destiny: Beyond Einstein Program**

- How did the Universe Begin - what powered the Big Bang.
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**Structure and Evolution: Pathways to Life Program**

- How Did we Get Here - follow evolution of universe, galaxies, stars, elements, planets and ultimately life itself.
Three startling predictions of Einstein’s relativity:

**Expanding Universe**
- Hubble discovered the expanding Universe in 1929.

**Black Holes**
- Black holes found in our Galaxy and at the center of quasars over the past three decades.

**Dark Energy**
- Evidence for an accelerating Universe was observed in 1998.
There are pressing questions related to, or left over from Einstein’s work, that challenge the foundations of physics:

What is the nature of gravity, space and time?

What is the Universe made of?

What powered the big bang?

Answering these questions is the major challenge facing Physics and Astronomy for the 21st century.
The Three Extremes of Gravity

*Gravity* on the universal scale
X-ray Spectroscopy

*Gravity* in the early universe
Cosmic Microwave Background

*Gravity* in the vicinity of black holes
x-ray Interferometry

What is the nature of gravity, space and time?

What powered the big bang?

What is the Universe made of?
During its early moments the Universe is thought to have undergone a rapid period of expansion called inflation.

Gravitational Waves Can Escape from Earliest Moments of the Big Bang and provide a means to directly observe and test the nature of inflation.

First light [WMAP, Planck]
LISA uses a laser based Michelson interferometer to monitor the separation between proof masses in separate spacecraft

- Three spacecraft separated by 5 million km
- Each spacecraft includes two freely falling test masses with drag free operation
- Distance changes measured with precision of 4 pico-meter RMS over 100 seconds (250X smaller than an atom)
Inflation Probe (IP)

Cosmic Microwave Background (CMB) Polarization test the inflation paradigm by measuring primordial gravity waves.

Precursor Missions:
- COBE – 0.2 m, 1.5 K
- MAP – 1.4 m, 70 K

IP Requirements:
- 2 - 4 m diameter
- Diffraction Limited at 0.5 mm
- 10K Operational Temp
- Low Cost
Universe: What Happens at the Edge of a Black Hole?

HST and Chandra find Black Holes at center of every Galaxy.

Chandra deep image reveals Black Holes are 10X more common than thought contributing significantly to total Universe energy output.

Each point of x-ray light is a Black Hole!

Black Holes are a prediction of Einstein’s theory of General Relativity and can be used to test the theory in the strongest possible gravity fields.
Roadmap to a Black Hole

Now

Chandra

XMM-Newton

RXTE

Find them & Probe properties

2015-2020

LISA

Gravitational Waves
Black Hole mergers

2015-2020

Constellation-X

X-ray Spectroscopy
at the event horizon

Evolution & environment
at the event horizon

BHI

10 million times
Chandra angular resolution

Black hole imager!

2020-2030

Direct observation of GR effects
Constellation-X

Use X-ray spectroscopy to observe

- Black holes:
  - Probe close to the event horizon
  - Evolution with redshift
- Dark Matter and Dark Energy:
  - Clusters of galaxies
  - Large-scale structure
- Production and recycling of the elements:
  - Supernovae and interstellar medium

- 25-100 times sensitivity gain for high resolution spectroscopy in the 0.25 to 10 keV band

- Reference mission design is four satellites at L2 operating as one with advanced X-ray spectrometers

Enable high resolution spectroscopy of faint X-ray sources
Collecting Area: 30,000 cm² at 1keV
25-100X Chandra & XMM for high resolution spectroscopy
4 Identical Space Craft – launched 2 at a time.

Band Pass: 0.25 to 40 keV
100X more sensitive than Rossi XTE at 40 keV

Angular Resolution
Soft X-Ray Telescope < 15 arc-sec - Mirror Figure and Alignment
Hard X-Ray Telescope < 1 arc-min - Mirror Figure and Coatings
Constellation-X consists of four identical spacecraft and sets of instrumentation.

Each SXT mirror is a Wolter I grazing incidence mirror with a 10 m focal length and a 1.6 m diameter.

The mirror is composed of many (100-250) nested Wolter-I reflectors.

The SXT mirror is azimuthally segmented and gang aligned.

1.6 m outer diameter
10 m focal length
20-50 cm reflector length
18 Small Modules
(6 inner, 12 outer)
70-250 nested reflector pairs
mirror mass ≤500 kg
**Depth-graded multilayer mirrors**
Conic-approximation grazing-incidence optics
Highly-nested thin shells (replicated full-shell or segmented)
Graded multilayer coatings extend energy range to $E \geq 50$ keV

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**Key Technical Issues to be Demonstrated**
Thin Ni shells yet to be produced in required dimensions
Epoxy replicated foils have not been mounted using precision technique
Neither Ni nor thin glass have demonstrated desired resolution
Replication of multilayers from mandrels must be demonstrated for Ni
Surface roughness of epoxy replicas must be improved
Black Hole Imager

Sub-micro arc-sec angular resolution requires X-ray Interferometry

Formation Fly provides multiple simultaneous spacings & rotation angles to sample UV plane

32 flats, 3 x 0.1 meter, 20 nm rms figure

<table>
<thead>
<tr>
<th>$D$ (m)</th>
<th>$\mu$ arc sec</th>
<th>Mission</th>
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<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>Pathfinder</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
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<tr>
<td>100</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>0.1</td>
<td>BHI</td>
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</table>
Universe: What is Dark Energy?

We do not know what 95% of the universe is made of!

Dark Energy is causing the expansion of the Universe to accelerate. Solving this mystery will fundamentally change our view of the Universe!
Joint Dark Energy Mission

JDEM a simple experiment to study the dark energy

*Dedicated instrument*, essentially no moving parts

**Telescope**: 2 meter aperture, diffraction limited beyond 1 micron

**Photometry**: with 1deg FOV half-billion pixel mosaic camera, high-resistivity, rad-tolerant p-type CCDs and HgCdTe arrays. (0.4-1.7 μm)

**Integral field optical and IR spectroscopy**: 0.4-1.7 μm, 2”x2” FOV
Universe Exploration Objectives

**Origin and Destiny: Beyond Einstein Program**
- How did the Universe Begin - what powered the Big Bang.
- Understand properties of space, time, and matter at edge of black hole.
- How will the Universe End - investigate dark energy

**Structure and Evolution: Pathways to Life Program**
- How Did we Get Here - follow evolution of universe, galaxies, stars, elements, planets and ultimately life itself.
Universe: Pathways to Life

Formation of elements, galaxies, stars, planets and the conditions for life?

How are the chemical elements distributed through the universe?
Where are the baryons in the local universe?
How do galaxies and black holes form?
How do stars and planetary systems form?
How does star formation proceed over time?
How does star formation change its surroundings and influence future generations of stars and planets?
James Webb Space Telescope (JWST)
The First Light Machine
A Brief History of Time

- Big Bang
- 3 minutes
- 300,000 years
- 100 million years
- 1 billion years
- 13.7 Billion years

- Ionization
- First Galaxies Form
- Galaxies Evolve
- Planets, Life & Intelligence

- Particle Physics
- Atoms & Radiation

- MAP
- COBE
- JWST
- HST
- Ground Based Observatories
JWST vs. HST - orbit

JWST will operate at the 2nd Lagrange Point (L2) which is 1 Million miles away from the earth.

HST flies in Low Earth Orbit, ~300 miles up.

Imaging is greatly affected by proximity to Earth.
JWST Requirements

Optical Telescope Element
- 25 sq meter Collecting Area
- 2 micrometer Diffraction Limit
- 0.6 to 27 micrometer Range
- < 50K (~35K) Operating Temp

Primary Mirror
- 6.5 meter diameter
- < 25 kg/m² Areal Density
- < $4 M/m² Areal Cost
- 18 Hex Segments in 2 Rings
- Drop Leaf Wing Deployment

Segments
- 1.315 meter Flat to Flat Diameter
- < 20 nm rms Surface Figure Error

<table>
<thead>
<tr>
<th>Condition</th>
<th>RMS Error</th>
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<tbody>
<tr>
<td>Low (0-5 cycles/aper)</td>
<td>4 nm</td>
</tr>
<tr>
<td>CSF (5-35 cycles/aper)</td>
<td>18 nm</td>
</tr>
<tr>
<td>Mid (35-65K cycles/aper)</td>
<td>7 nm</td>
</tr>
<tr>
<td>Micro-roughness</td>
<td>&lt;4 nm</td>
</tr>
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AMSD – Ball & Kodak

Specifications

- Diameter: 1.4 meter point-to-point
- Radius: 10 meter
- Areal Density: < 20 kg/m²
- Areal Cost: < $4M/m²

Beryllium Optical Performance

- Ambient Fig: 47 nm rms (initial)
- Ambient Fig: 20 nm rms (final)
- 290K – 30K: 77 nm rms
- 55K – 30K: 7 nm rms

ULE Optical Performance

- Ambient Fig: 38 nm rms (initial)
- 290K – 30K: 188 nm rms
- 55K – 30K: 20 nm rms
SAFIR – Single Aperture Far Infrared

“To take the next step in exploring this important part of the spectrum ...”

A Probe of Cosmic Beginnings

• Star Formation
• Galaxy Formation before Metals
• Chemistry of Life from Clouds to Planets
• Formation of Planetary Systems

A 10m far infrared telescope that will build upon the deployable technologies from JWST
SAFIR Requirements

Optical Telescope Element
- > 50 sq meter Collecting Area
- 40 micrometer Diffraction Limit
- Transmission 10 to 1000 micrometer
- < 10K (~4K) Operating Temp

Primary Mirror
- 10 meter Diameter
- < 12.5 kg/m² Areal Density
- < $1 M/m² Areal Cost
- Architecture TBD

Segments
- 2.0 meter Diameter
- < 400 nm rms Surface Figure Error

SAFIR requires
- Larger Cryogenic Mirrors
- Colder Mirrors & Actuators
- Actively Cooled Mirrors
- Lower Areal Cost Mirrors
Universe Exploration Timeline

Beyond Einstein

Competed Probes
- Big Bang Observer
- Black Hole Imager
- Pathways To Life Observatories
  - LUVO
  - FIRSI
  - UVOI
  - EUXO
  - LF, PI

Future Competed Explorers

Pathways to Life

2005  2015  >2025

LIGO -> Planck -> GLAST

WMAP -> Chandra -> NuSTAR

HST -> Swift

Spitzer

JWST

Herschel

GALSA -> Con-X -> JDEM

IP -> BHFP

Competed Probes
An Integrated Universe Program

Planets & Life

Pathways to Life (Structure and Evolution)

Beyond Einstein (Origin and Destiny of the Universe)
Search for Earth Like Planets Objectives

Are We Alone?

Find planets and nearby Earth-like worlds.
Profile planetary characteristics and biomarkers.
Understand planet formation and habitability.
Are We Alone?

*Search for life outside the solar system*

Search for other planetary systems
- Keck, HST and Spitzer
- Kepler, SIM, JWST

Search for habitable planets
- TPF-C

Remotely detect bio-signatures
- TPF-I

Search for biological “smoking guns”
- LF
Recent Achievements (1995-2005)

**Planet Detection**
- 150 and counting extrasolar planets detected.

**Planet Characterization**
- Spitzer directly detects thermal emission from hot Jupiters
- Transit surveys measure mass and radii of extrasolar planets.
- HST characterizes atmosphere of transiting hot Jupiter

**Planet Formation and Habitability**
- HST and Spitzer reveal galaxies in formation
- Spitzer observes proto-planetary disks around stars
- Spitzer detects icy organic compounds, ingredients for life, in star-forming region

**Future Questions**
- How many planets are there around nearby stars?
- Where are the nearest Terrestrial Planets?
- What are their properties and could they harbor life?
- How does star formation lead to planet formation?
- How do components of life form and come to reside in planets?
- Is there life on any planet beyond the Earth?
Search for Earth Like Planets Mission Set

**Planet Search and Characterization Missions**
- Kepler (2008): statistical frequency of earth-mass planets around solar-type stars
- SIM PlanetQuest (2014): indirect astrometric planet detection
- TPF-C (TBD): Direct visible-light detection of planets and planetary systems around other stars
- TPF-I (TBD): Direct infrared detection and spectroscopy of planets and their atmospheres

**Planet Formation and Habitability**
- SOFIA (TBD): circumstellar disks, star, and planet formation
- JWST (2013): formation of planets, stars, and galaxies

**Vision Missions**
- SAFIR: formation of planetary systems
- LUVO: chemical evolution of the early universe
- FIRSI: high-resolution imaging of proto-planetary disks
- Life Finder: unambiguous signs of life around nearby stars
- Planet Imager: multi-pixel resolution images of nearby planets
TPF Coronagraph Requirements

Optical Telescope Element
  Off-Axis Un-obscured TMA
  TBD sq meter Collecting Area
  0.5 micrometer Diffraction Limit
  TBD Operating Temp

Primary Mirror
  4 x 6 meter ellipse
  < 25 kg/m² Areal Density

Deformable Mirror to correct low spatial frequency errors

Coating Reflectance Amplitude

<table>
<thead>
<tr>
<th>Spatial Frequency Range</th>
<th>Reflectance Amplitude</th>
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Advanced Telescopes & Observatories
Capability Roadmap

Optics Capability
4.1 Optics Capabilities

Optics Capability is defined as a system of components such as mirror substrates, coatings, actuators, and their respective manufacture & test processes necessary to enable the ability to collect and concentrate electromagnetic radiation.

Four basic capabilities based upon wavelength region of the electromagnetic spectrum have been defined:

1.1 Cryogenic Optics (for IR, Far-IR, Sub-MM, Microwave)
1.2 Precision Optics (for EUV, FUV, UV, Visible)
1.3 Grazing Incidence Optics (for X-Ray)
1.4 Diffractive, Refractive & Novel Optics (for Gamma, X-ray or other)

Associated with each Capability are several Technology Figures of Merit which are closely related to system technical performance.
Technical Challenges

Optics and WFSC
  Critical enablers for many missions, near and far term
  Direct linkage with Science Enabled
Distributed/Advanced Spacecraft capabilities (inc formation flying)
  Enable a majority of longer term missions
  Spiral technology development approach needed
Test Facilities
  New facilities already needed to test next generation observatories
  Future larger space telescopes will not be ground testable
  Requires investment in modeling and validation approaches
Complex space telescopes may benefit from servicing and assembly/testing
Challenges for Optical & X-Ray Telescopes:

Areal Density to enable up-mass for larger telescopes.

Cost & Schedule Reduction.

Primary Mirror | Time & Cost
--- | ---
HST (2.4 m) | ≈ 1 m²/yr  ≈ $10M/m²
Spitzer (0.9 m) | ≈ 0.3 m²/yr  ≈ $10M/m²
AMSD (1.2 m) | ≈ 0.7 m²/yr  ≈ $4M/m²
JWST (6 m) | > 6 m²/yr  < $3M/m²

Note: Areal Cost in FY00 $
### Description of Capability needed:

Large-Aperture Modest-Quality Mirrors that enable IR/FIR/SMM/MW science missions operating at temperatures from 4 to 40K.

Low Operating Cost Mirrors that enable mission affordability, i.e. lower areal cost, shorter fabrication schedules and lower areal density.

Polarization Preservation & Uniformity

### Need/Gap Assessment:

**Manufacturing:**
- 10X Decrease in Areal Cost
- 0 to 3X Increase in Mirror Segment Size
- 2X Decrease in Areal Density
- Polarization Coatings

**Demonstrated Key Metrics:**
- Figure Quality
- Thermal/Mechanical Stability
- Thermal Deformation

### History/State-of-the-art:

- **State-of-the-art/Mission History**
  - Spitzer, WMAP, AMSD (flight/pathfinder)
  - JWST, Herschel, SPICA (in development)

- **Leading Candidates**
  - Beryllium (incumbent)
  - SiC
  - Glass – ULE, SiO2, Bk7
  - Others – Si, MgGr

- **Current TRL**
  - AMSD (TRL 5)
  - Various SBIR’s (TRL 4)

### Mission/Strategic Drivers:

- **Potential Missions**
  - SAFIR
  - Probes
  - Inflation Probe
  - TPF-I
  - FISI

- **Key external requirement:**
  - Cryo-Cooler Temp vs Aperture Dia
  - Launch Vehicle Up-Mass vs Areal Density
  - Architecture: Assembly vs Deploy vs Docking

- **Date:** Continuous Cyclic Improvement
### 4.1.2 Precision Optics

**Description of Capability needed:**
- Large-Aperture Extremely-Smooth Extremely-Stable Ambient-Temperature Mirrors that enable EUV/UV/O science missions.
- Edge Control and Phasing of Segmented Mirrors.
- Optical Test Instrumentation.
- Low Operating Cost Mirrors that enable mission affordability, i.e. lower areal cost, shorter fabrication schedules and lower areal density.
- High Reflectance Coatings from 90 to 1000 nm.
- Extremely Uniform Reflectance and Polarization Coatings from 400 to 1000 nm.

**Need/Gap Assessment:**
- Manufacturing:
  - Precision figure large low-stiffness mirrors
  - Polish all the way to Edges
  - Optical Testing – spatial, convex & fixture
  - 10X Decrease in Areal Cost
  - 2X Decrease in Areal Density
- Actuator Technology with 0.1 nm precision
- Coating Technology:
  - 2X Reflectivity Increase 90 to 120nm (80% Goal)
  - 10X Reflectivity Uniformity (0.1% Required)
  - 10X Polarization Uniformity
  - Dichroic, Spectral and Combiner Coatings

**History/State-of-the-art:**
- State-of-the-art/Mission History
  - HST, FUSE, SUMI, AMSD, TDM (flight/pathfinder)
  - KECK, ALOT (ground system)
- Leading Candidates
  - Glass (incumbent)
  - Alternative substrate materials
- Current TRL
  - AMSD (TRL 5)

**Mission/Strategic Drivers:**
- Potential Missions (Diameter)
  - TPF-C (4 x 8 meter)
  - Origin’s Probes (JDEM, etc.) (2.4 meter)
  - EOR Lasercomm (3 meter)
  - MTRAP (5 meter)
  - Earth Science (2 to 5 meter)
  - UV/O Interferometer (1 meter)
  - Big Bang Observer (3 meter)
  - Life Finder (25 meter)
- Key external requirements:
  - Coatings & Aperture vs Detector Sensitivity
  - Passive Figure vs Active Control, i.e. DM
  - Launch Vehicle Up-Mass vs Areal Density
  - Architecture: Assembly vs Deploy vs Docking
- Date: Continuous Cyclic Improvement
### 4.1.3 Grazing Incidence Optics

#### Description of Capability needed:

- Large-Aperture Precision-Quality Grazing Incidence Mirrors that enable X-Ray/FUV science missions.
- Radically Low Operating Cost Mirrors that enable mission affordability:
  - significantly lower areal cost,
  - shorter fabrication schedules and
  - radically lower areal density.

#### Need/Gap Assessment:

<table>
<thead>
<tr>
<th>Manufacturing</th>
<th>Mechanical</th>
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<tr>
<td>100X Decrease in Areal Cost</td>
<td>Mounting, Support &amp; Alignment</td>
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<tr>
<td>100X Decrease in Areal Density</td>
<td>Mechanical Stability</td>
</tr>
<tr>
<td>0 to 2X Increase in Mirror Segment Size</td>
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<tr>
<td>Replicated Surface Figure</td>
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</tbody>
</table>

#### History/State-of-the-art:

- State-of-the-art/Mission History
  - Einstein HEAO-B, EUVE, TMA, XMM, Chandra
  - SXI, Solar B
- Leading Technology Candidates
  - Glass Slumping
  - Nano-laminate
  - Replication
  - Silicon Pore Mirrors
  - Active Mirrors
  - Revolutionary
- Current TRL
  - Glass Slumping (TRL 2/3)

#### Mission/Strategic Drivers:

- Potential Missions (Diameter)
  - Advanced Solar X-Ray Imager (ASXI)
  - ConX
  - Reconnection and Microscale (RAM)
  - EUXO
  - Black Hole Imager
  - RAM
- Key external requirements are:
  - Launch Vehicle Up-Mass vs Areal Density
  - Architecture: Assembly vs Deploy vs Docking
- Date: Continuous Cyclic Improvement
### 4.1.4 Diffract., Refract. & Novel Optics

#### Description of Capability needed:

- Diffractive/Refractive Optics for specific missions such as coded aperture & occulting imaging.

- Revolutionary Optics to enable presently unachievable large-aperture science missions.

- Revolutionary Optics for alternate implementations of planned future missions.

#### Need/Gap Assessment:

- Manufacturing:
  - 1000X Decrease in Areal Cost
  - 1000X Decrease in Areal Density
  - 100X Increase in Optic Size

#### History/State-of-the-art:

- State-of-the-art/Mission History
  - Compton Telescope
  - Coronagraph

- Leading Technology Candidates
  - Laue Lens – Gamma Ray
  - Fresnel Lens – Gamma Ray, X-Ray, UV/O
  - Multi-Layer Normal Incidence X-Ray Mirrors
  - Diffractive/Refractive X-Ray Lens
  - Occulting Screens, Pin Hole Camera
  - Gossamer/Membrane Mirrors
  - Laser Trapped or Magnetic Trapped Mirrors

- Current TRL = 1/2

#### Mission/Strategic Drivers:

- Potential Missions (Diameter)
  - Life Finder (LF)/Planet Imager (PI)
  - Extreme Universe X-ray Observatory (EUXO)
  - Other Future Space Science Missions

- Key external requirements are:
  - Launch Vehicle Up-Mass vs Areal Density
  - Architecture: Assembly vs Deploy vs Docking
  - Architecture: Alternative Photon Collection
Summary

NASA has defined a suite of missions to answer the Big Questions:

- How did the Universe Begin?
- How will the Universe End?
- How did We get Here?
- Are We Alone?

These drive optical technology development for next 20 years:

- Large Aperture
- Lightweight & High Stiffness
- Precision Figure, X-Ray and Cryogenic