The Universe, seen through Hubble's Eye

#NASAWFIRST
The Hubble Deep Field
But, what if you could see the world only through a telephoto lens?
The Hubble Deep Field

#NASAWFIRST
Dark Energy and Exoplanets
NASA’s WFIRST Mission
(Wide Field Infrared Survey Telescope)

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#NASAWFIRST
The “Speed” of WFIRST is Unprecedented

Hubble - a spectacular start

The Hubble Ultra Deep Field - 10,000 galaxies back to 500M years after the Big Bang

JWST - seeing farther with more than 6× Hubble’s mirror!

A JWST Ultra Deep Field - 10,000 galaxies back to 200M years after the Big Bang

WFIRST - 100× Hubble Field of View!

A WFIRST Deep Field – 1,000,000 galaxies back to 300M years after the Big Bang!
A Mission of Superlatives

100x the Hubble Field of View (at the same sensitivity and resolution)

First High-Resolution Maps of the Universe

High Performance Space Coronagraphy

Technology Transfer of a Hubble-Sized Mirror from the DoD to Science

Ushers in the “Big Data Era” of NASA Astrophysics
Our Guiding Principle

Dark Energy and the Fate of the Universe

Wide-Field Infrared Surveys of the Universe (Guest Observer & Investigator Opportunities)

The full distribution of planets around stars

National Academy of Sciences
Astronomy & Astrophysics
Decadal Survey (2010)

Technology Development for Exploration of New Worlds
Identification and characterization of nearby habitable exoplanets

Gravitational wave astronomy
Time domain astronomy
The epoch of reionization

Astrometry

Nature of first objects and formation epoch
Formation and evolution of cosmic structures
Connections b/w dark and luminous matter
Formation of stars
Universe’s beginning
Evolution of disks to planetary systems
Stellar rotation and magnetism

Baryon cycling
Black hole growth and influence
Mass, radius, and spin of compact objects
Flows in the CGM
Mass-energy chemical cycles

Acceleration of the Universe
Properties of neutrinos
Nature of dark matter

Diversity of planetary systems
Massive star death
Type Ia progenitors

Habitable worlds
WFIRST makes a direct and major impact on the science theme.

WFIRST provides unique value to the science theme through synergistic observations:
- Imaging discoveries for JWST, ALMA spectroscopic follow-up
- High-resolution follow-up of LSST transients
- Search for optical counterparts to gravitational wave detections
- …

WFIRST is ancillary or not responsive to the science theme:

- Universe’s beginning
- Time domain astronomy
- Mass-energy chemical cycles
- Gravitational wave astronomy
- Identification and characterization of nearby habitable exoplanets
- Formation of stars
- Nature of first objects and formation epoch
- Baryon cycling
- Properties of neutrinos
- Flows in the CGM
- Habitable worlds
- Stellar rotation and magnetism
- Mass, radius, and spin of compact objects
WFIRST: Mapping the Universe
Our Guiding Principle

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Technology Development for Exploration of New Worlds
The Universe as a Pie Chart

Dark energy 69%
Dark matter 25%
Atomic matter 5%

Neutrinos 0.1%
Photons 0.01%
Black holes 0.005%
Fundamental Nature of the Universe

\[ G_{\mu\nu} = 8\pi T_{\mu\nu} + \Lambda g_{\mu\nu} \]

- Spacetime
- Matter & Energy
- What’s this?

“Cosmological Constant”
Modified gravity?
Another form of energy?
Dark Matter is Driving the Growth of Galaxies

A remnant of the Big Bang (Cosmic Microwave Background)

Galaxies in the Distant Universe (Hubble Ultra Deep Field)

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Dark matter causes light to follow a **distorted** path. The background galaxy images are magnified and sheared; mapping a circle into an ellipse.
A Penny in a Pool
Dark Energy: An Accelerating Expansion
Push-Pull: Dark Energy vs Dark Matter

Dark Energy
Is a repulsive force
Affects the speed at which the Universe expands
Causes everything to move away from everything else

Dark Matter
Affected by the attractive force of gravity
Affects how “clustered” objects are
Causes objects to want to move towards one another

One Possible Future
Dark Energy will eventually rip the Universe apart!
...sorry.
To be sure, let's go and measure both dark matter and dark energy!

#NASAWFIRST
WFIRST will measure galaxy shapes to map dark matter and measure the growth of galaxies over the Universe’s life.
WFIRST will map the positions of galaxies to establish a cosmic standard ruler to measure the Universe’s expansion history.
Baryon Acoustic Oscillations
Standard Ruler tied to the CMB
WFIRST will discover exploding stars (supernovae) across cosmic time to establish precise distances to galaxies.
Supernovae

Standard Candle tied to the physics of Type Ia supernovae

Supernova are “standardizable candles”
WFIRST’s Dark Universe Roadmap

- Galaxy Shapes
- Galaxy Positions
- Standard Candle

Growth of Structure (also Expansion History)
Expansion History (also Growth of Structure)
Expansion History

Determine the Universe’s End Fate!

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BIG BANG TO BIG RIP

Approximately 13.7 billion years ago

Now

Approximately 22 billion years from now

Formation of Atoms

Galaxy Formation

Star Formation Peaks

Solar System Forms

You Are Here

Galaxies Destroyed

Solar System Breaks Apart

Earth Explodes

Atoms Ripped Apart

Inflation

Accelerating Expansion
Our Guiding Principle

- Dark Energy and the Fate of the Universe
- The full distribution of planets around stars
- Wide-Field Infrared Surveys of the Universe (Guest Observer & Investigator Opportunities)
- New Worlds, New Horizons in Astronomy and Astrophysics
- Technology Development for Exploration of New Worlds

National Academy of Sciences
Astronomy & Astrophysics
Decadal Survey (2010)
What Is Planet Formation?

Simple.

Take micron-sized grains in protoplanetary disks.

Add some challenging physical processes (gravitational collapse, radiation, turbulence, orbital dynamics, chemistry, magnetic fields, charging, etc.).

Grow by $10^{-13-14}$ in size and $10^{38-41}$ in mass.

End up with a set of planets of certain size, composition, distance from star.
Equivalent Search Areas

Kepler’s Search Area
Equivalent Search Areas

Kepler’s Search Area

WFIRST’s Search Area
Microlensing
(Penny et al. in prep)
Monitor hundreds of millions of bulge stars continuously on a time scale of ~10 minutes.

Event rate $\sim 10^{-5}$/year/star.

Detection probability $\sim 0.1$-$1\%$.

Shortest features are $\sim 30$ minutes.

Relative photometry of a few \%.

Deviations are few – 10\%.

Resolve main sequence source stars for smallest planets.

Masses: resolve background stars for primary mass determinations.
Ground Vs. Space

Infrared Wavelengths
More extinted fields
Higher number density

High Resolution
Low-magnification events
Isolate light from the lens star

Better Visibility
Complete coverage

Smaller systematics.
Better characterization
Robust quantification of sensitivities

The field of microlensing event MACHO 96-BLG-5 (Bennett & Rhie 2002)
Microlensing Simulations

Mass of the Moon @ 5.2 AU

Free floating Mars

\[ M = 2.02M_{\text{Moon}} \quad a = 5.20 \text{ AU} \quad M_* = 0.29M_\odot \quad \Delta \chi^2 = 716 \]

\[ M = 0.1M_\odot \quad \Delta \chi^2 = 552 \]

2 × Mass of the Moon @ 5.2 AU

(~27 sigma)

Free floating Mars

(~23 sigma)

(Penny et al. in prep)
The Microlensing Watershed.

Ground & Space
Masses and distances.
Mass function and Galactic distribution of planets.
Free-floating planets masses.

WFIRST
Detections en masse.
Complete the census of exoplanets started by Kepler.

(Udalski et al. 2014; Yee et al. 2014, 2015; Calchi Novati et al. 2014, 2015; Zhu et al. 2015a,b,c; Shvartzvald et al. 2015; Street et al. 2015; Poleski et al. 2015; Henderson et al. 2015; Bozza et al. 2016)
WFIRST Exoplanet Census

Microlensing will dramatically expand our knowledge of other solar systems and will provide a first glimpse at the planetary families of our nearest neighbor stars.

Monitor 200 million Galactic bulge stars every 15 minutes for 1.2 years

- 2600 cold exoplanets
- 300 Earth-mass planets
- 40 Mars-mass or smaller planets
- 40 free-floating Earth-mass planets

Complete the Exoplanet Census

- Inventory the outer parts of planetary systems, potential source of water for habitable planets.
- Quantify frequency of solar systems like our own.
- Confirm and improve Kepler’s estimate of the frequency of potentially habitable planets.
- When combined with Kepler, provide statistical constraints on the densities and heavy atmospheres of potentially habitable planets.
Science from the WFIRST Microlensing Survey

- Mass and distance measurements of the host stars and planetary systems.
  - Aspects: Parallax; lens flux; finite source effects; relative lens-source proper motion; astrometric microlensing; source parallax, lens parallax, ...
- Characterization of a (subset) of the host stars
- Constraints on orbital elements.
- Multiple planet systems.
- Planets in binaries, including circumbinary planets.
- Free-floating planets.
- Moons of planets.
- Transiting planets.
- Other astrophysics. (KBOs, astroseismology, etc.)
Our Guiding Principle

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Wide-Field Infrared Surveys of the Universe
(Guest Observer & Investigator Opportunities)

The full distribution of planets around stars

Technology Development for Exploration of New Worlds

National Academy of Sciences
Astronomy & Astrophysics
Decadal Survey (2010)
Exploring the Stellar Graveyard of the Milky Way

Hubble’s Camera

WFIRST’s Camera
Exploring the Stellar Graveyard of the Milky Way

#NASAWFIRST
Hubble Peering into our Galactic Neighborhood

Seeing Galaxies as Collections of Stars - The Panchromatic Hubble Andromeda Treasury Program (PI J. Dalcanton)
Wide-Field, High-Resolution Surveys of the Universe

- Low-Resolution Map of the Milky Way Center
- The First Wide-Field, High-Resolution Map of the Milky Way

Global environment of the nuclear star cluster
Influence of extreme environments on star formation
Cause of asymmetries (e.g., CMZ) around the Supermassive Black Hole
Distribution, formation, and disruption of young star clusters
Wide-Field, High-Resolution Surveys of the Universe

Surveying Nearby Galaxies with WFIRST
(In the time that Hubble took to survey Andromeda, WFIRST could survey 100 nearby galaxies)

- Resolved galaxy archaeology studies over all galaxy types
- Initial mass function and timescale for stellar evolution
- Stellar feedback and dust formation and distribution
- Exquisite tests of galaxy formation and dark matter models on small scales
The WFIRST Telescope
Designed for High-Resolution, Wide-Field Imaging

#NASAWFIRST
The WFIRST Telescope
Designed for High-Resolution, Wide-Field Imaging

Former Spy Satellite
Transferred to NASA Science

First Detailed Map
of the Universe

#NASAWFIRST
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National Academy of Sciences Decadal Survey (2010)
Are there Other Living Worlds Near Us?


Is
There are currently more than 4000 exoplanets known...

...but, we don’t know what any of them look like...

...WFIRST will directly image the nearest and brightest ones.
An Upcoming Boom in the Census of Nearby Exoplanets
WFIRST will directly image nearby exoplanets with a high-performance coronagraph capable of suppressing starlight by a factor of up to a billion to 1.
WFIRST will seek to discover a few more around Suns like ours
...and lay the foundation for answering the question...are we alone?
What can we learn from a dot?
What can we learn from a dot?

“Blue Sky” (measures total amount of atmosphere)

“Vegetation Jump” (indicates plants)

Carbon Dioxide (suggests possible volcanic activity)

Methane (indicates presence of anaerobic bacteria)

Oxygen & Ozone (produced by living organisms)

Water Vapor (suggests habitability)
WFIRST will be the first space telescope capable of direct imaging with a starshade.
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Astronomy & Astrophysics
Decadal Survey (2010)
WFIRST’s Wide Field Instrument

WFIRST’s Coronagraph

High Performance Space Coronagraphy

Hubble’s Camera

100x the Hubble Field of View (at the same sensitivity and resolution)

WFIRST’s Camera

Wide Field Instrument
- 300M pixel camera w/ 18 4K detectors
- 100x the Hubble FoV, w/ 0.1” pixels
- Space “Big Data” complement to LSST
- Highly synergistic w/ JWST

Coronagraph Instrument
- Starlight suppression by factors up to 1 billion to 1
- Builds the foundation for future large telescopes to search for biosignatures on nearby worlds

Donated 2.4m Telescope Undergoing Testing

Science Instruments Under Development
Breakthroughs
Orders of Magnitude Astrophysics

High-resolution Mapping of the Universe

Over its amazing 26-year history, Hubble’s imaging cameras have surveyed just 1-2% of the Universe.

- WFIRST will survey Hubble’s Universe in 10 weeks, at the same sensitivity and resolution.

Gain over Current Capabilities: Factor of 100

Expansion of the Universe

Present Figure of Merit: ~30
Supernovae & BAO, plus CMB

- WFIRST will measure dark energy in the universe with a FoM~1000

Gain over Current Capabilities: Factor of 30

Directly Imaging Other Worlds

Current state-of-the-art ground and space light-suppression techniques achieve contrast ratios of ~1,000,000:1

- WFIRST’s high-performance coronagraph will achieve light-suppression of up to 1,000,000,000:1

Gain over Current Capabilities: Factor of 1,000

Structure of Dark Matter

The Dark Energy Survey will measure dark matter via weak lensing using 200M galaxies ~ 0.9” resolution

- WFIRST will survey dark matter 380M galaxies at 0.12” resolution

Gain over Current Capabilities: Factor of 100

The First Galaxies and Early Universe

Hubble, Spitzer, ground telescopes have discovered ~100 galaxies at z > 8, and only a few at z > 10

- WFIRST’s High Latitude Survey will discovery >50,000 z > 8 galaxies, and several 100 z > 10 galaxies

Gain over Current Capabilities: Factor of 500

Census of Exoplanets

Number of Earth/Super-Earths at 1AU and beyond: 1 known

- WFIRST will discover 300+ Earth-mass planets beyond 1AU

Gain over Current Capabilities: Factor of 300
“Once we lose our fear of being tiny, we find ourselves on the threshold of a vast and awesome Universe…”

Carl Sagan