From Cosmic Birth to Living Earth

A Vision for Space Astronomy Beyond the 2020s

A Study Commissioned by the Associated Universities for Research in Astronomy
The “Beyond JWST” Committee

Co-Chairs: Sara Seager (MIT)
Julianne Dalcanton (Washington)

Presenter: Jason Tumlinson (STScI)

Motivations

Co-Chairs:

Julianne Dalcanton
(Washington)

Sara Seager (MIT)

Develop a shared vision for UVOIR astronomy in the 2020s and after…

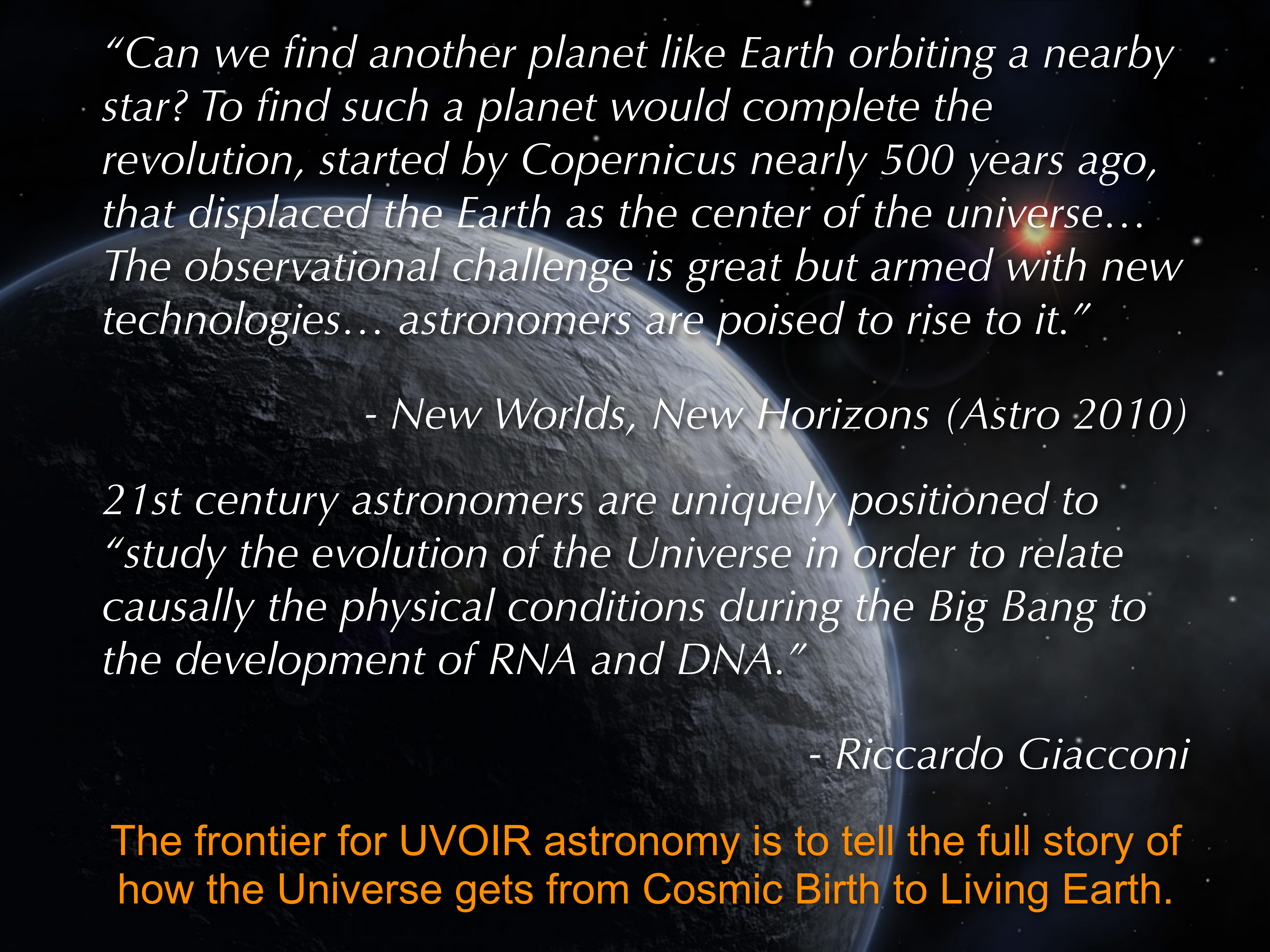
…based on PAG-led common ground between "exoplanet" and "cosmic origins" communities…

…and a conviction that large scale requirements for transformative science in both areas are compatible.

Suzanne Aigrain
Steve Battel
Niel Brandt
Charlie Conroy
Lee Feinberg
Suvi Gezari
Olivier Guyon
Walt Harris

Chris Hirata
John Mather
Marc Postman
David Redding
David Schiminovich
Phil Stahl
Jason Tumlinson
Heidi Hammel
(AURA ex officio)

Technologists Instrument Builders



"Can we find another planet like Earth orbiting a nearby star? To find such a planet would complete the revolution, started by Copernicus nearly 500 years ago, that displaced the Earth as the center of the universe… The observational challenge is great but armed with new technologies… astronomers are poised to rise to it."

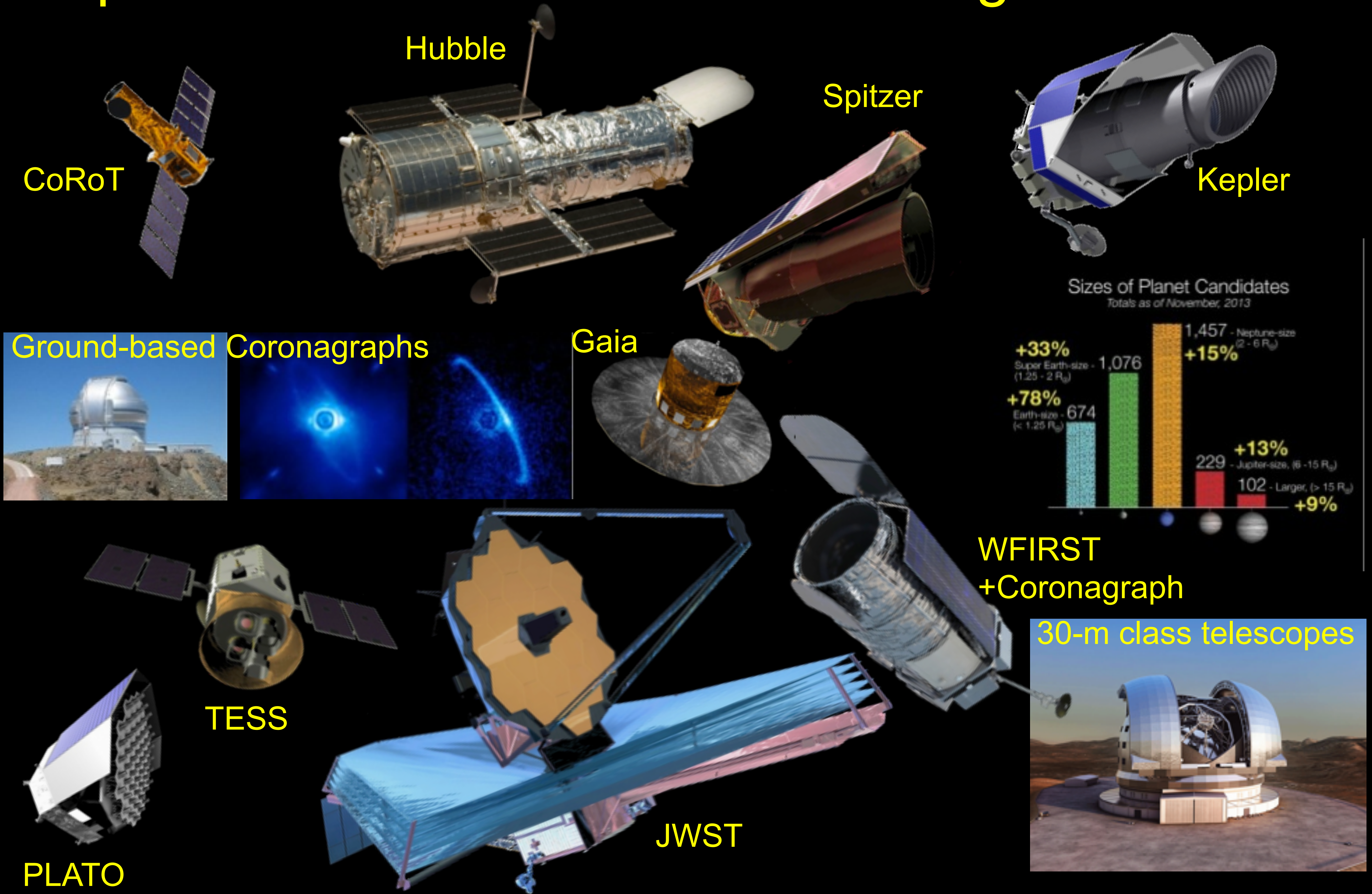
- New Worlds, New Horizons (Astro 2010)

21st century astronomers are uniquely positioned to "study the evolution of the Universe in order to relate causally the physical conditions during the Big Bang to the development of RNA and DNA."

- Riccardo Giacconi

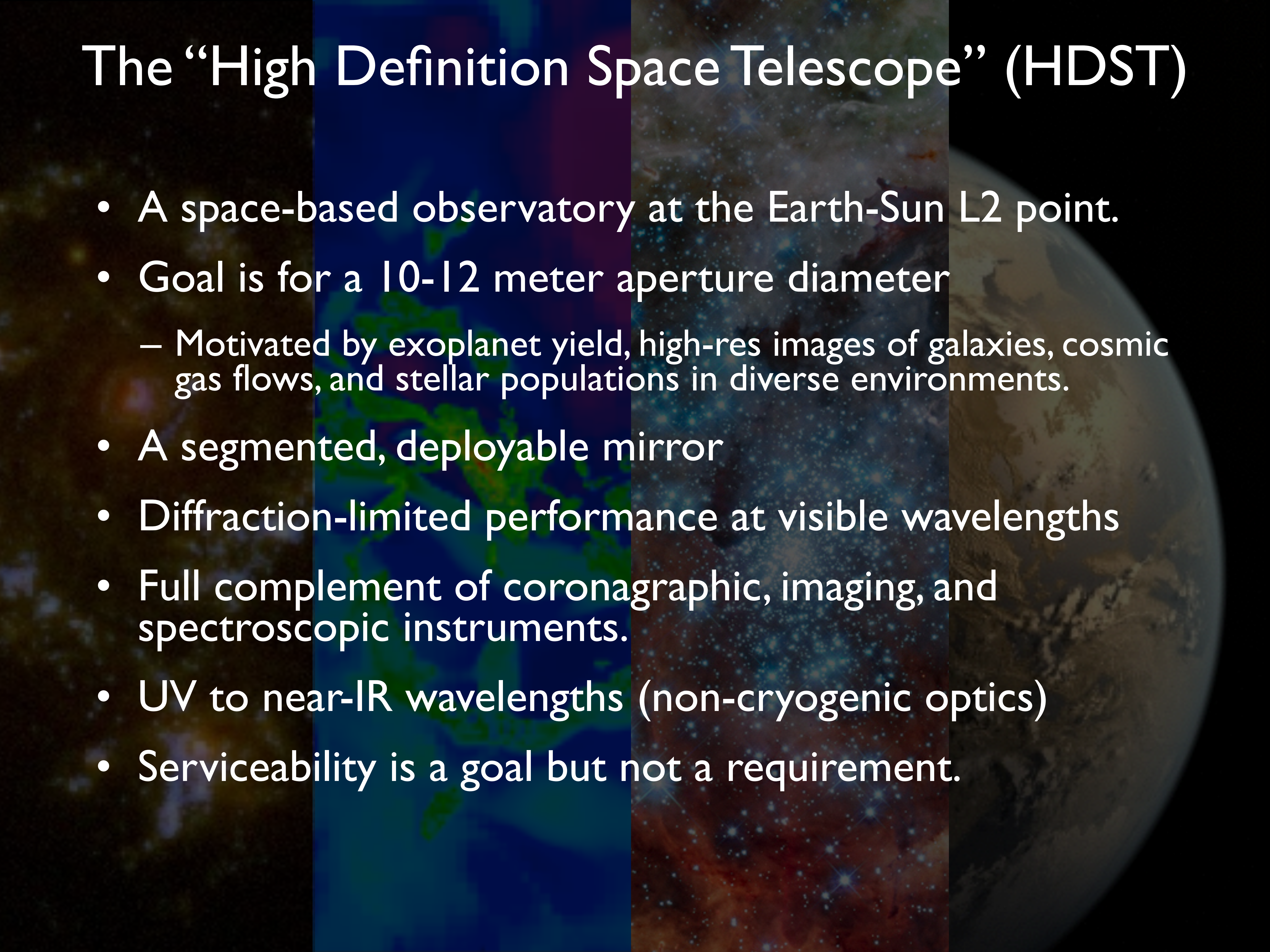
The frontier for UVOIR astronomy is to tell the full story of how the Universe gets from Cosmic Birth to Living Earth.

The path has been laid for discovering Earth 2.0. . .



What is the next logical step?

The “High Definition Space Telescope” (HDST)

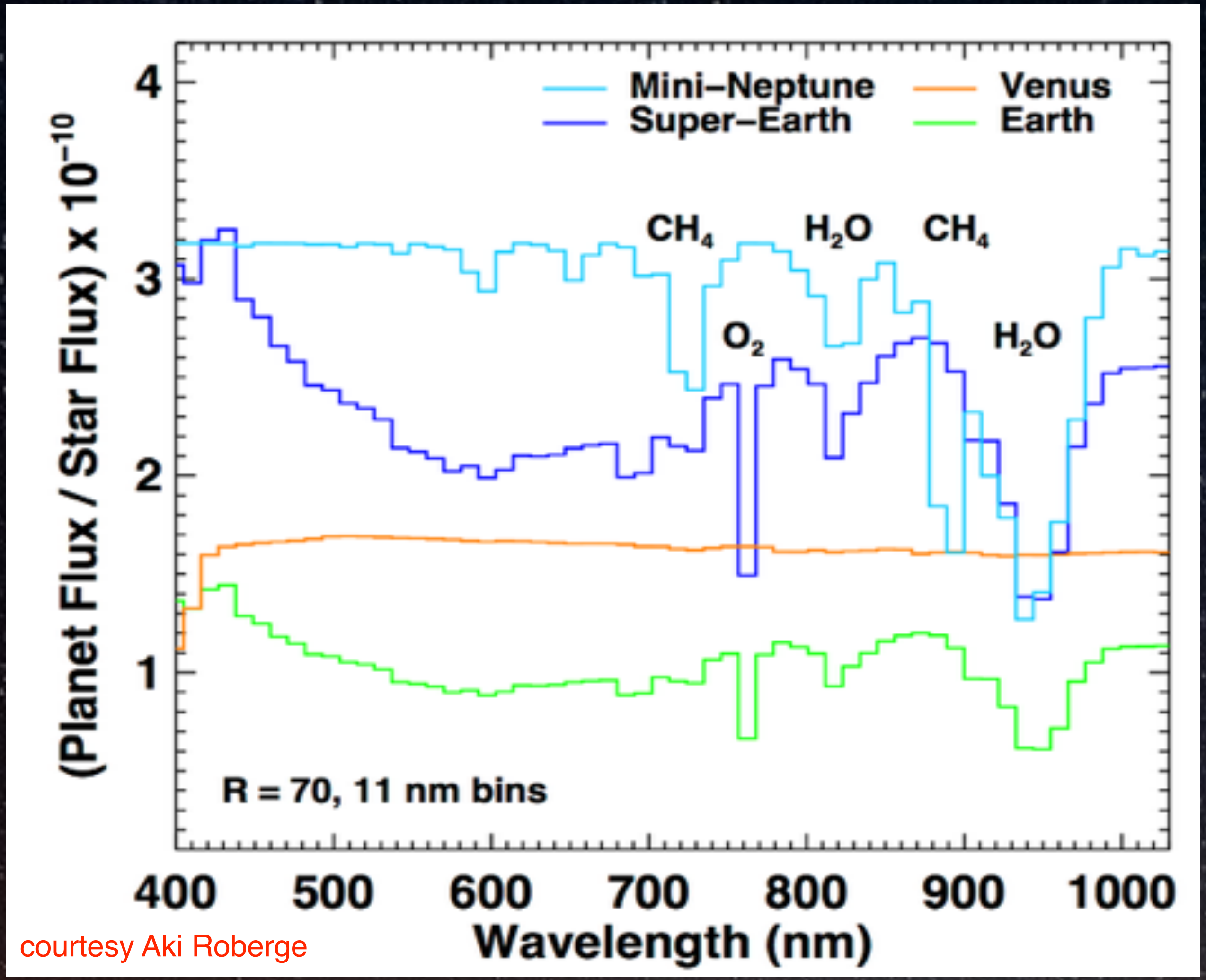


- A space-based observatory at the Earth-Sun L2 point.
- Goal is for a 10-12 meter aperture diameter
  - Motivated by exoplanet yield, high-res images of galaxies, cosmic gas flows, and stellar populations in diverse environments.
- A segmented, deployable mirror
- Diffraction-limited performance at visible wavelengths
- Full complement of coronagraphic, imaging, and spectroscopic instruments.
- UV to near-IR wavelengths (non-cryogenic optics)
- Serviceability is a goal but not a requirement.

The Ulimate Goal: Another "Living Earth"

Schoolchildren on Earth already learn that there are worlds orbiting other stars.

We aim for future generations to know, with the same certainty, that there is life on some of those worlds.



courtesy Aki Roberge

We are the first generation that can meet this lofty and ambitious goal, because we have the capability to identify Earths and search for signs of life there.

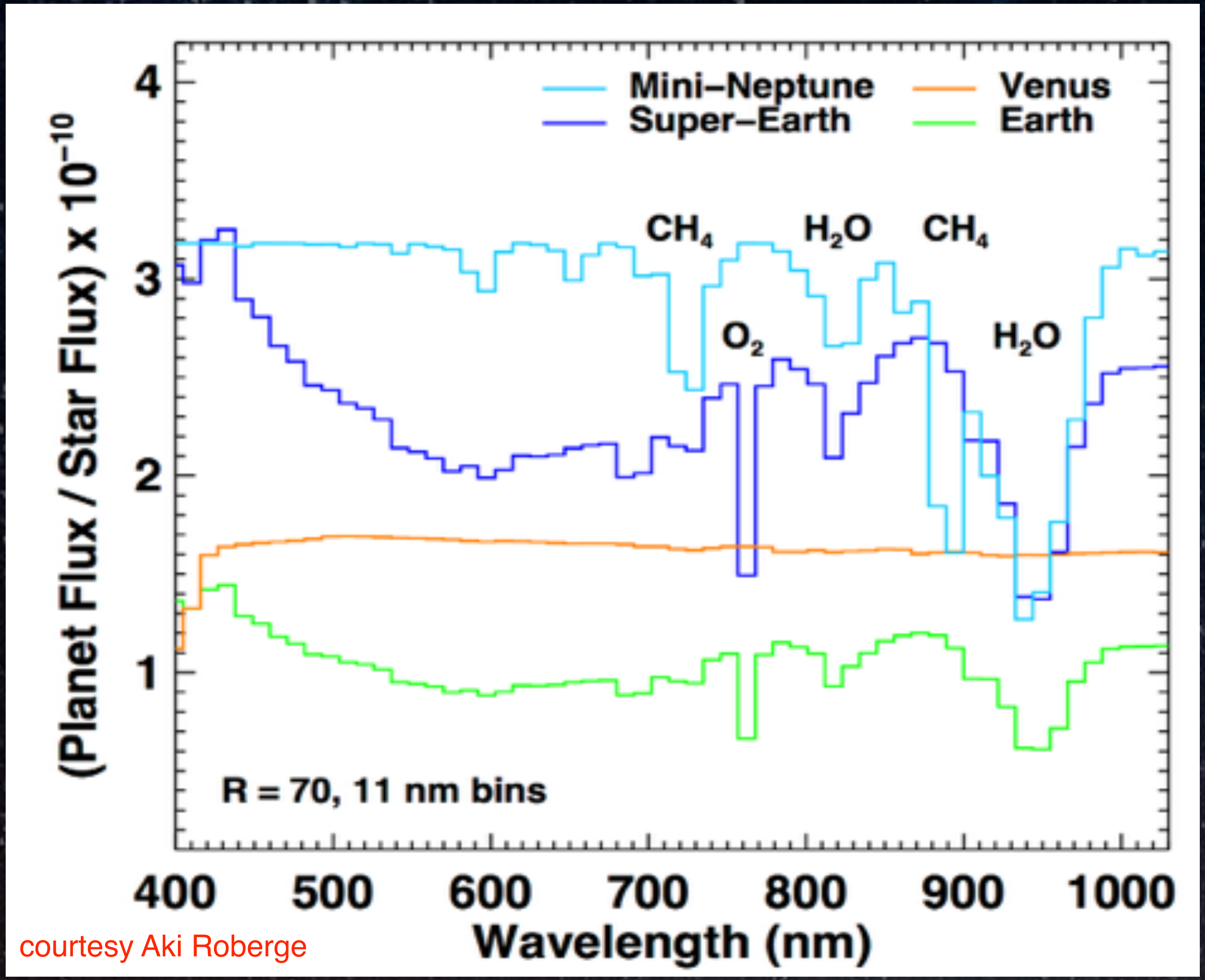
How Many Planets Must We Search?

Earth-like planets in their HZ may have diverse atmospheric properties owing to differences in mass, solar irradiation, and complex history.

We want to maximize our chances of detecting these biosignature gases on Earth-like planets.

If biomarkers can be found on 10% of Earth-like planets, and we want to reduce the chance of randomly missing it to <1%, 50 planets must be observed.

With N = 10, it must occur at 37% probability to have <1% chance of missing it.



courtesy Aki Roberge

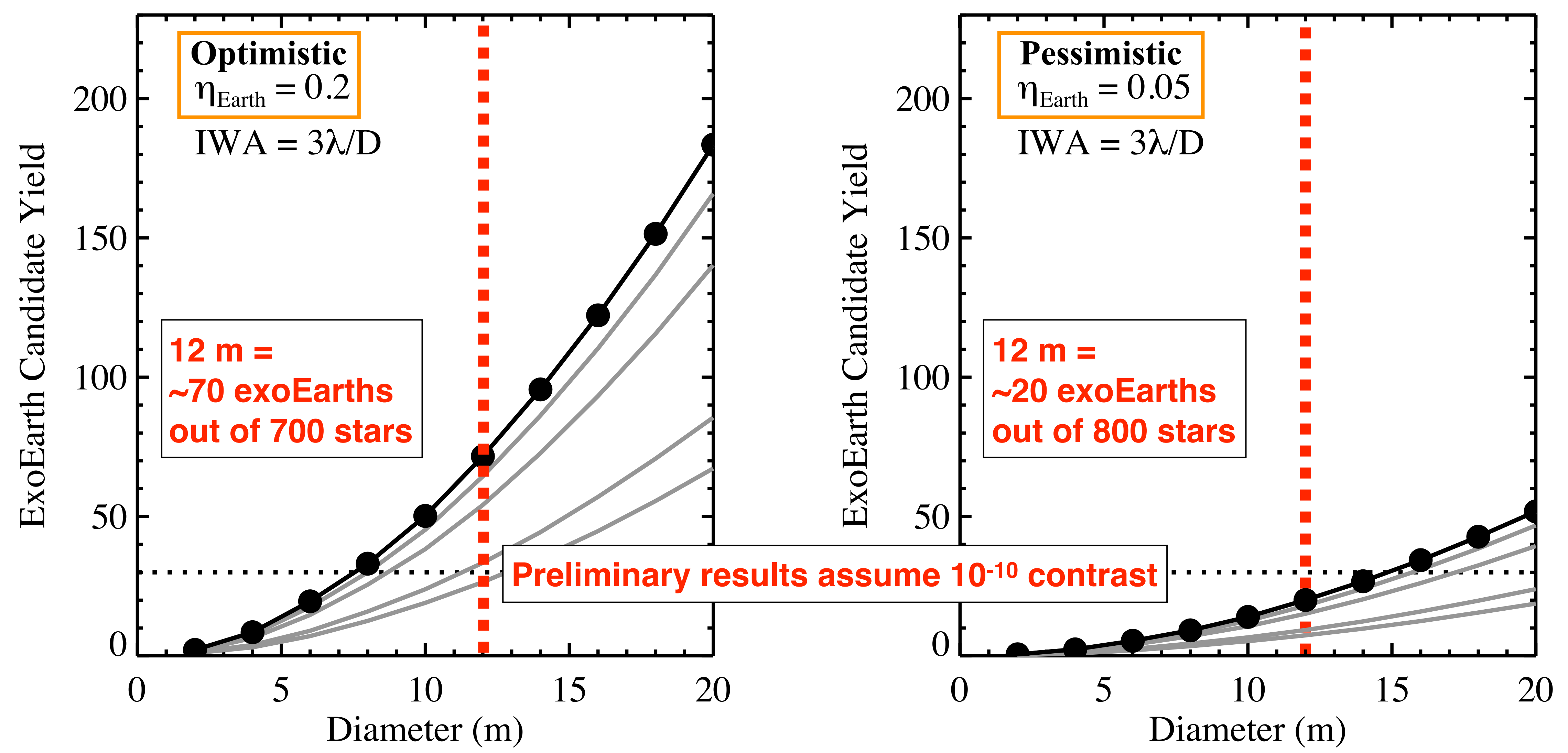
Searching hundreds of stars also insures against η_{Earth} on low side of present estimates.

To find signs of life, even if it is uncommon on Earthlike worlds, we must search dozens of Earth-like planets orbiting in their habitable zones.

How Many Planets Can We Search?   The Yield

- Only direct imaging can reach rocky planets around hundreds of Sun-like stars for atmospheric characterization: Venus and Earth are distinguishable only by direct imaging and transits (which have low probability).
- Exoplanet direct imaging is more challenging than faint object photometry and spectroscopy due to planet-star contrast, angular resoultion, and the planet-star projected separation.
- Need to be able to parameterize yield as a function of aperture and uncertain astrophysical parameters (particularly η_{Earth} and exozodi brightness).
- “Altruistic Yield Optimization” simulations assume: 10^{-10} contrast, $3\lambda/D$ inner working angle, R=0.66-1.5 $R_\oplus$, 1 year of total integration time (no overheads), and revisits for strong candidates (for details see Stark et al. arXiv:1409.1528)

How Many Planets Can We Search? The Yield



12 m = ~70 exoEarths out of 700 stars

12 m = ~20 exoEarths out of 800 stars

Preliminary results assume 10^{-10} contrast

Obscurational and photometric "completeness" drive the scaling of exoplanet yield to telescope aperture diameter $\propto D^{1.9}$ (versus idealized volume-limited surveys which scale as D^3).

Yield is most sensitive to telescope diameter, then coronagraph inner working angle, followed by coronagraph contrast, and finally coronagraph contrast noise floor. There is a surprisingly weak dependence of exoEarth candidate yield on exozodi level. Yield scales linearly with η_{Earth}.

A 12-meter telescope can reach 20-70 Earth-like planets: this is enough to detect or significantly constrain the incidence of biomarker molecules.

Good Statistics Yield the Answer to: Are We Alone?

While we can already estimate the probability of Earth-like worlds orbiting other stars, we do not know how often life occurs on those planets.

This is what we are trying to determine!

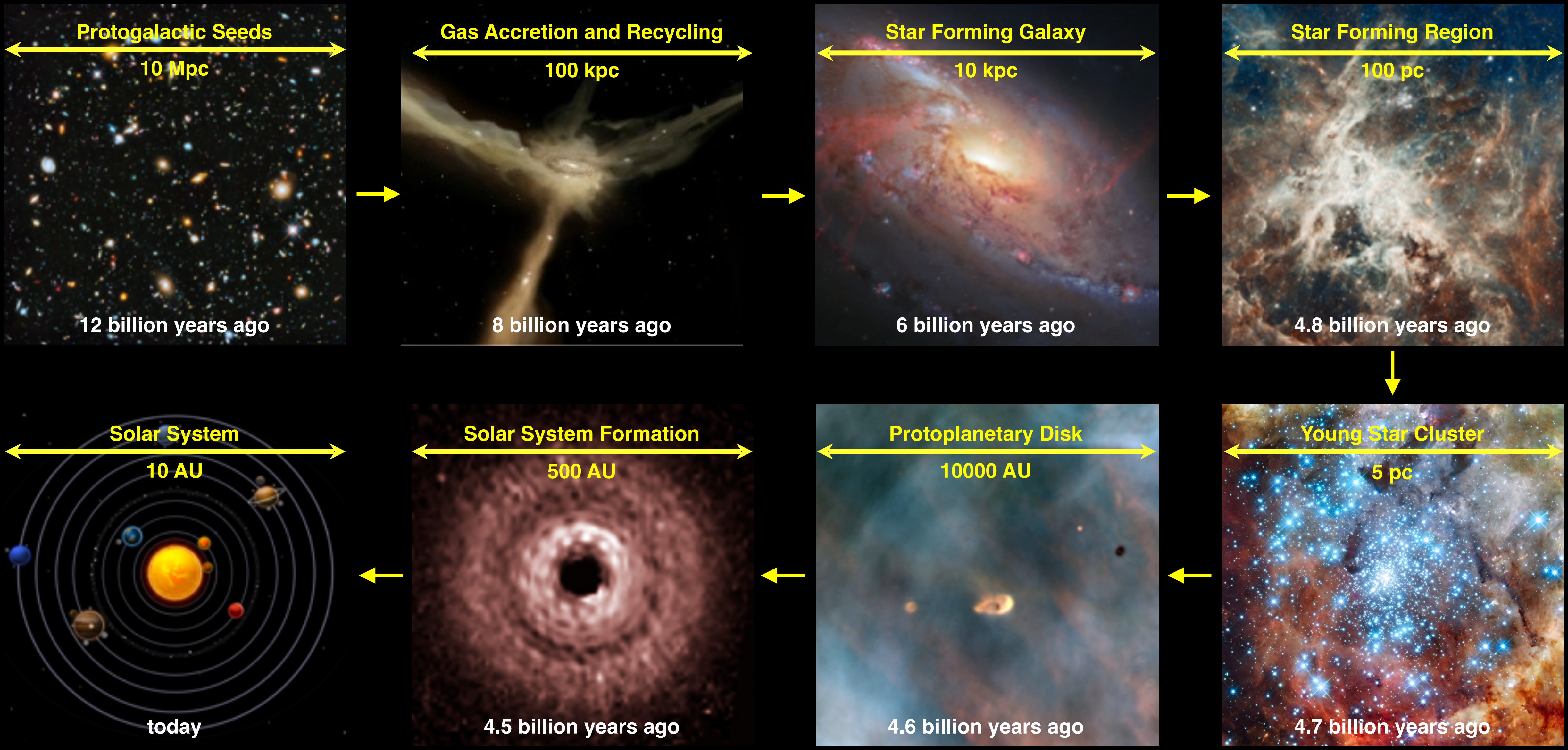
The incidence of life and its biomarker molecules may be small: 10% or even 1% on otherwise Earth-like planets in their HZ.

If so, a small sample of planets (~10 or less) is very likely to fail to answer our most important question.

Only by surveying dozens of worlds do we make the chance of detecting life's signature a good one, even if it is uncommon.

An HDST-like telescope will be able to detect dozens of Earth-like planets orbiting in their habitable zones and systematically search for biosignature gases to address "Are We Alone?" with a robust statistical sample.

From Cosmic Birth to Living Earths



Protogalactic Seeds
10 Mpc
12 billion years ago

Gas Accretion and Recycling
100 kpc
8 billion years ago

Star Forming Galaxy
10 kpc
6 billion years ago

Star Forming Region
100 pc
4.8 billion years ago

Young Star Cluster
5 pc
4.7 billion years ago

Protoplanetary Disk
10000 AU
4.6 billion years ago

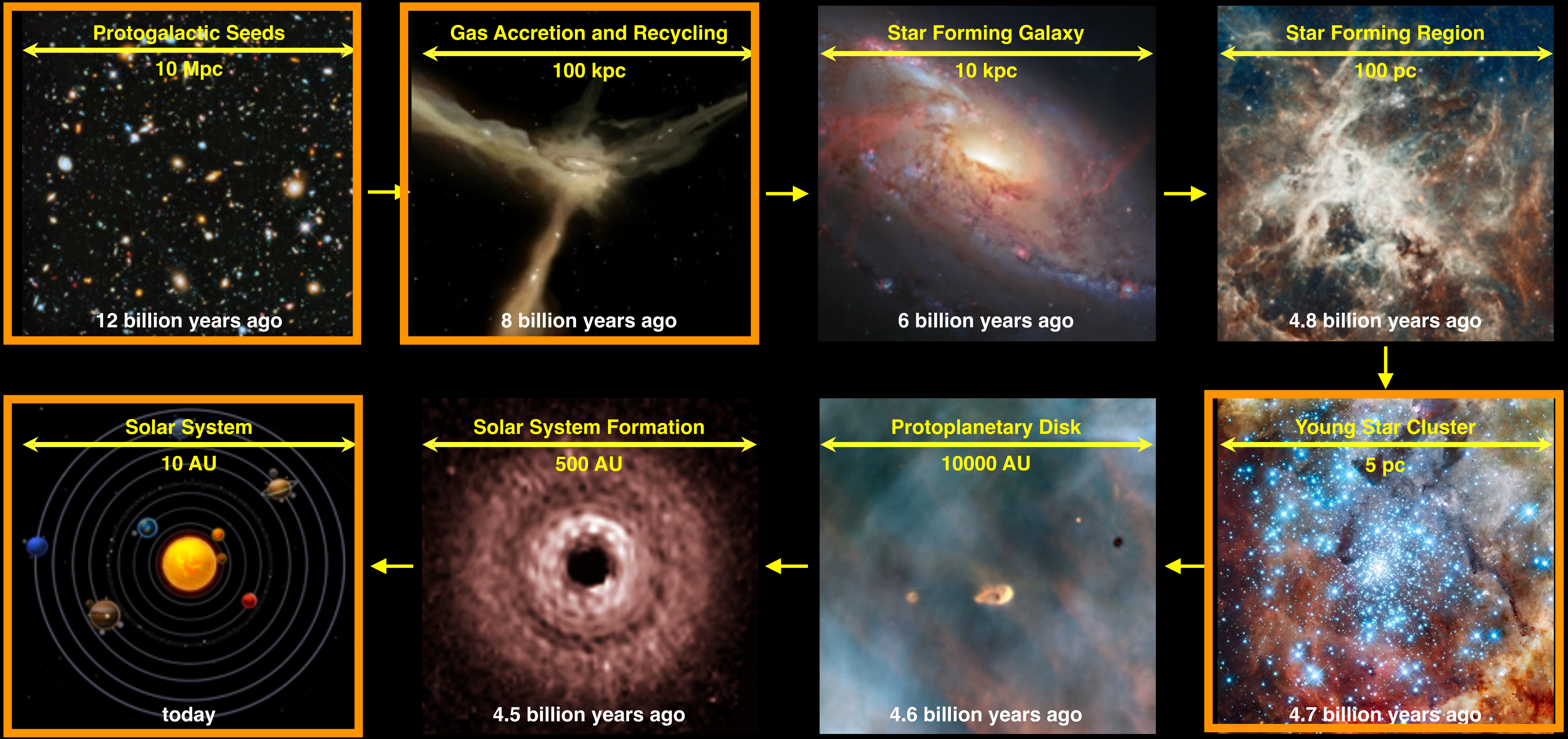
Solar System Formation
500 AU
4.5 billion years ago

Solar System
10 AU
today

As astonishing as it might be to find life on other worlds, we already know that, alien is it might be, the story of all life in the cosmos arises from galaxies, stars, and planets formed from heavy elements made in stars.

Let's look at five problems where HDST is uniquely suited to rewrite important chapters in the story of Cosmic Birth.

From Cosmic Birth to Living Earths



Protogalactic Seeds
10 Mpc
12 billion years ago

Gas Accretion and Recycling
100 kpc
8 billion years ago

Star Forming Galaxy
10 kpc
6 billion years ago

Star Forming Region
100 pc
4.8 billion years ago

Young Star Cluster
5 pc
4.7 billion years ago

Protoplanetary Disk
10000 AU
4.6 billion years ago

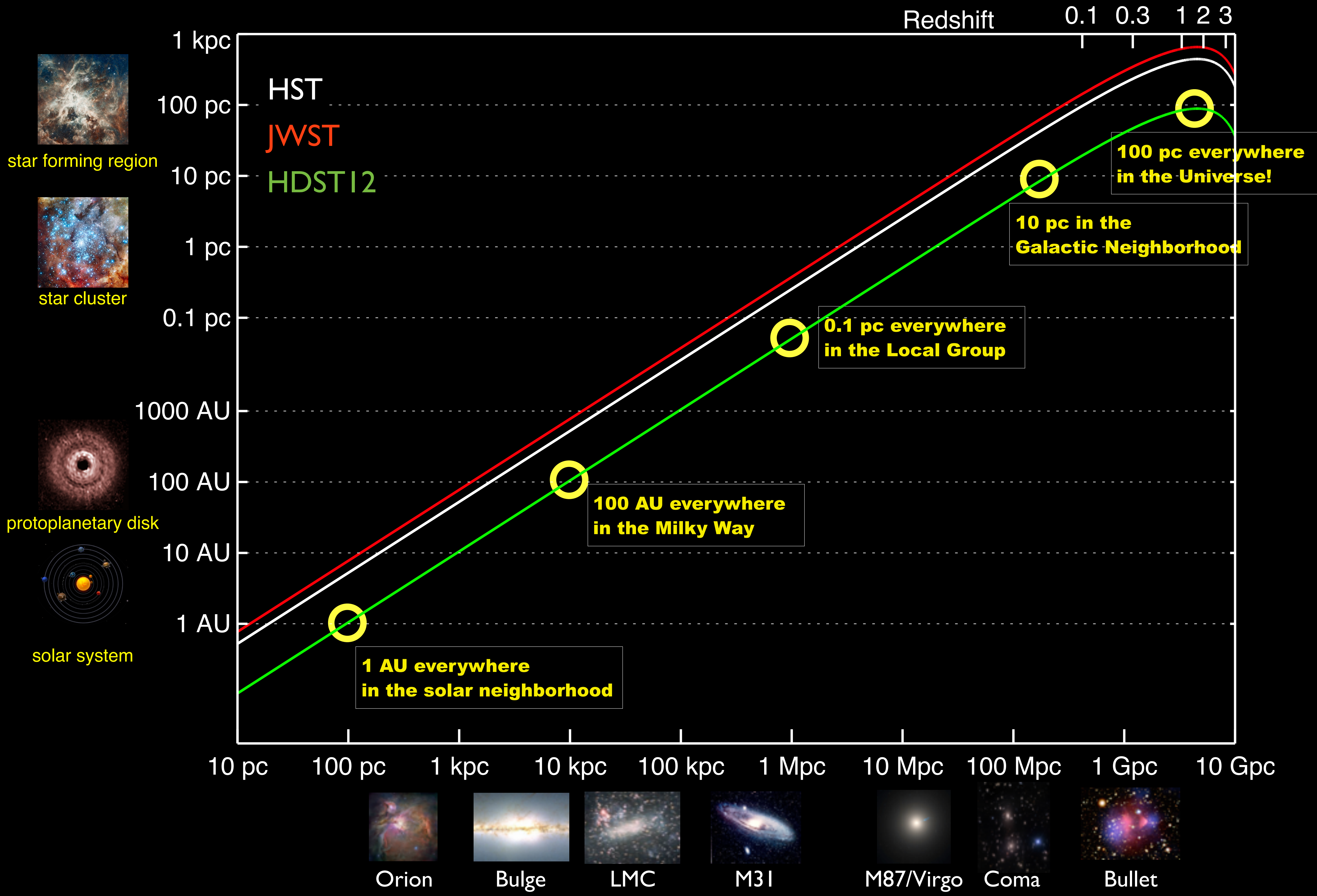
Solar System Formation
500 AU
4.5 billion years ago

Solar System
10 AU
today

As astonishing as it might be to find life on other worlds, we already know that, alien is it might be, the story of all life in the cosmos arises from galaxies, stars, and planets formed from heavy elements made in stars.

Let's look at five problems where HDST is uniquely suited to rewrite important chapters in the story of Cosmic Birth.

HDST: Breaking Resolution Barriers



100 pc everywhere in the Universe!

10 pc in the Galactic Neighborhood

0.1 pc everywhere in the Local Group

100 AU everywhere in the Milky Way

1 AU everywhere in the solar neighborhood

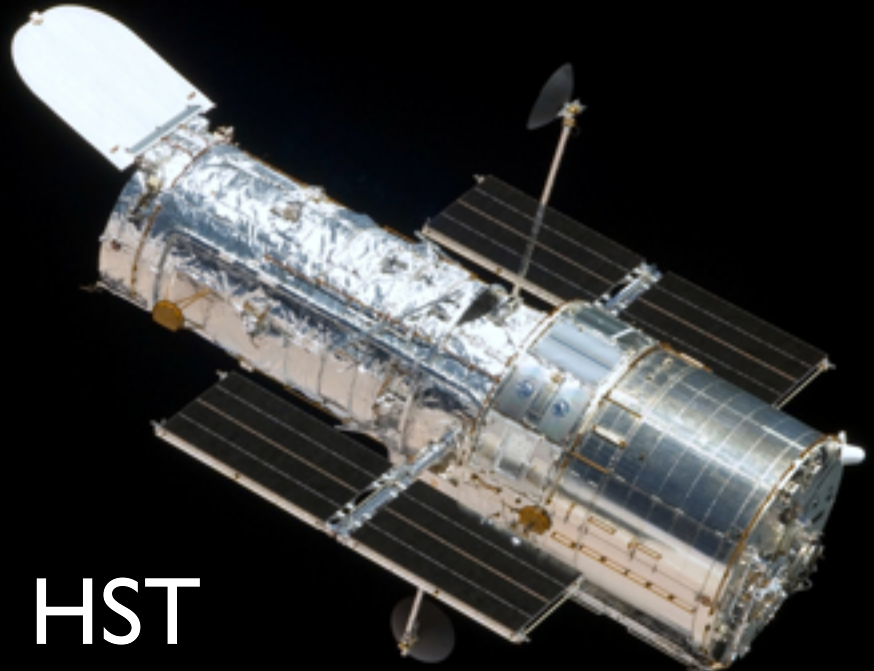
SDTV

720x480

24x pixel density →

UltraHD

3820x2160



HST

2.4 m

24x image sharpness →

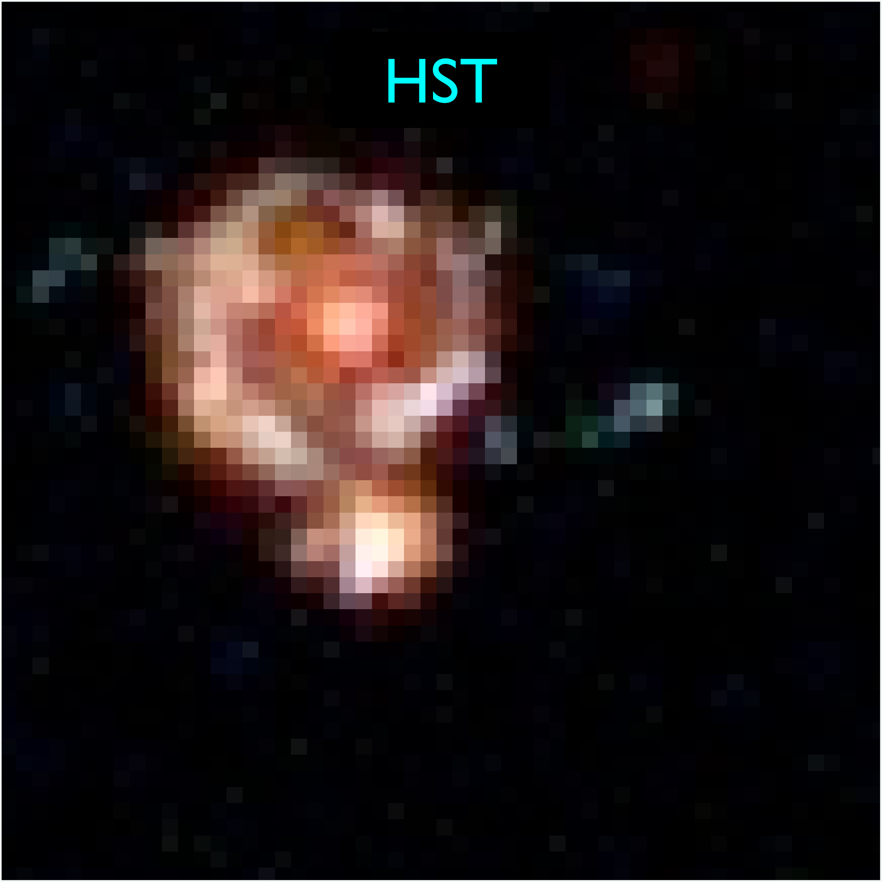
HDST

12 m

How Did the Milky Way Form from its Earliest Seeds?

Epoch
z = 1 - 4

Resolution
30-100 pc



With <u>unique 100 parsec resolution</u> in the optical at all redshifts, HDST can resolve ALL the building blocks of galaxies: individual star forming regions and dwarf satellites, including progenitors of the present-day dwarf spheroidals.

HDST's unique spatial resolution and depth will reveal the full formation history of galaxies like the Milky Way.

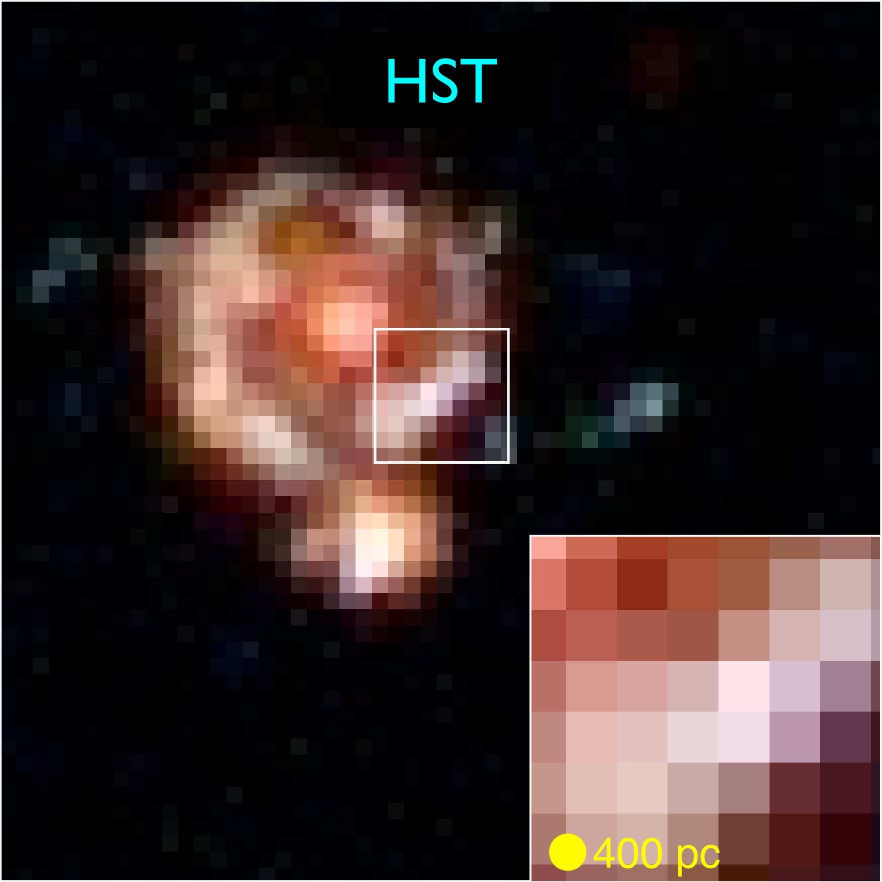
These high-resolution images will complement ELT and ALMA spectroscopy of the galaxies and their molecular gas.

Images simulated by Greg Snyder (STScI)

How Did the Milky Way Form from its Earliest Seeds?

Epoch
z = 1 - 4

Resolution
30-100 pc



With <u>unique 100 parsec resolution</u> in the optical at all redshifts, HDST can resolve ALL the building blocks of galaxies: individual star forming regions and dwarf satellites, including progenitors of the present-day dwarf spheroidals.

HDST's unique spatial resolution and depth will reveal the full formation history of galaxies like the Milky Way.

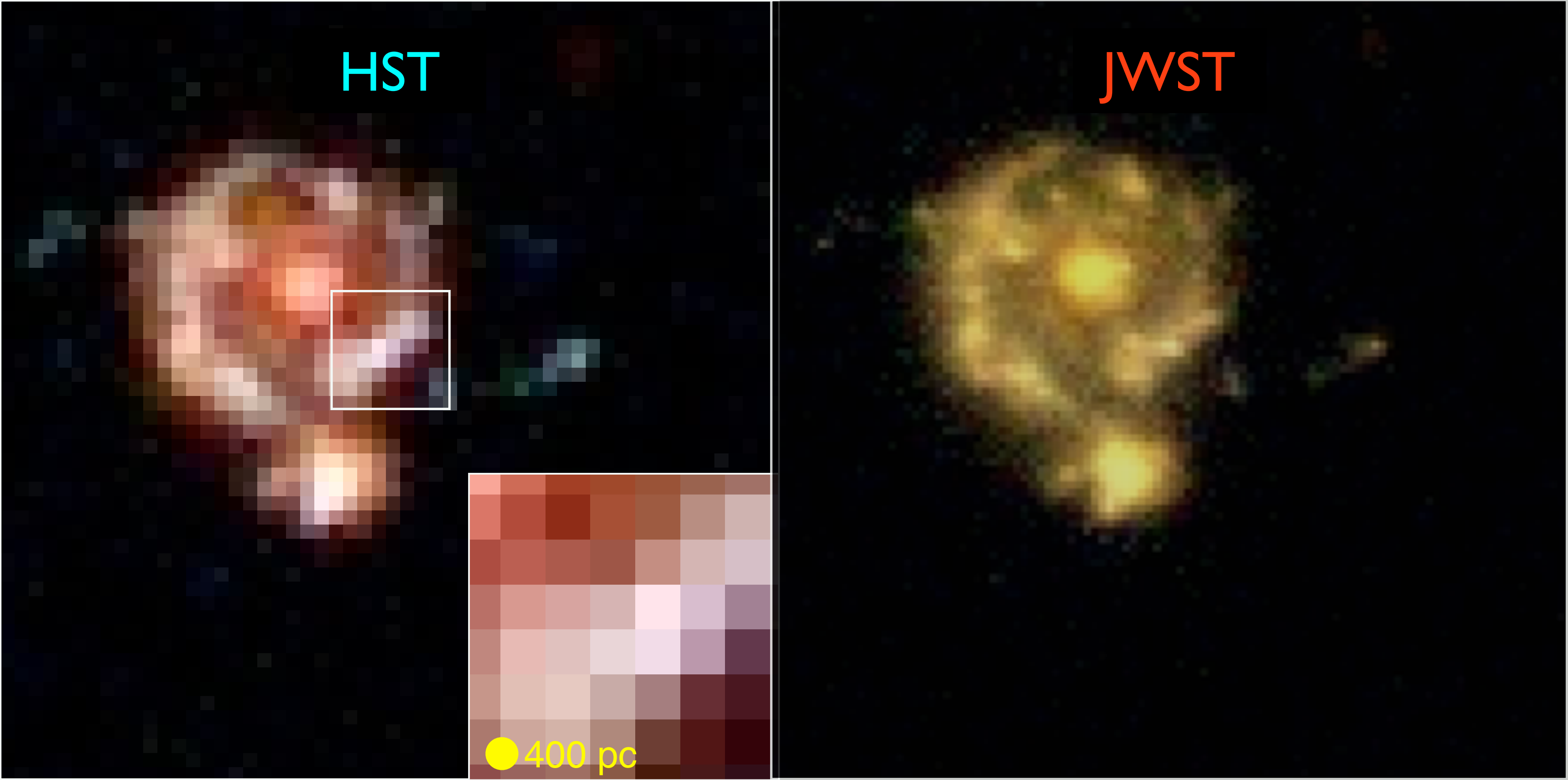
These high-resolution images will complement ELT and ALMA spectroscopy of the galaxies and their molecular gas.

Images simulated by Greg Snyder (STScI)

How Did the Milky Way Form from its Earliest Seeds?

Epoch
z = 1 - 4

Resolution
30-100 pc



With unique 100 parsec resolution in the optical at all redshifts, HDST can resolve ALL the building blocks of galaxies: individual star forming regions and dwarf satellites, including progenitors of the present-day dwarf spheroidals.

HDST's unique spatial resolution and depth will reveal the full formation history of galaxies like the Milky Way.

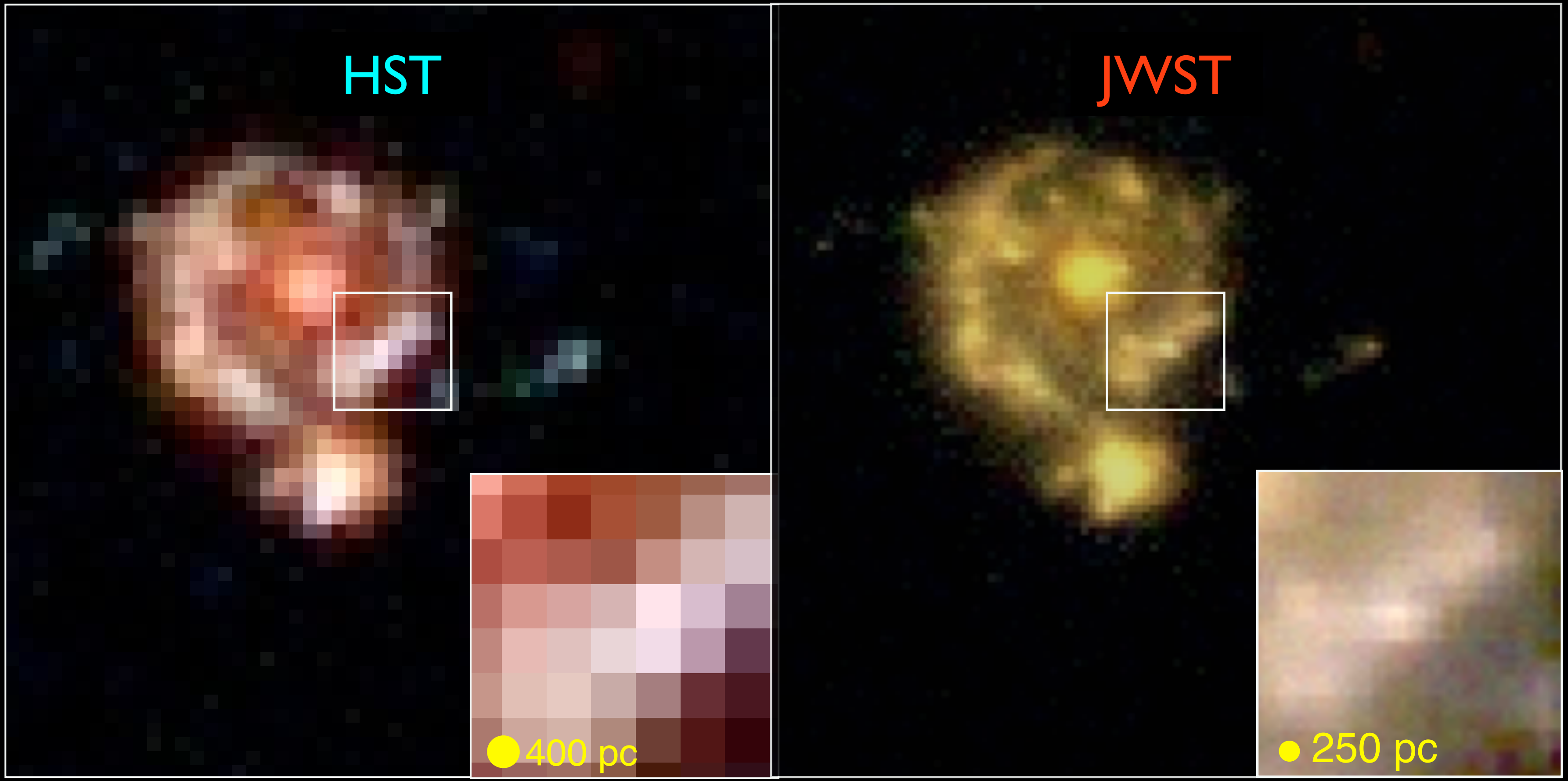
These high-resolution images will complement ELT and ALMA spectroscopy of the galaxies and their molecular gas.

Images simulated by Greg Snyder (STScI)

How Did the Milky Way Form from its Earliest Seeds?

Epoch
z = 1 - 4

Resolution
30-100 pc



With unique 100 parsec resolution in the optical at all redshifts, HDST can resolve ALL the building blocks of galaxies: individual star forming regions and dwarf satellites, including progenitors of the present-day dwarf spheroidals.

HDST’s unique spatial resolution and depth will reveal the full formation history of galaxies like the Milky Way.

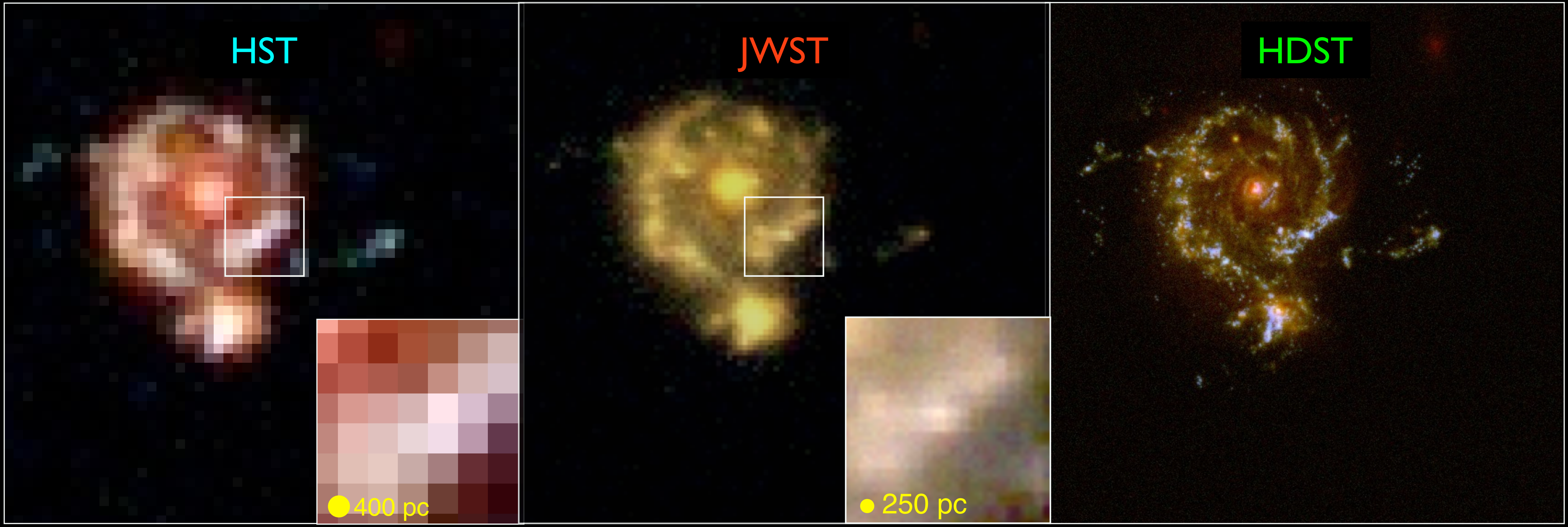
These high-resolution images will complement ELT and ALMA spectroscopy of the galaxies and their molecular gas.

Images simulated by Greg Snyder (STScI)

How Did the Milky Way Form from its Earliest Seeds?

Epoch
z = 1 - 4

Resolution
30-100 pc



With unique 100 parsec resolution in the optical at all redshifts, HDST can resolve ALL the building blocks of galaxies: individual star forming regions and dwarf satellites, including progenitors of the present-day dwarf spheroidals.

HDST’s unique spatial resolution and depth will reveal the full formation history of galaxies like the Milky Way.

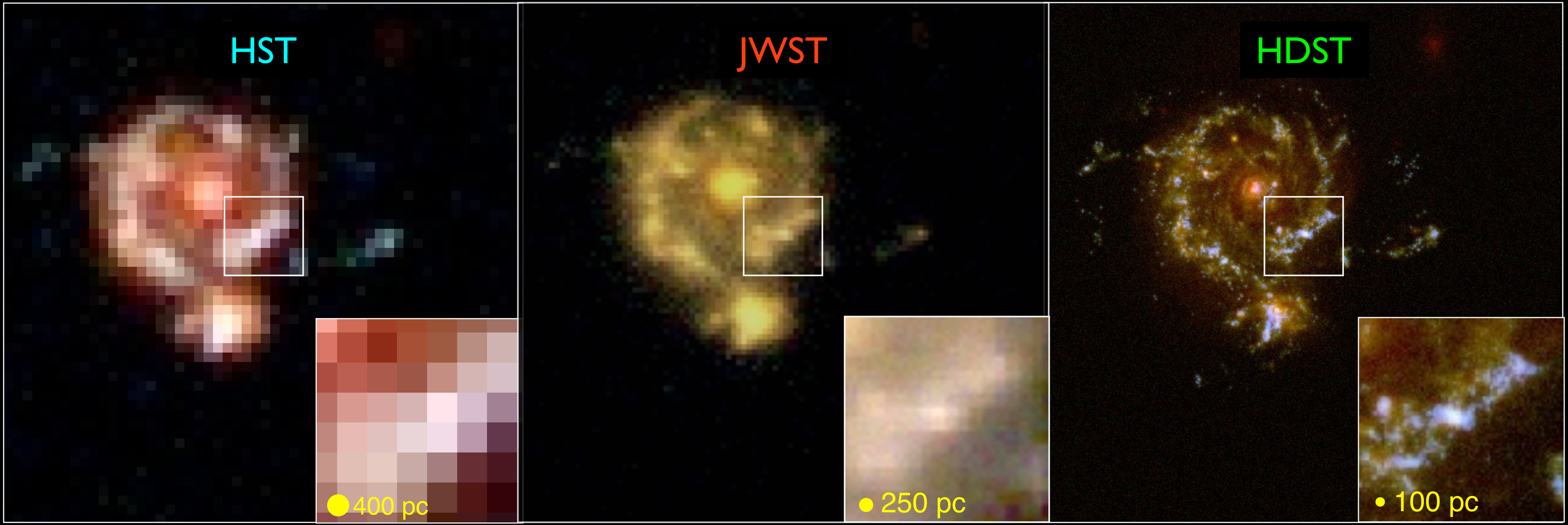
These high-resolution images will complement ELT and ALMA spectroscopy of the galaxies and their molecular gas.

Images simulated by Greg Snyder (STScI)

How Did the Milky Way Form from its Earliest Seeds?

Epoch
$z = 1 - 4$

Resolution
30-100 pc



With unique 100 parsec resolution in the optical at all redshifts, HDST can resolve ALL the building blocks of galaxies: individual star forming regions and dwarf satellites, including progenitors of the present-day dwarf spheroidals.

HDST's unique spatial resolution and depth will reveal the full formation history of galaxies like the Milky Way.

These high-resolution images will complement ELT and ALMA spectroscopy of the galaxies and their molecular gas.

Images simulated by Greg Snyder (STScI)

How Do Galaxies Acquire, Process, and Recycle Their Gas?

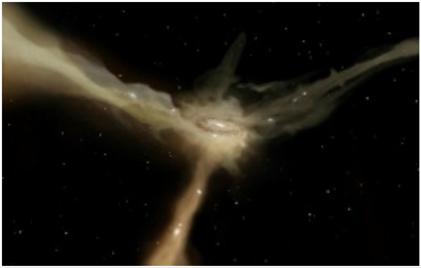
Epoch
$z < 1$

Resolution
10-100 pc

How Do Galaxies Acquire, Process, and Recycle Their Gas?

Epoch
$z < 1$

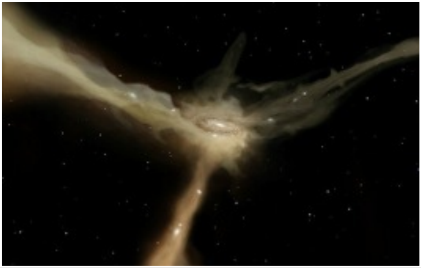
Resolution
10-100 pc

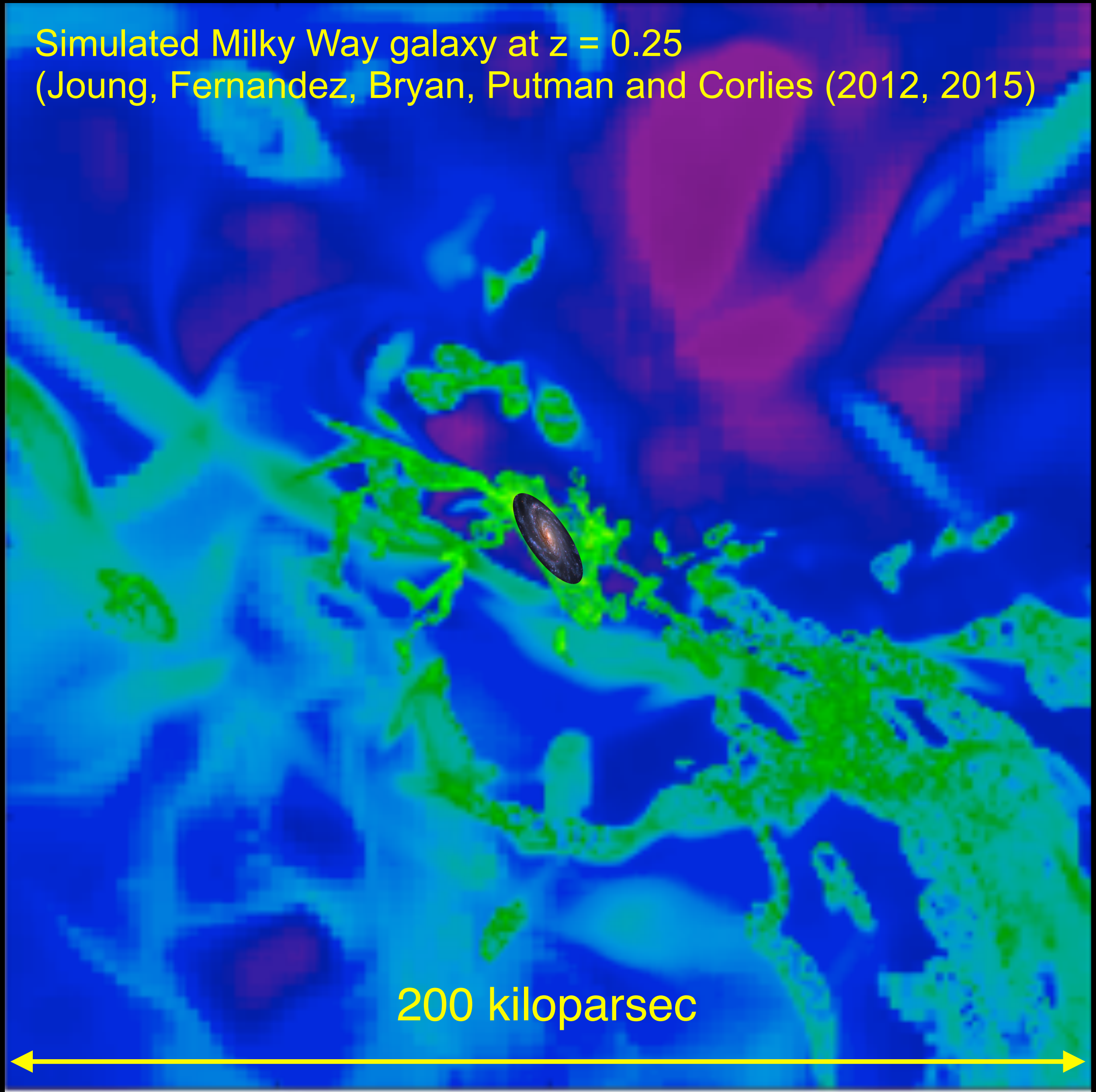


How Do Galaxies Acquire, Process, and Recycle Their Gas?

Epoch
$z < 1$

Resolution
10-100 pc





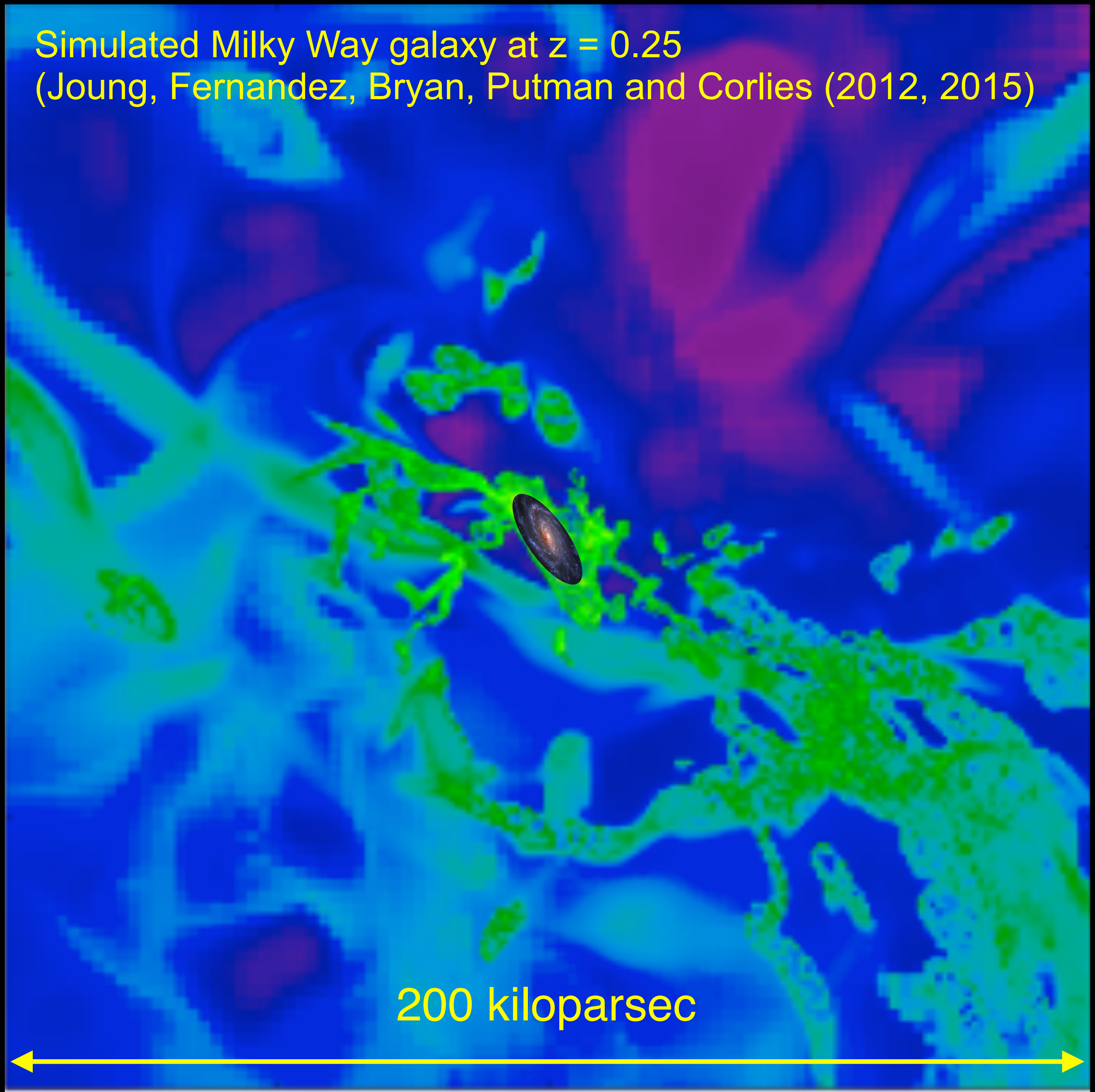
Simulated Milky Way galaxy at $z = 0.25$
(Joung, Fernandez, Bryan, Putman and Corlies (2012, 2015)

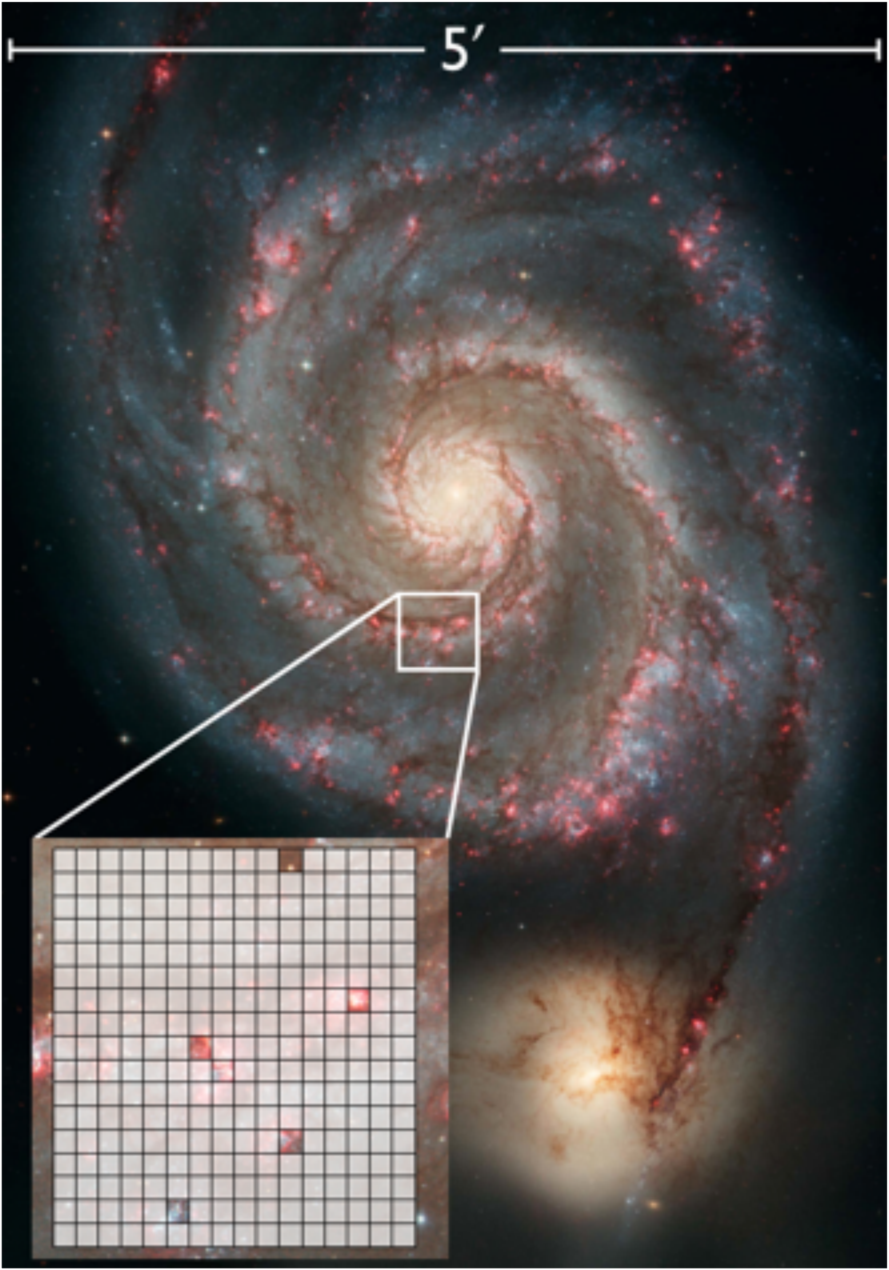
Using powerful and unique <u>multiobject UV spectroscopy</u>, HDST will be able to map the “faintest light in the Universe” emitted from gas filaments entering galaxies and energetic feedback headed back out.

How Do Galaxies Acquire, Process, and Recycle Their Gas?

Epoch
$z < 1$

Resolution
10-100 pc


Simulated Milky Way galaxy at z = 0.25
(Joung, Fernandez, Bryan, Putman and Corlies (2012, 2015)



Using powerful and unique multiobject UV spectroscopy, HDST will be able to map the "faintest light in the Universe" emitted from gas filaments entering galaxies and energetic feedback headed back out.

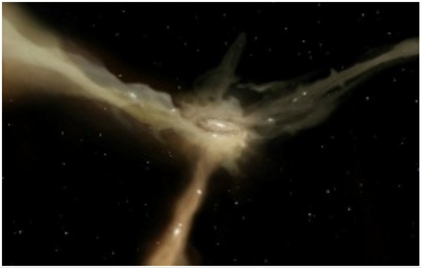
With UV multiplexing, HDST will be able to map the properties of young stellar clusters and, using them as background sources, the outflows they drive into the ISM and IGM.

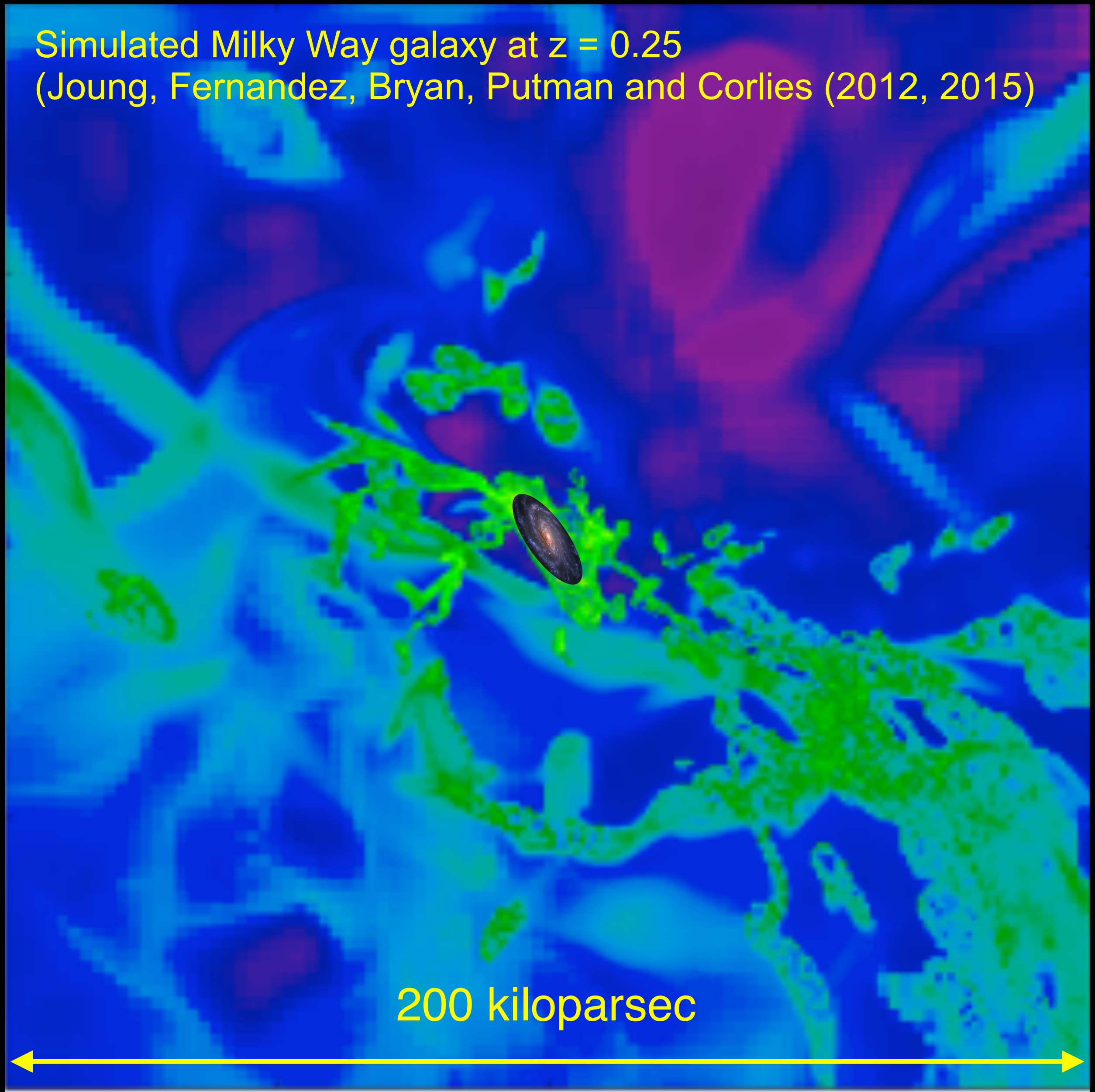
These problems **require** UV capability.

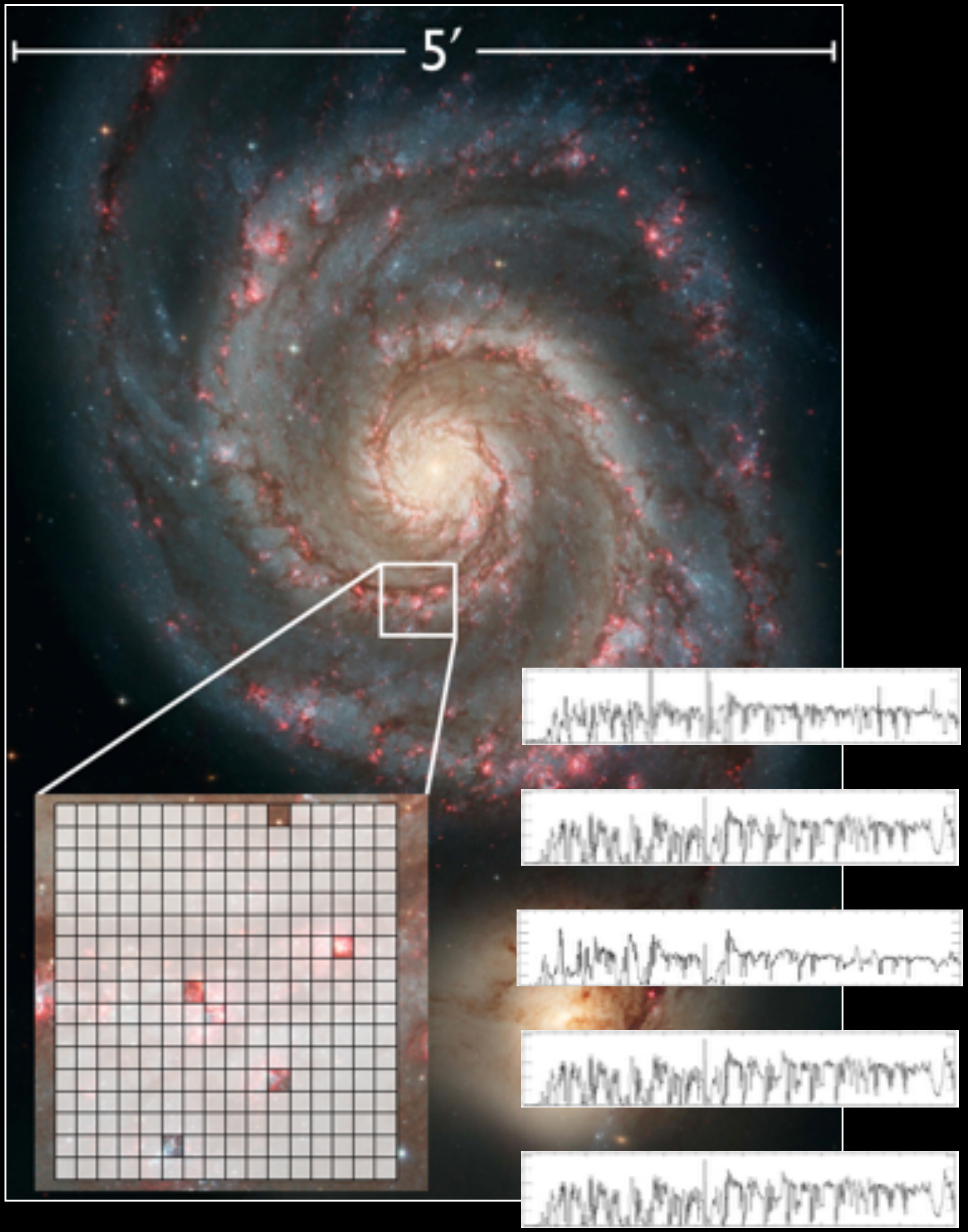
How Do Galaxies Acquire, Process, and Recycle Their Gas?

Epoch
z < 1

Resolution
10-100 pc




Simulated Milky Way galaxy at z = 0.25
(Joung, Fernandez, Bryan, Putman and Corlies (2012, 2015))



Using powerful and unique multiobject UV spectroscopy, HDST will be able to map the "faintest light in the Universe" emitted from gas filaments entering galaxies and energetic feedback headed back out.

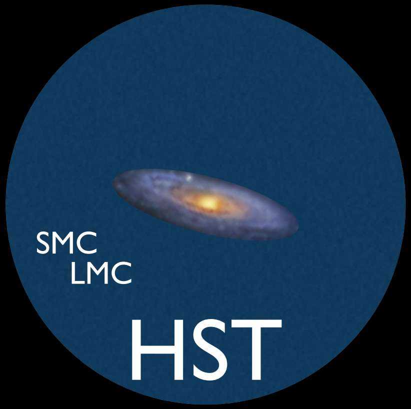
With UV multiplexing, HDST will be able to map the properties of young stellar clusters and, using them as background sources, the outflows they drive into the ISM and IGM.

These problems **require** UV capability.

How Does the IMF Vary with Environment?
How and When is the IMF Established?

Volume
< 100 kpc

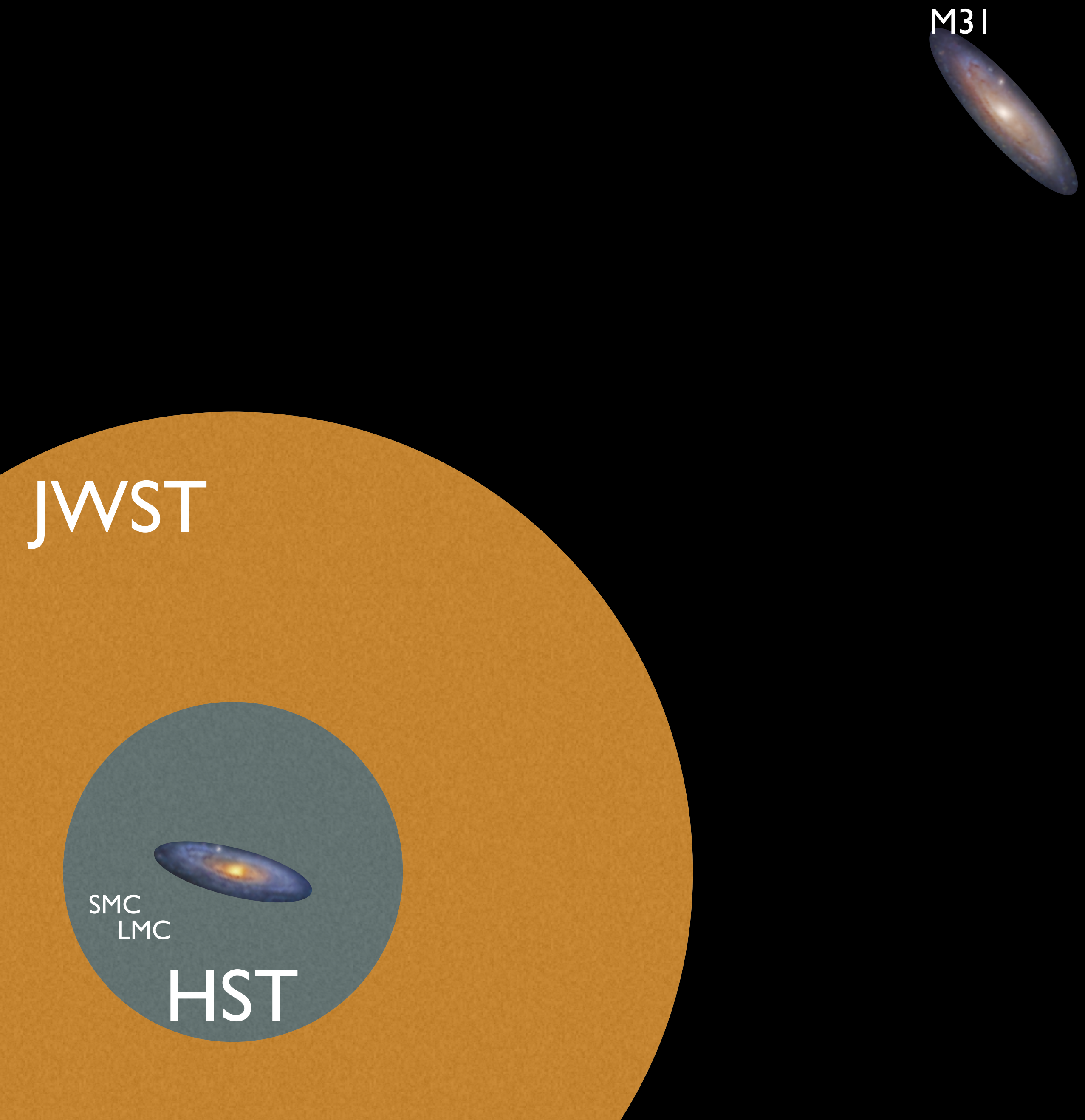
Resolution
10-100 AU



How Does the IMF Vary with Environment? How and When is the IMF Established?

Volume
< 100 kpc

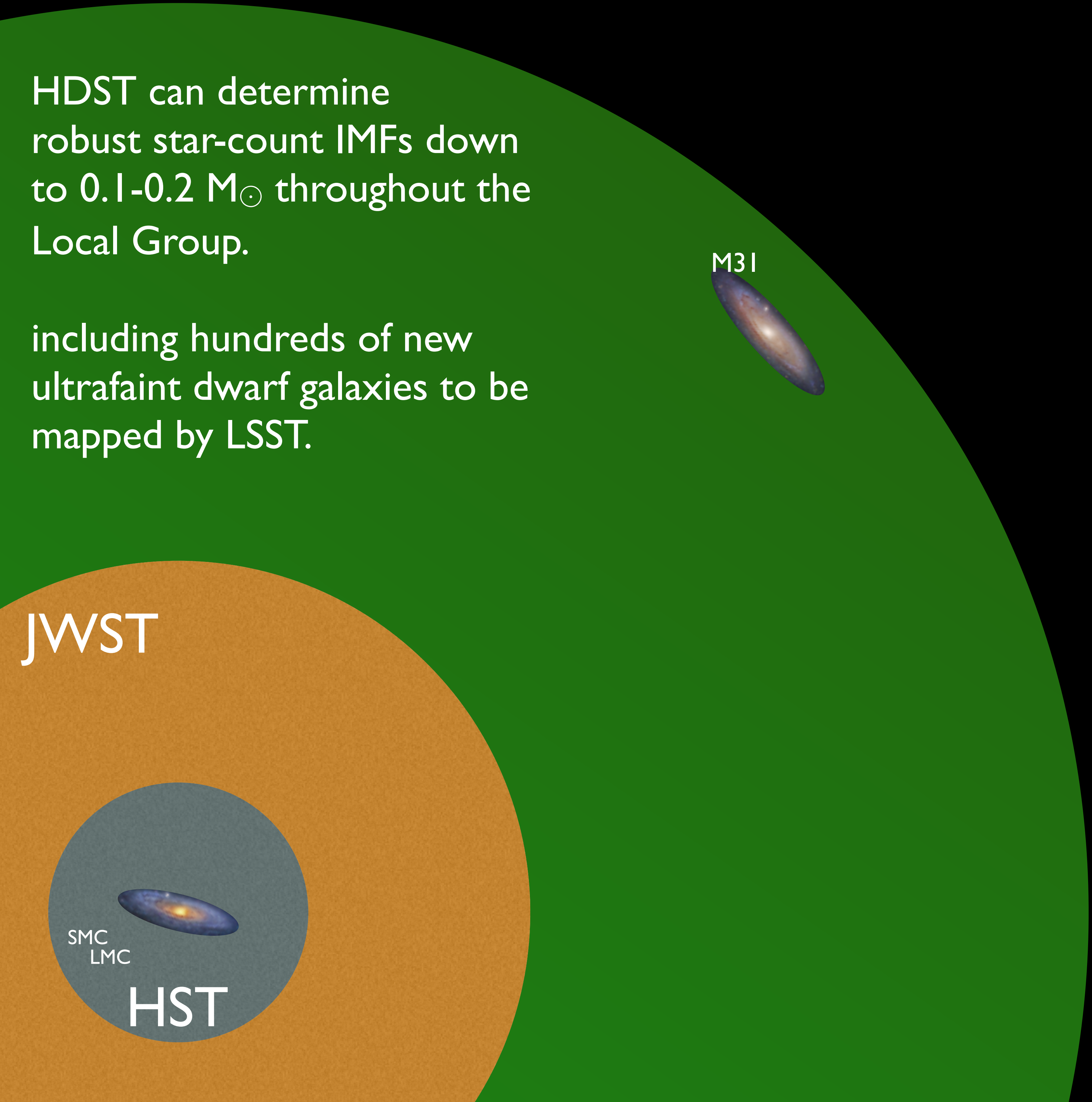
Resolution
10-100 AU



How Does the IMF Vary with Environment? How and When is the IMF Established?

Volume
< 100 kpc

Resolution
10-100 AU



HDST can determine robust star-count IMFs down to 0.1-0.2 $M_\odot$ throughout the Local Group.

including hundreds of new ultrafaint dwarf galaxies to be mapped by LSST.

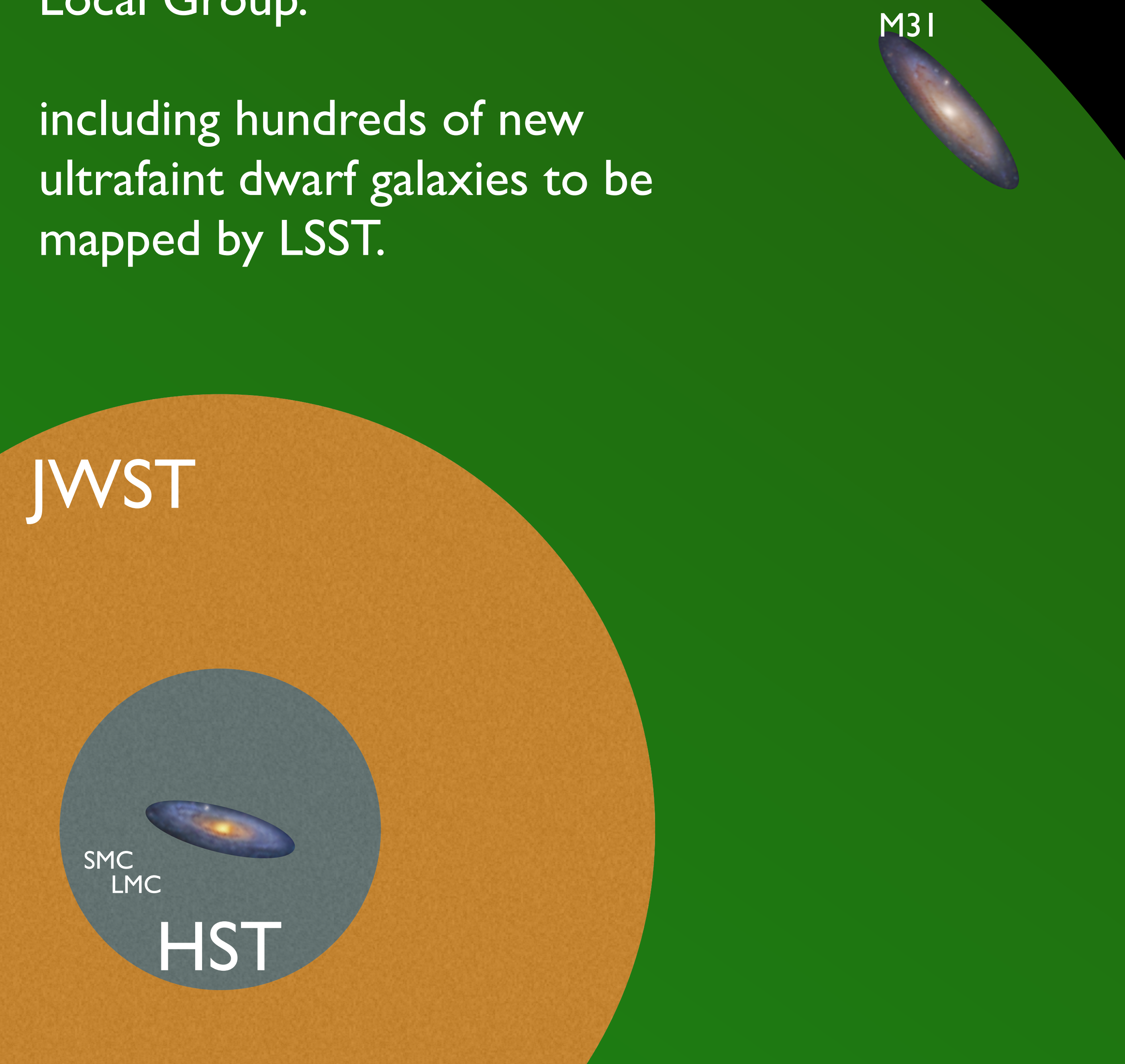
How Does the IMF Vary with Environment? How and When is the IMF Established?

Volume
< 100 kpc

Resolution
10-100 AU

HDST can determine robust star-count IMFs down to 0.1-0.2 $M_\odot$ throughout the Local Group.

including hundreds of new ultrafaint dwarf galaxies to be mapped by LSST.



30 Doradas in the Large Magellanic Cloud

Most Sun-like stars are born in clusters that too dense for Hubble to resolve individual stars: 10-100 stars / arcsec^2.

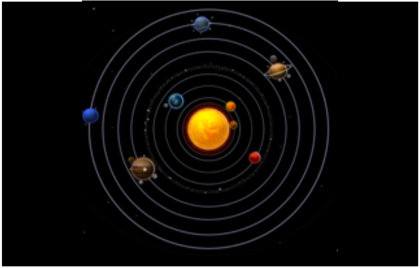
UV light provides a direct estimate of stellar accretion rate from the protostellar disk, but only if single stars can be resolved (≥10 meter aperture for the Magellanic Clouds).

Resolving individual stars allows direct measurements of the stellar IMF (e.g. holy grail) and direct UV / optical estimates of accretion rate for stars still embedded in their disks.

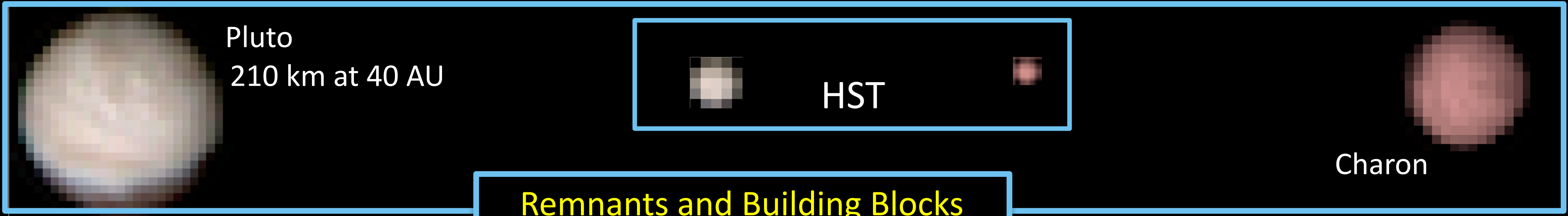
What Are The Building Blocks of the Solar System Made Of?

Volume
<50 AU

Resolution
20-100 km

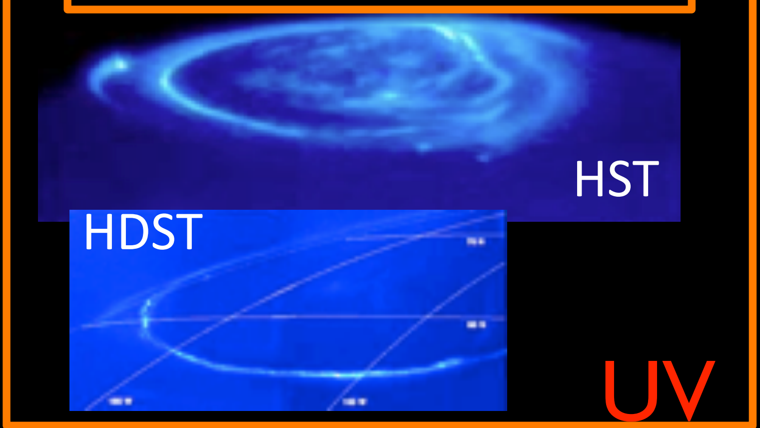


Remnants and Building Blocks

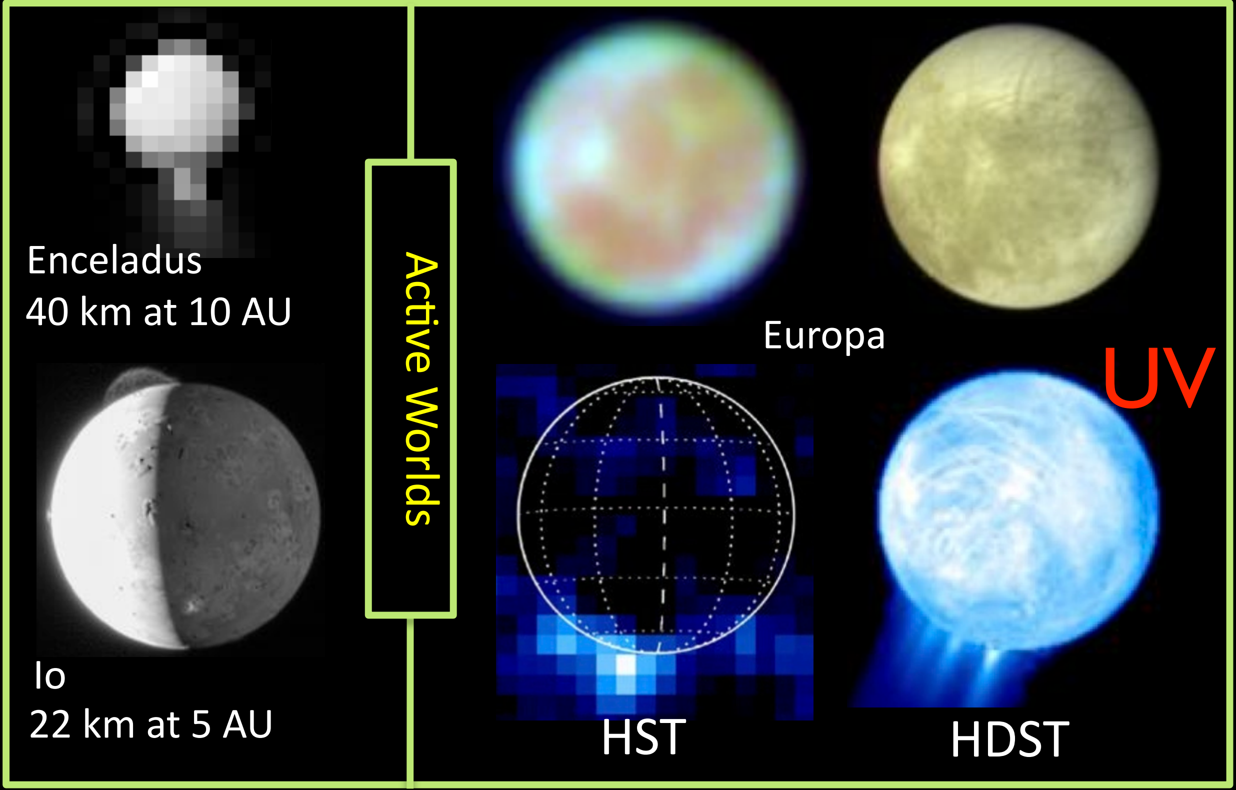


The Solar System:
A laboratory for planet formation and evolution

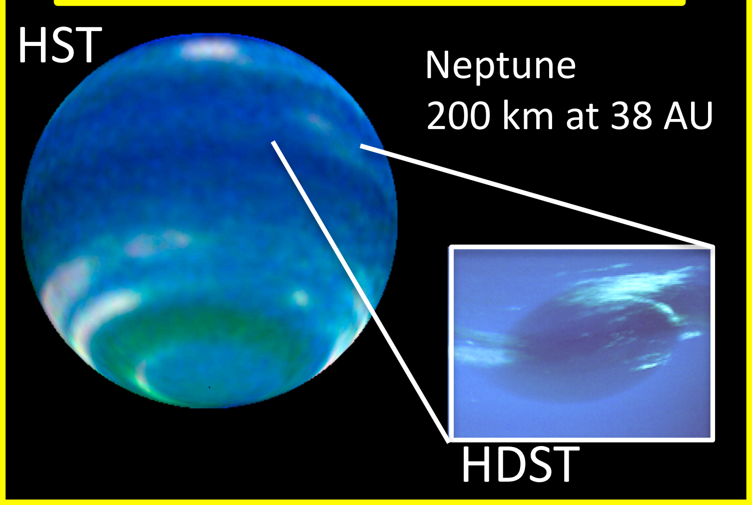
Sun Planet Connection



Active Worlds



Dynamics and Weather



With its unique spatial resolution and UV capability, HDST will open new avenues in Solar System research.

What can a >10 meter space telescope do?

…resolve every galaxy in the Universe to 100 parsec or better…

…detect virtually every star-forming galaxy at the epoch when the Milky Way formed…

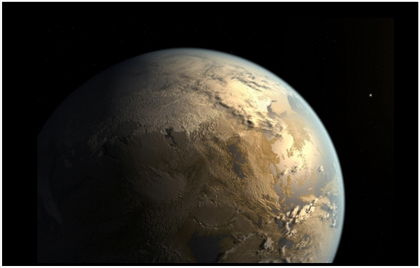
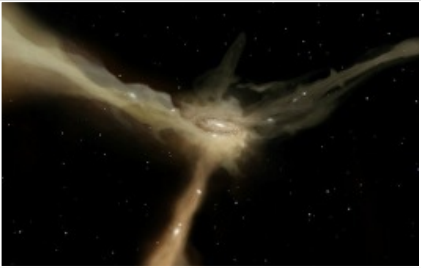
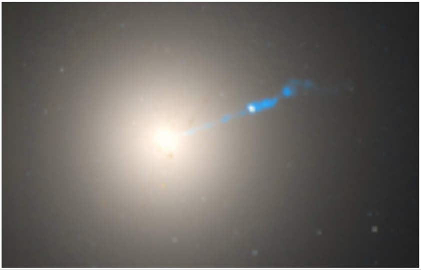
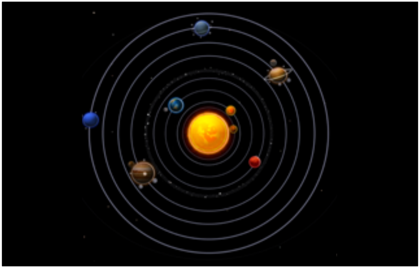
…observe individual supernovae at the dawn of cosmic time…

…see the nearly invisible diffuse gas feeding galaxies…

…watch the motion of virtually any star in the Local Group…

…observe objects the size of Manhattan at the orbit of Jupiter …

. . . which allows us to map the galactic, stellar, and planetary environments where life forms, and follow the chemical ingredients of life itself, over the 14 billion year history of the Universe.

		Aperture Drivers	UV Drivers
ExoEarths		Detect dozens of ExoEarths in high-contrast direct images. Obtain deep spectroscopy of the leading candidates for biomarker searches.	Observe flares on exoplanet host stars to measure incident UV radiation and veto possible biomarker false postives.
z = 1 - 4		Resolve ALL galaxies to 100 parsec or better, to individual SF regions.	
z < 1		Identify stellar progenitors and host environments for diverse transients, key to unraveling causes. Reach > 100s of background QSOs/AGN for outflow and IGM/CGM studies.	Detect UV emission from gas accreting into and ejected from galaxies. Detect hot plasma ejected by SMBHs acting as feedback on their galaxies.
< 100 Mpc		Resolve stellar pops down to $1 M_\odot$ out to the nearest giant ellipticals… …and to watch the motions of virtually ANY Milky Way star, Local Group satellites, and giant ellipticals in the Virgo cluster (~15 Mpc).	Use UV MOS/IFU to dissect multiphase gas feedback flows in nearby galaxies.
< 100 kpc		Examine protoplanetary disks at ~1-3 AU resolution out to > 100 pc… …and resolve individual stars in young clusters everywhere in the MW and Magellanic Clouds.	Measure protostellar accretion rates from UV continuum and lines out to MCs. …and obtain disk abundances of C, N, O, Si, Fe (from UV lines) that strongly influence planet mass and composition.
<50 AU		Resolve surface and cloud features down to 50 km at outer planets and 200 km at Kuiper belt.	Detect emission from planetary coronae, satellite plasma ejecta (and geysers!)

From Cosmic Birth to Living Earth

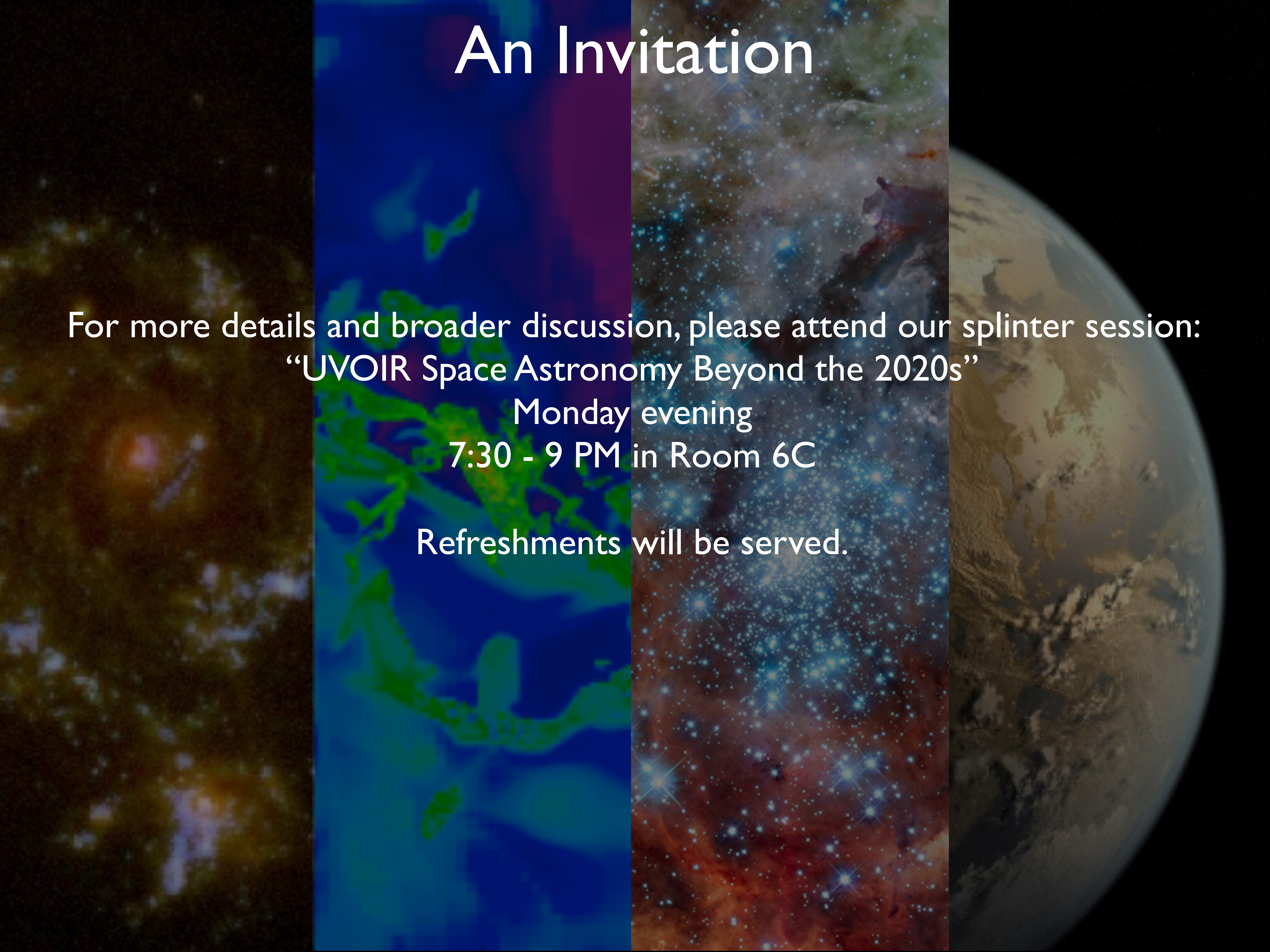
We recommend that NASA and its international partners proceed towards constructing a general purpose, long-life, space-based observatory that is capable of finding planets showing signs of life.

Such an observatory would be able to survey hundreds of planetary systems and detect dozens of Earth-like planets in the habitable zones around their stars.

It would also radically advance every area of astronomy from galaxy formation to star and planet formation, and from black hole physics to solar system objects.

This observatory will have unique power to transform our understanding of life and its origins in the cosmos in ways that are unreachable by a smaller telescope in space or larger ones on the ground.

An Invitation



For more details and broader discussion, please attend our splinter session:
“UVOIR Space Astronomy Beyond the 2020s”
Monday evening
7:30 - 9 PM in Room 6C

Refreshments will be served.

END

HDST vs. ELT comparison

Next generation ELTs (20-30m) plan adaptive optics that will provide diffraction limited imaging in the near-IR.

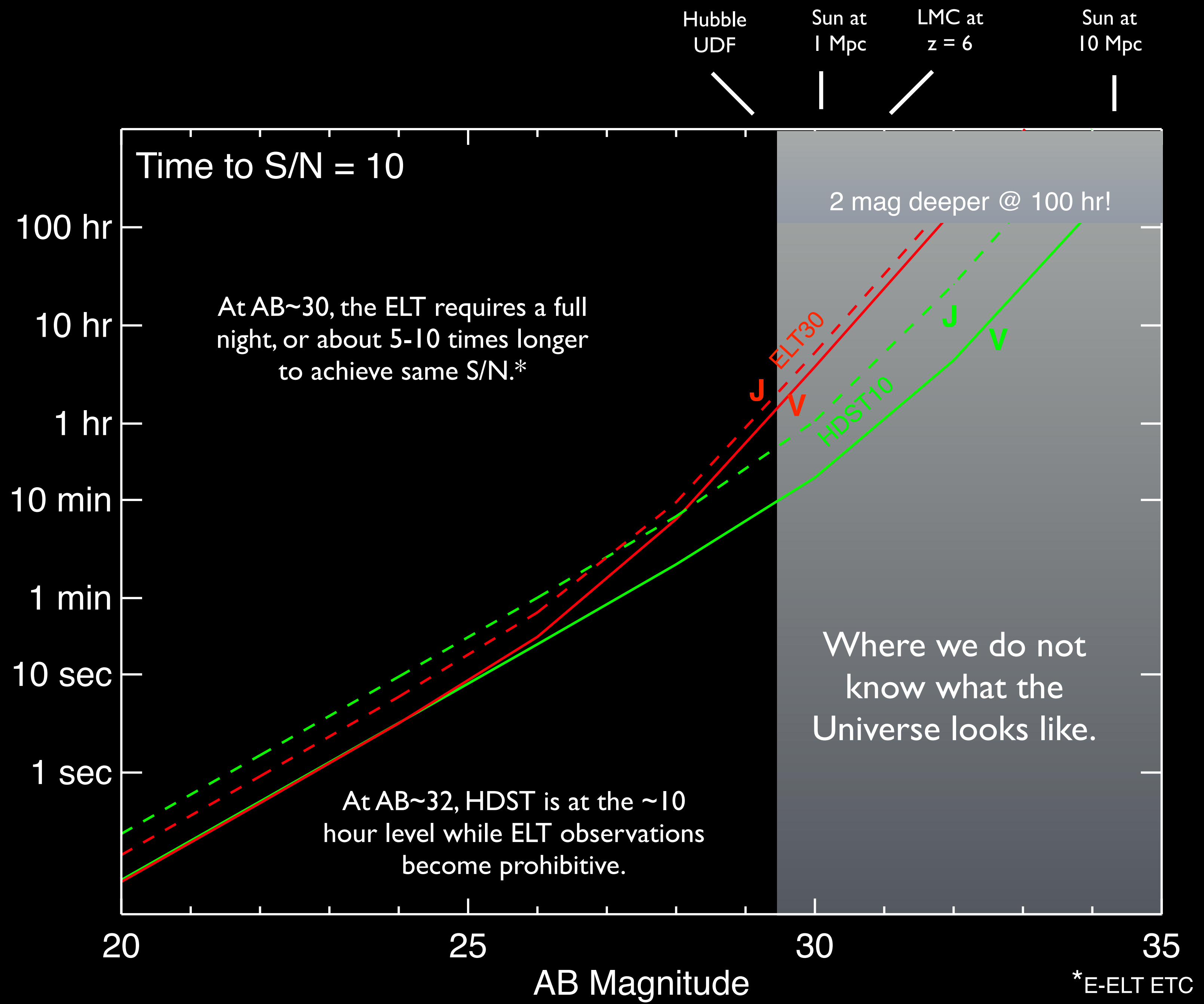
At 1.5 µm (H), a diffraction-limited 30m will reach the same spatial resolution as a space-based 10m at 0.5 µm.

Sky backgrounds prevent ground-based ELTs from applying their spatial resolution at the faintest desirable limits.

ELTs excel for:
-high res imaging on bright sources
-IR spectroscopy in atmospheric transmission windows
- high resolution optical spectroscopy

HDST excels for:
- deep/wide imaging at all wavelengths
- low-res/2D spectra at all wavelengths
- astrometry, high contrast (stable PSF)
- anything requiring the UV

They complement each other for:
- HDST detection in imaging, ELT spectroscopy for stars and galaxies
- multiphase gas diagnostics at all z



At AB~30, the ELT requires a full night, or about 5-10 times longer to achieve same S/N.*

At AB~32, HDST is at the ~10 hour level while ELT observations become prohibitive.

Where we do not know what the Universe looks like.

*E-ELT ETC

Image quality comparison