FROM COSMIC BIRTH TO LIVING EARTHS

THE FUTURE OF UVOIR SPACE ASTRONOMY

A Study by the AURA "Beyond JWST" Committee

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

Presenter: Jason Tumlinson (STScI)

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June 25, 2015

AURA

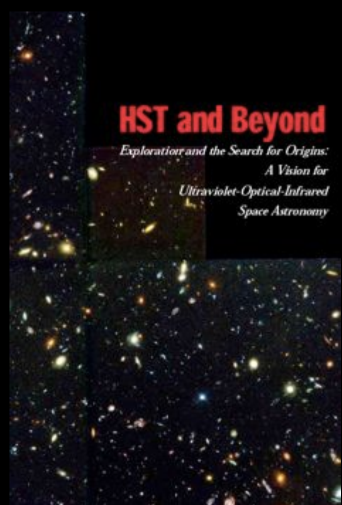

Where did we come from?
Astronomers ask big questions.
Are we alone?

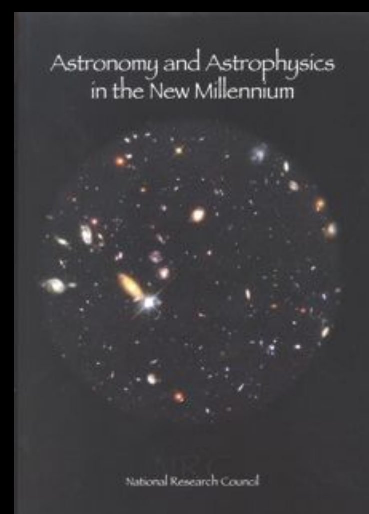
Big questions lead to strategic visions and investments

What comes next?

The Future Beyond HST

1995 2000 2018





2014 2020 2035

The Future Beyond JWST

Motivations

Co-Chairs:

Julianne Dalcanton (Washington)

Sara Seager (MIT)

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

. . . based on 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

The Challenge

"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."

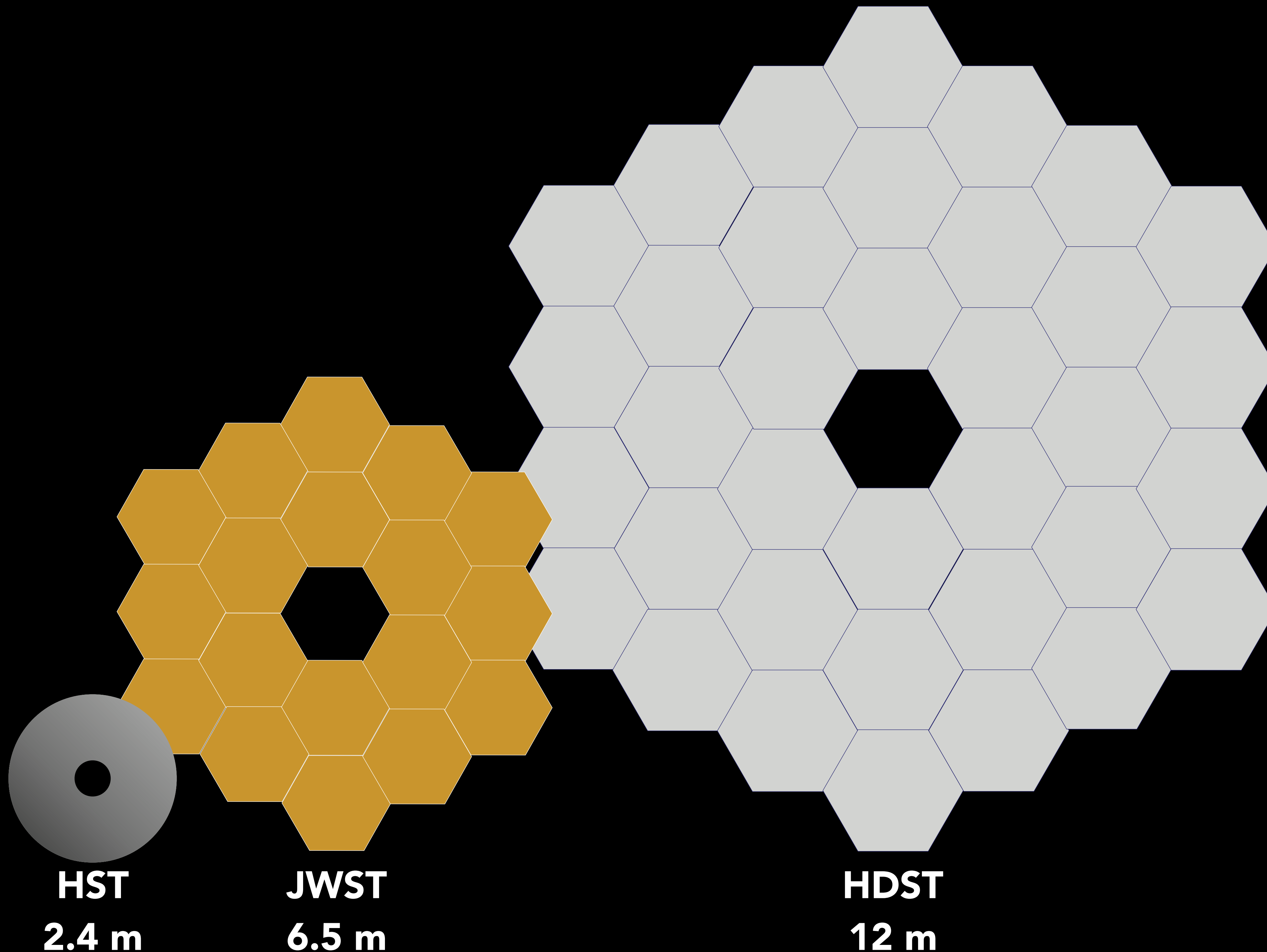
- New Worlds, New Horizons (2010)

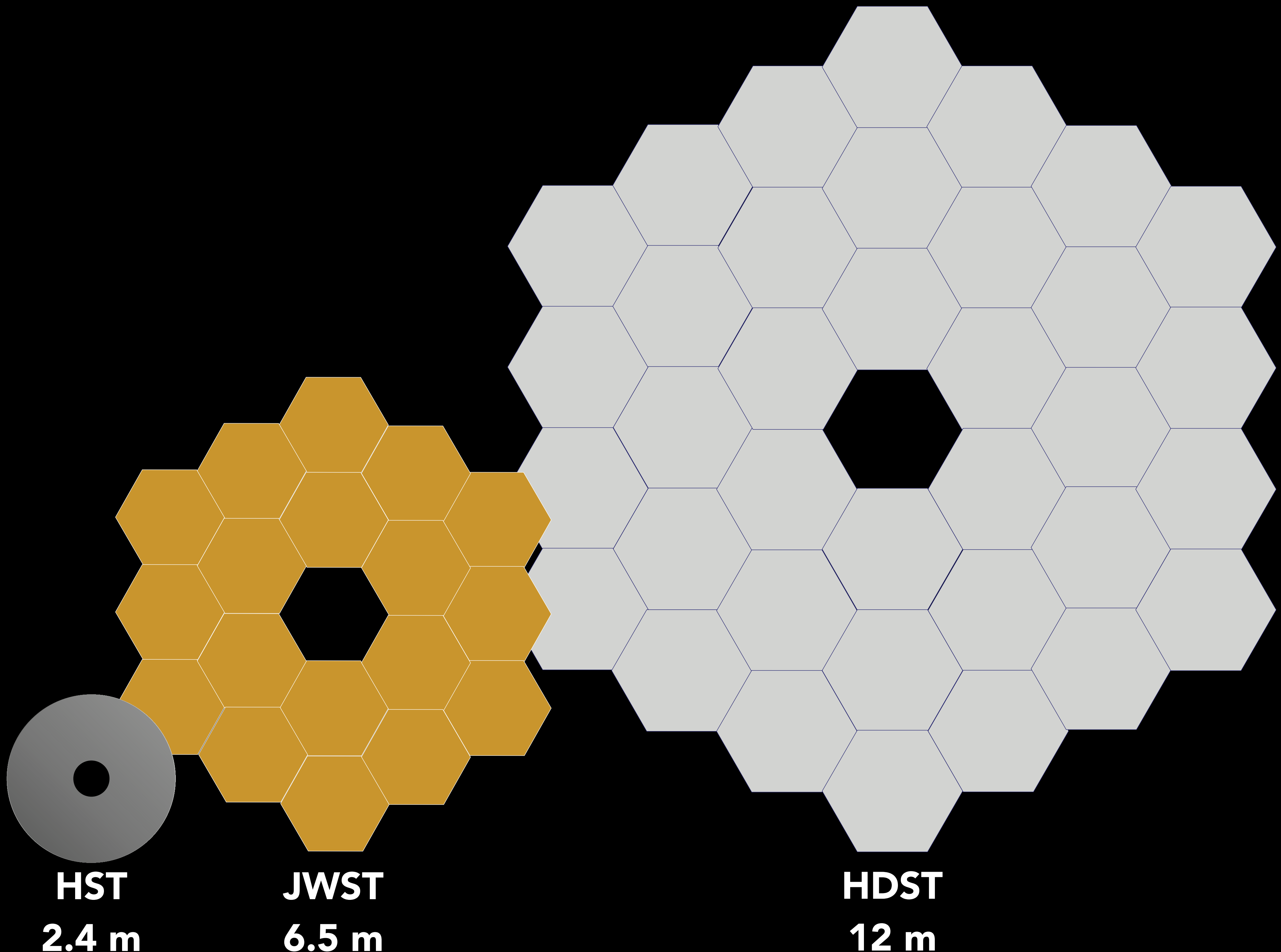
21st century astronomers are uniquely positioned to "study the evolution of the Universe in order to relate causally the physical conditions during the Big Bang to the development of RNA and DNA."

- Riccardo Giacconi (1997)

The "High Definition Space Telescope" (HDST)

- A space-based telescope in high orbit (e.g., Sun-Earth L2).
- Goal is for a 12 m filled-aperture telescope.
  - Motivated by exoplanet yield, high-res images of galaxies, cosmic gas flows, and spatially-resolved stellar populations in many environments.
- A segmented, deployable mirror.
- Diffraction-limited performance at visible (500-600 nm) wavelengths
- Full complement of coronagraphic, imaging, and spectroscopic instruments.
- UV to near-IR wavelengths (but with non-cryogenic optics).
- Serviceability is a goal but not a requirement.


HST
2.4 m
JWST
6.5 m
HDST
12 m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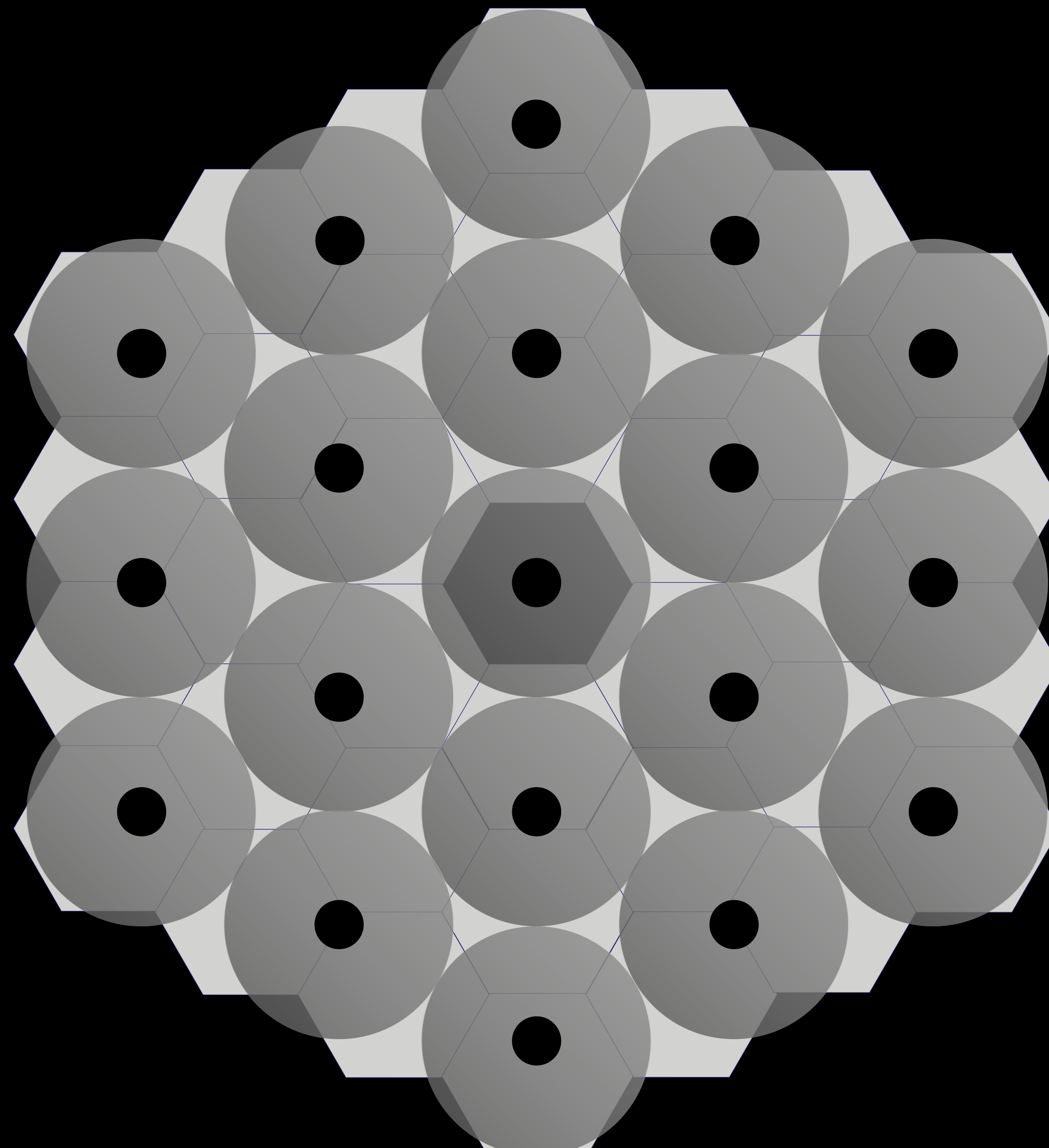

HDST
12 m

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Let's consider the search for "Living Earths"….

The Ultimate 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.

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 will we do this?

Direct Exoplanet Imaging

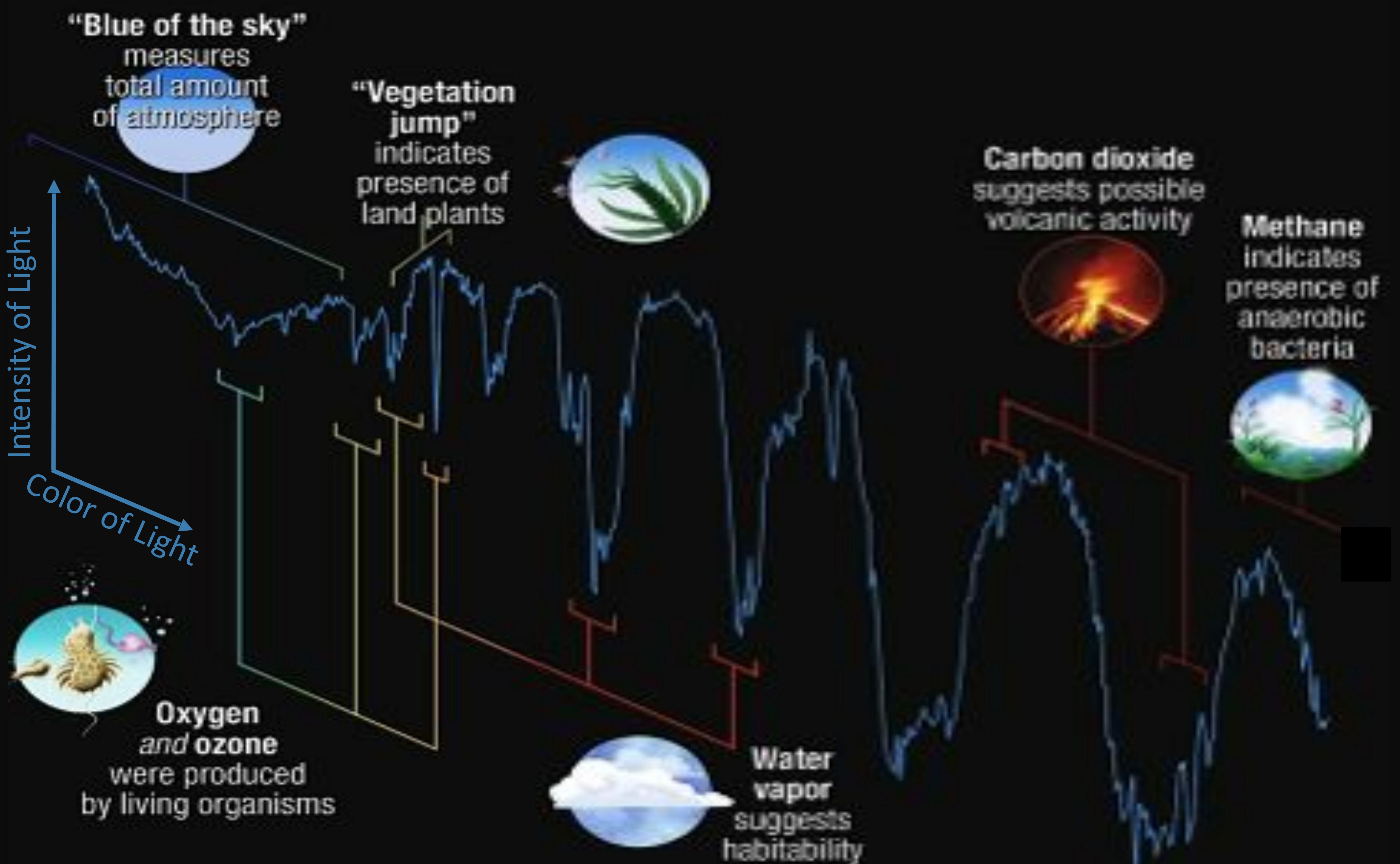
To the radial velocity and photometric transit detection techniques:

=

Only spectroscopy, obtained via "direct imaging" that separates the planet from the star*, can discriminate uninhabitable Venus from comfy Earth in a large sample of exoplanetary systems.

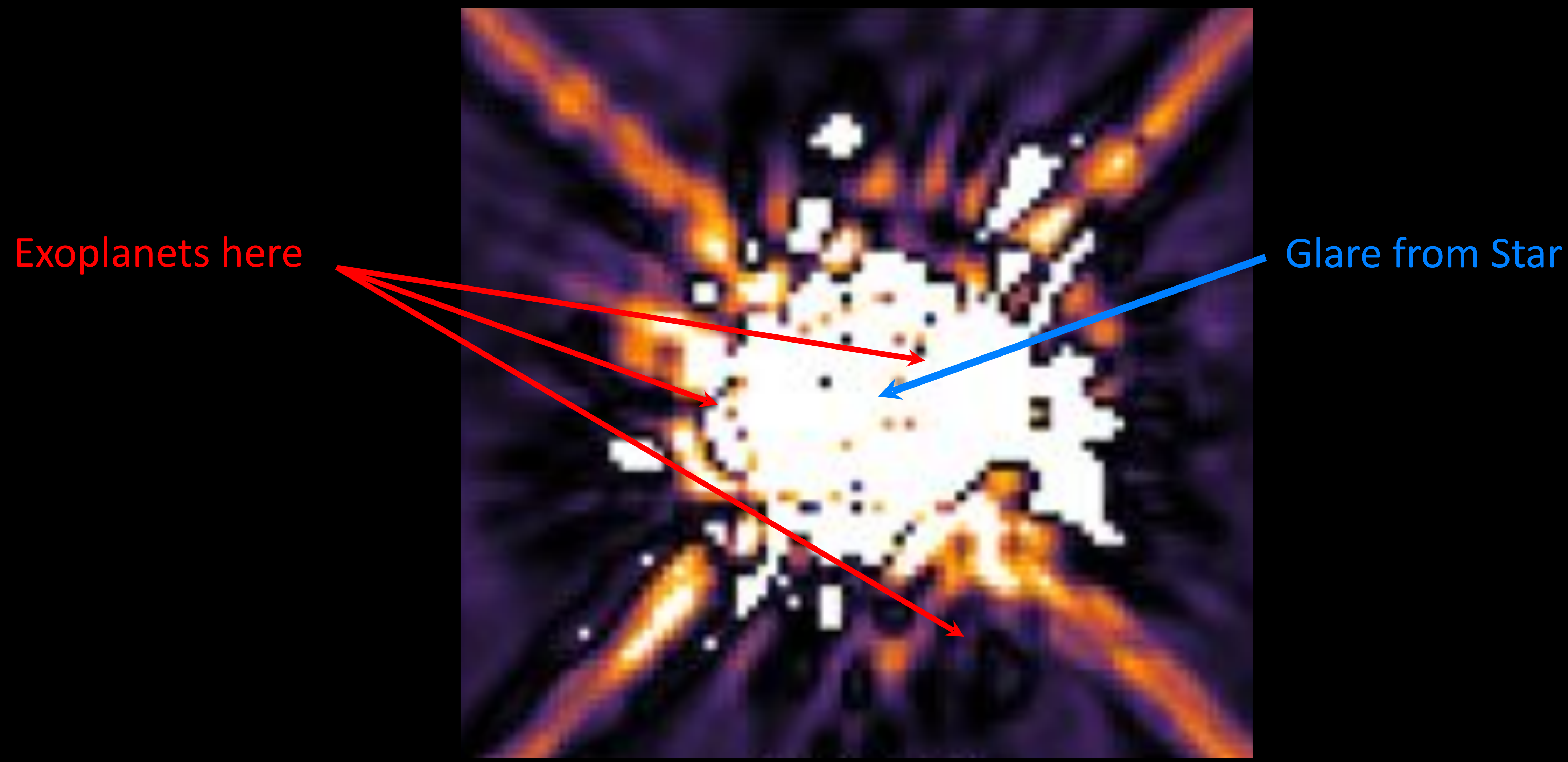
*there are some specialized techniques where certain spectral features can be detected without resolving the planet, but these do not provide a complete atmospheric characterization

What We Ultimately Need to Search for Life:



Getting an image of an Earth-like Exoplanet is hard!

In the visible part of the light spectrum, the Sun is **10 billion times** brighter than the Earth!



Earth-like planets lie deep within the bright glare of the stars they orbit. <u>**But it is possible**</u> with the right starlight suppression technology (coronagraph or starshade).

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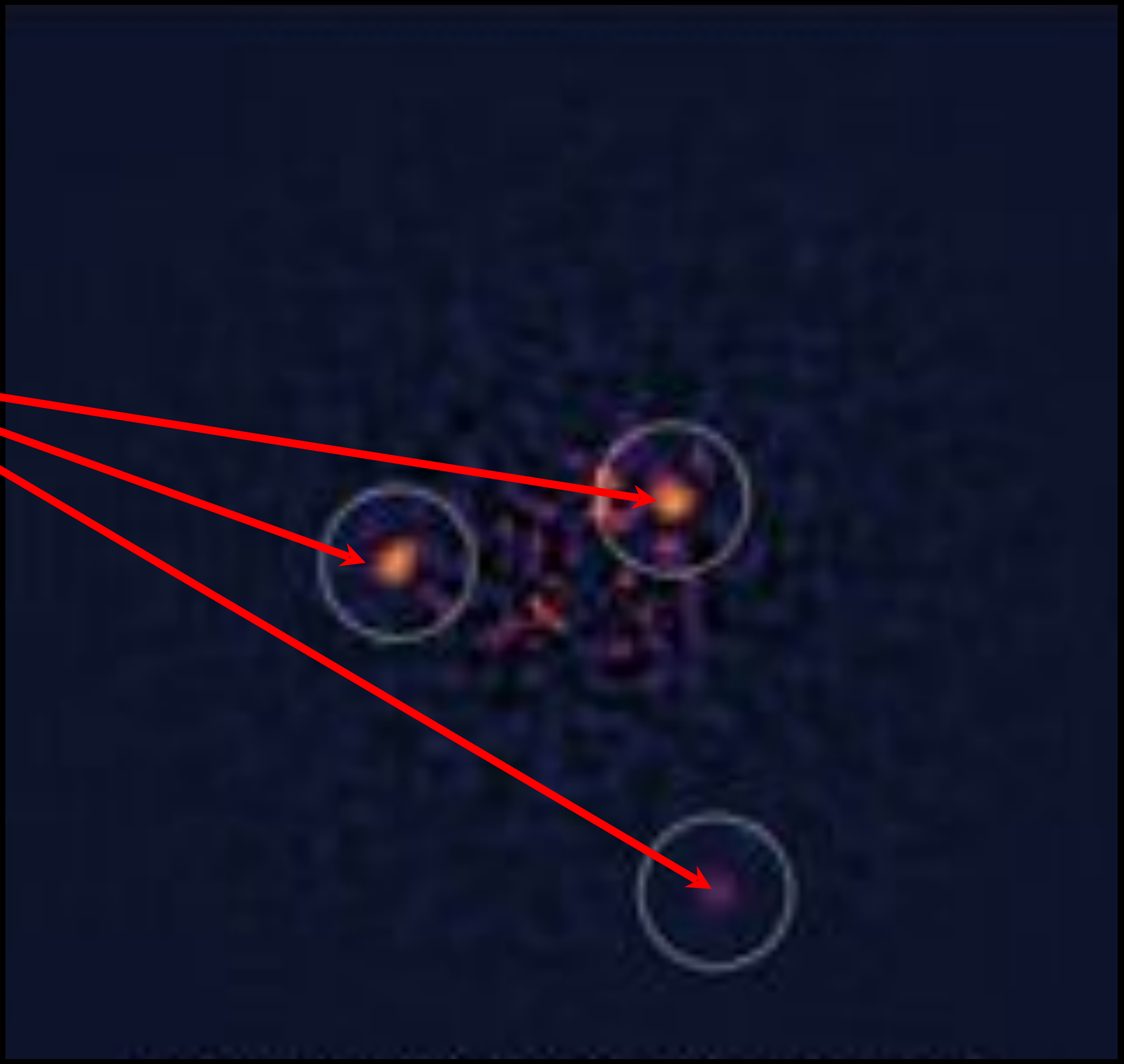
Exoplanets here



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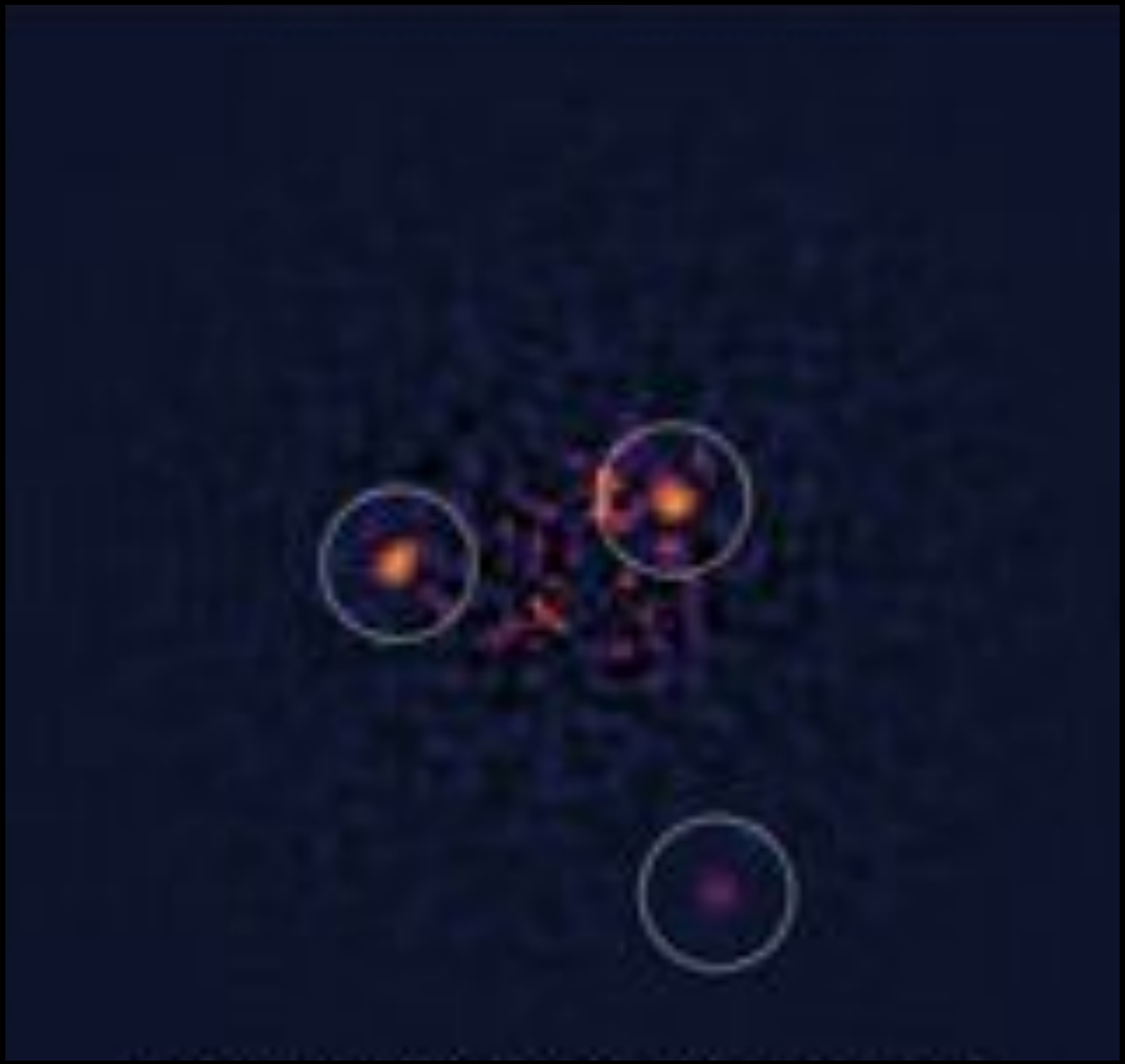


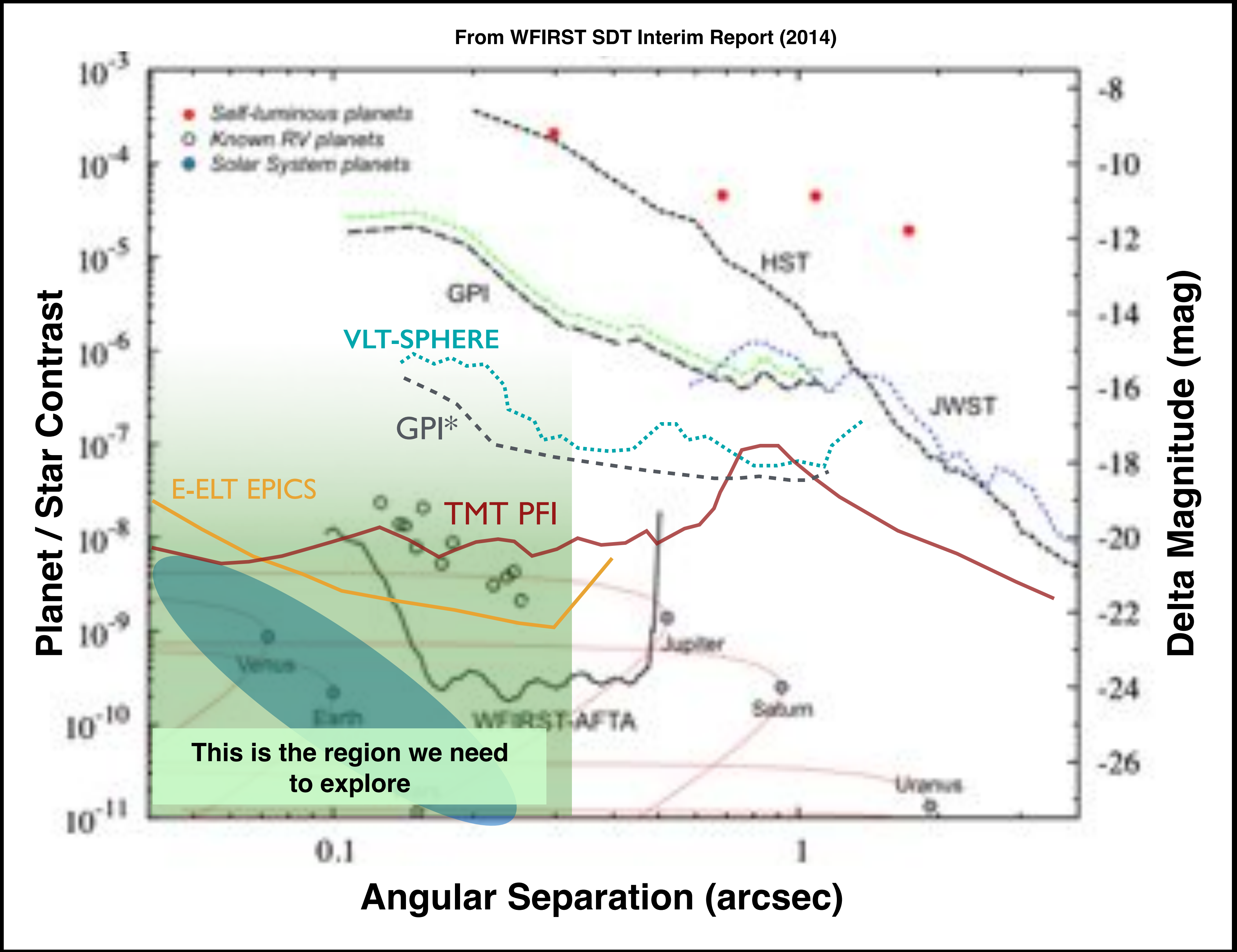
Earth-like planets lie deep within the bright glare of the stars they orbit. **But it is possible** with the right starlight suppression technology (coronagraph or starshade).

Direct Exoplanet Imaging - Discovery Space

Contrast

=

the stability of a space telescope



Faint

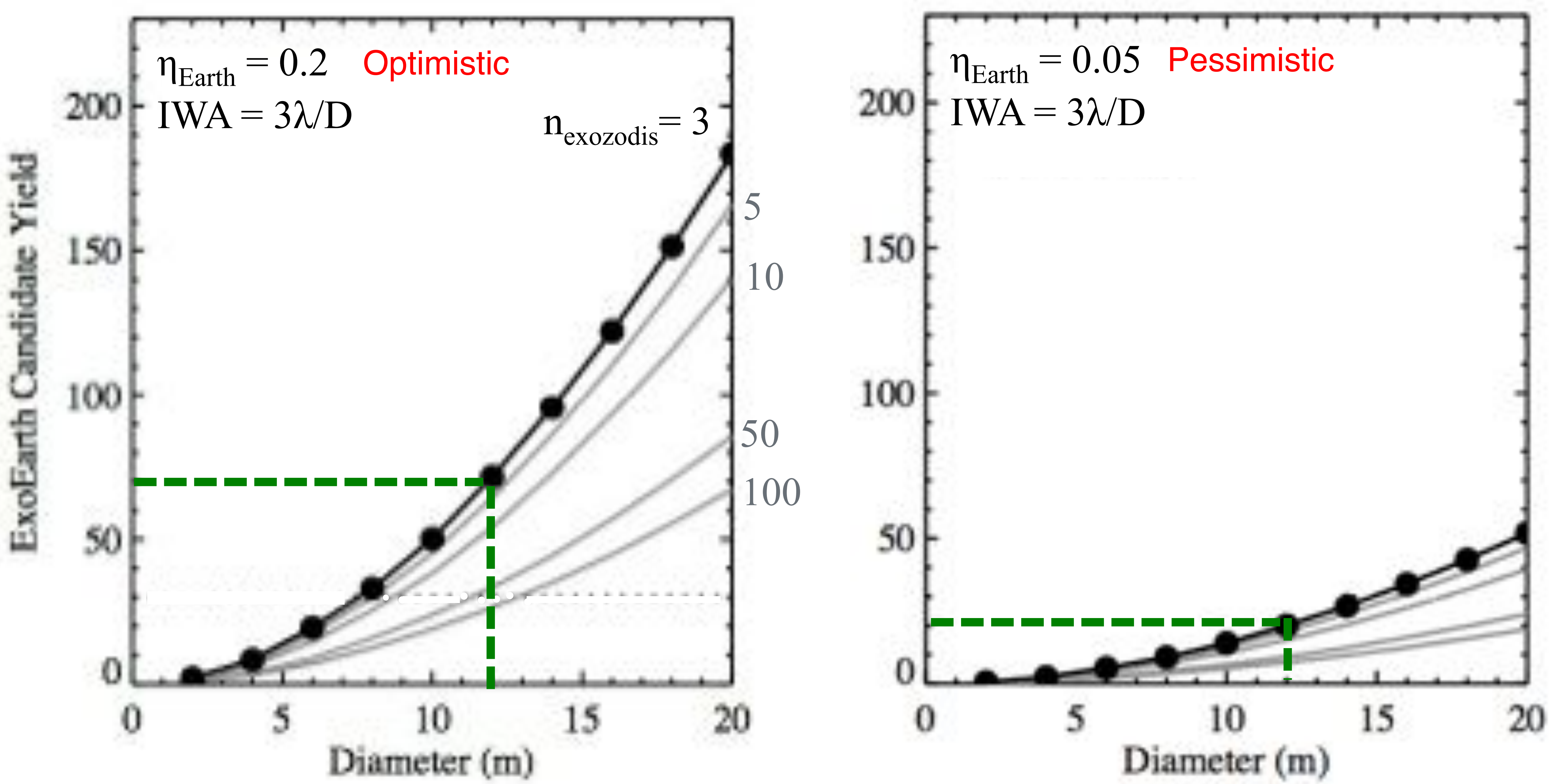
=

large collecting area

Resolution = Large Aperture Diameter

ExoEarth Yield Results

(see Stark et al. 2014; 2015)



$$N \propto \eta_{Earth} (Zodis)^{-0.23} (D_{Tel})^{1.88} (IWA)^{-0.64} (ExpTime)^{0.36} (QE)^{0.39} (Contrast)^{-0.09}$$

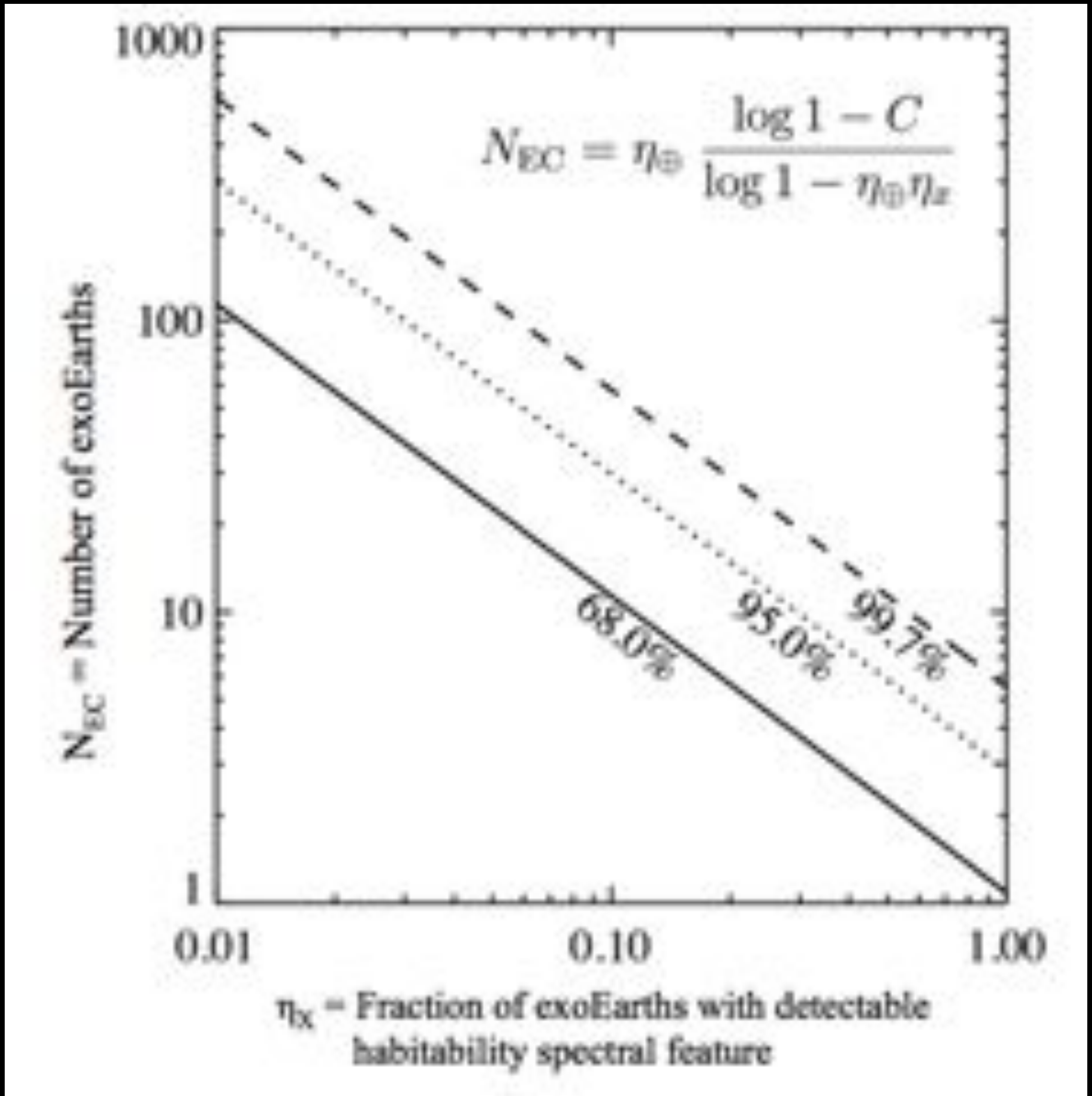
A 12-meter telescope can reach 20 - 70 Earth-like planets: this is enough to detect or significantly constrain the incidence of biomarker molecules.

How Many Planets Must We Search?

Even Earth-like planets in their HZ may have a great diversity of atmospheric properties owing to differences in mass, solar irradiation, and complex history.

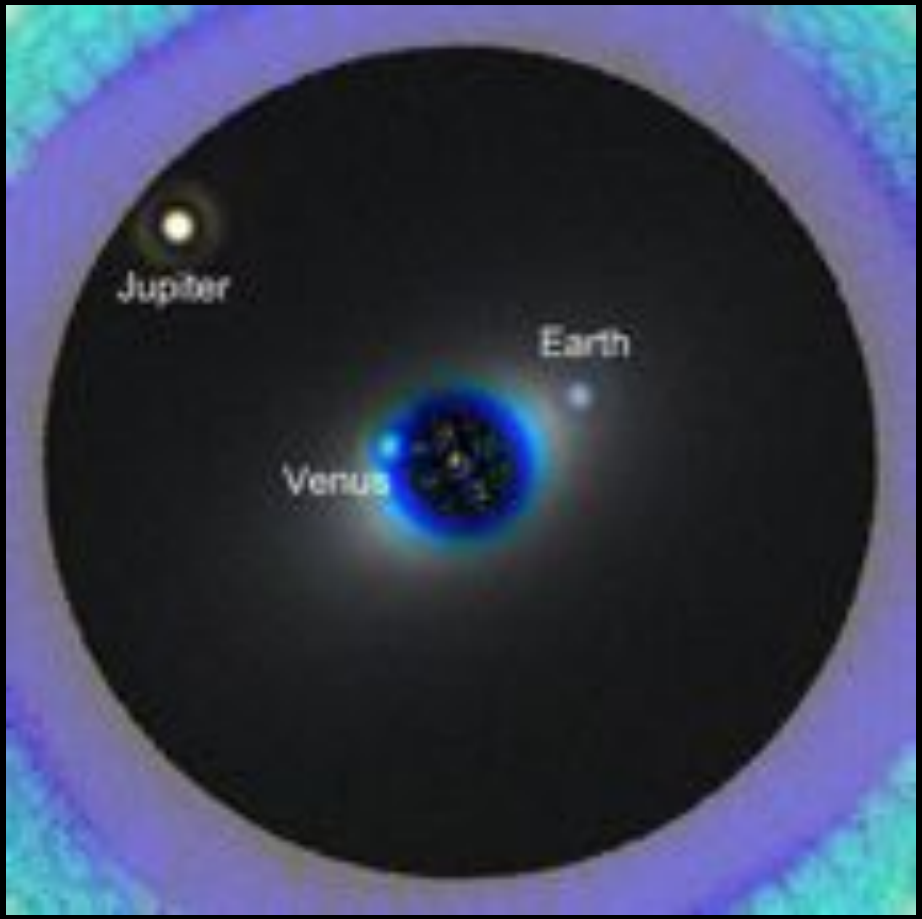
If biomarkers exist on 10% of Earth-like planets, and we want to reduce the chance of randomly missing these systems to <1%, spectra of ~50 planets must be obtained.

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



To find signs of life, even if it is uncommon, we must search <u>dozens</u> of Earth-like planets orbiting in their habitable zones.

Direct Exoplanet Imaging



Binary anodized pupil coronagraph (L. Pueyo).

Phase-Induced Amplitude Apodization coronagraph with small IWA (Guyon).


Free-flying 100 m starshade (Kuchner).

A twin of our solar system at ~10 pc as seen with three different starlight nulling techniques.

The Challenge

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."

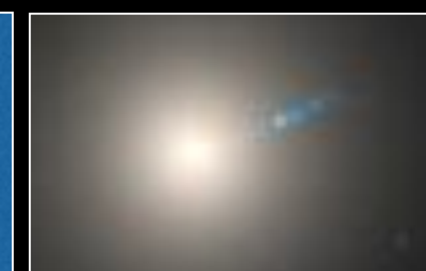
- Riccardo Giacconi (1997)


YOU WERE HERE
AND HERE
AND HERE
AND HERE
YOU ARE HERE
and so was all other life we might find in the Galaxy!

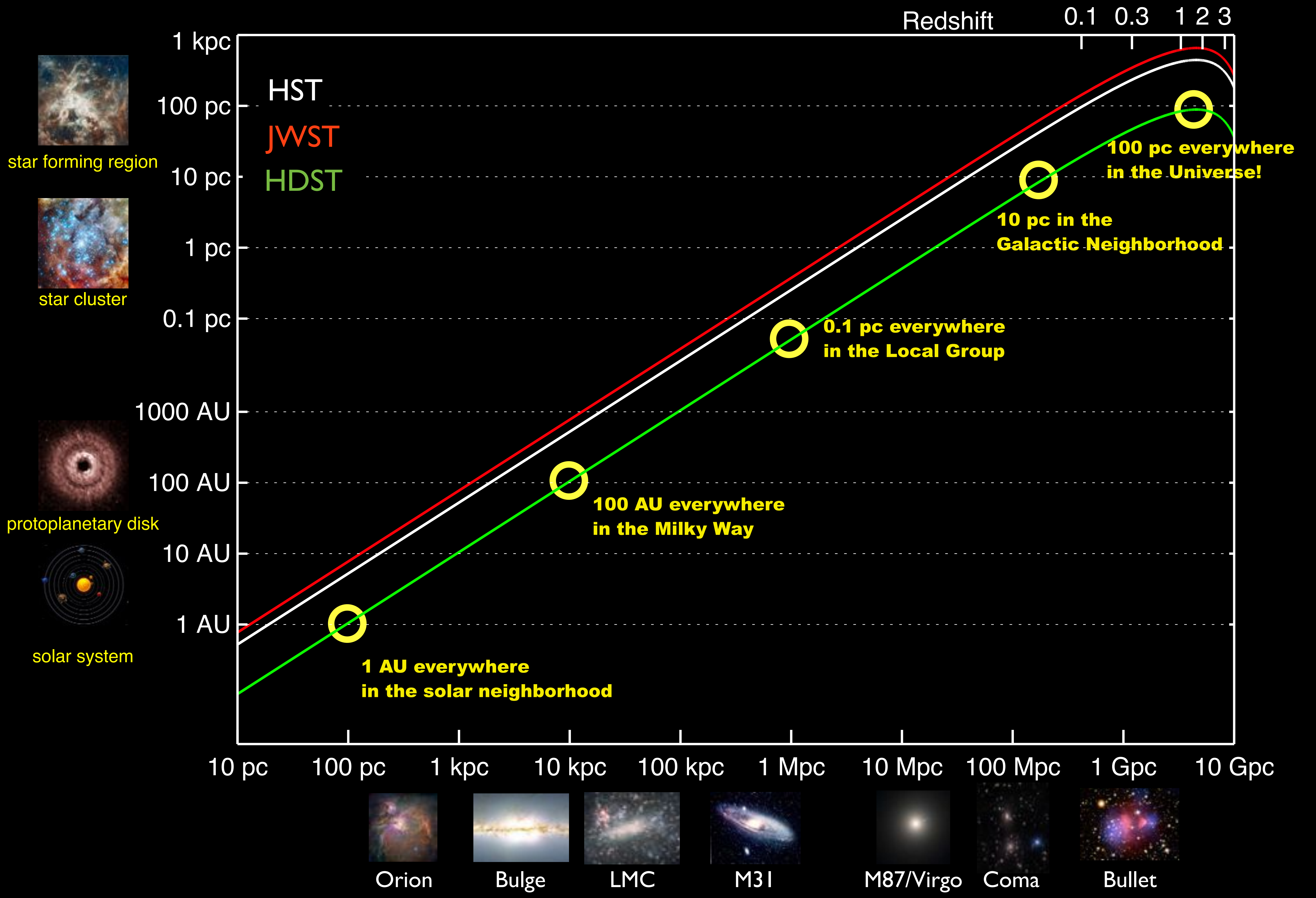
As astonishing as it might be to find life on other worlds, we already <u>know</u> that, alien as it might be, the story of all life in the cosmos arises from galaxies, stars, and planets formed from heavy elements made in stars.

Let's look at the cosmic epochs for which HDST is <u>uniquely suited</u> to rewrite important chapters in the story of Cosmic Birth.

Five epochs in which HDST is uniquely suited to rewrite important chapters in the story of Cosmic Birth.

The Epoch When the Milky Way Formed	z = 1 - 4	30-100 pc	
The Epoch When the Solar System Formed	z < 1	50-100 pc	
The Present in Our Galactic Neighborhood	< 100 Mpc	1 - 10 pc	
Star and Planet Formation in Our Galaxy	< 10 kpc	10-100 AU	
Solar Systems like our Own	<50 AU	20-100 km	

HDST: Breaking Resolution Barriers in the UV/Optical



SDTV

720x480

24x pixel density →

UltraHD

3820x2160

HST

2.4 m

24x image sharpness →

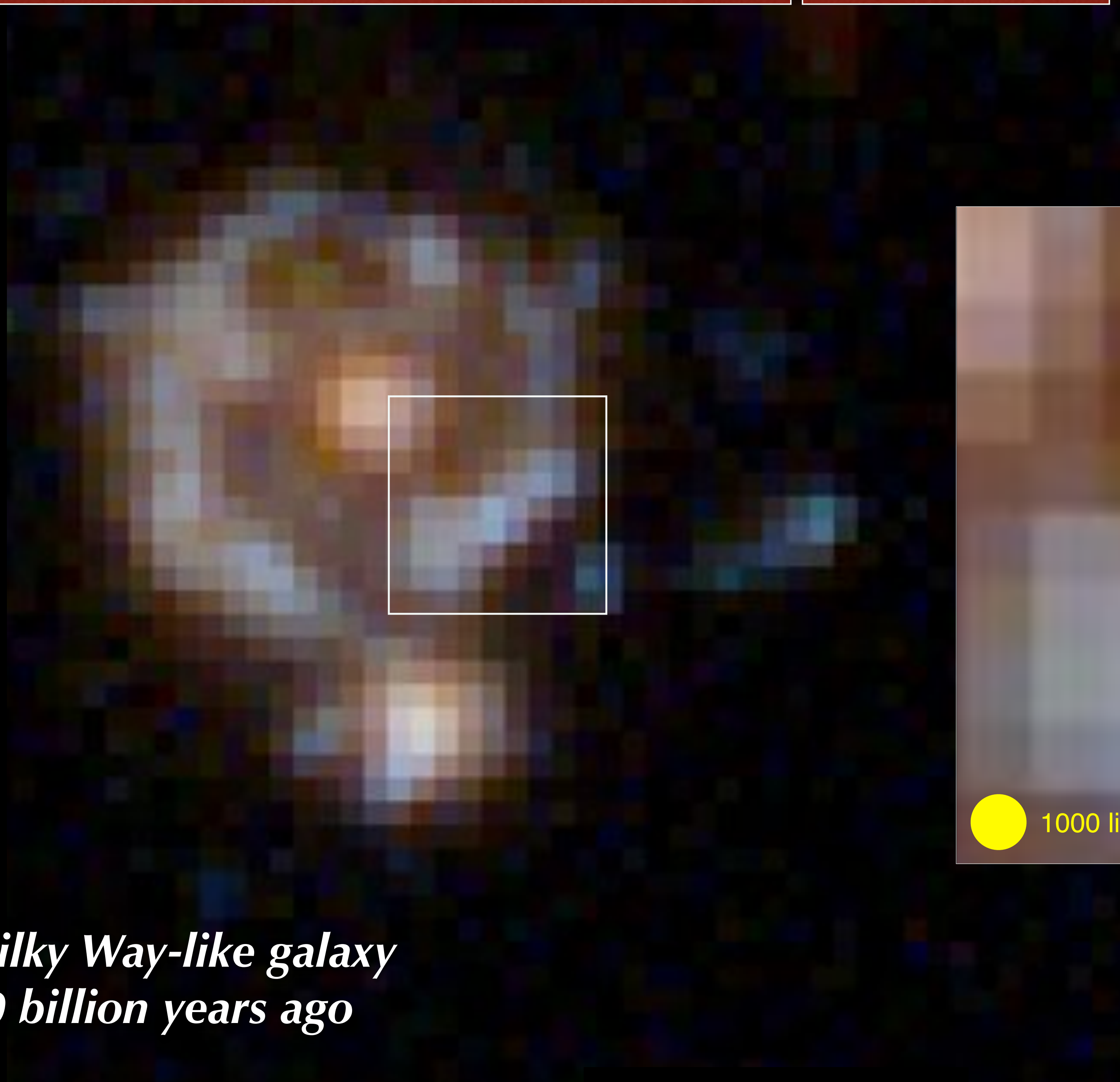
HDST

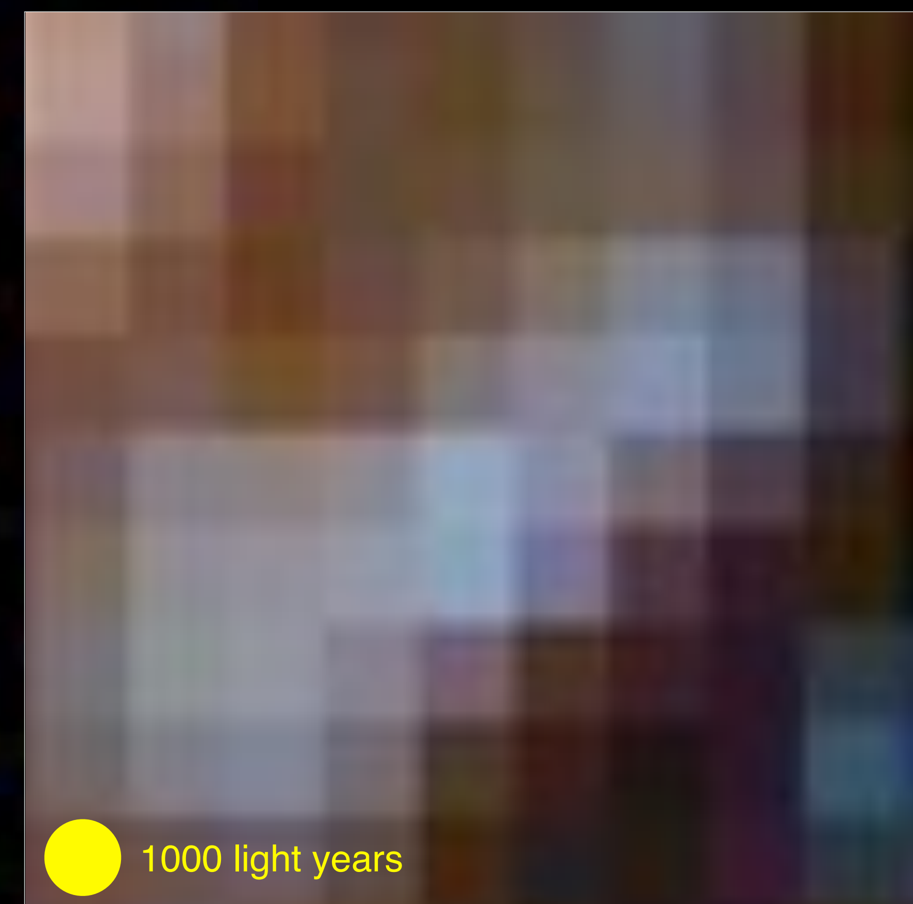
12 m

How Did the Milky Way Form from its Earliest Seeds?

Epoch
$z = 1 - 4$

Resolution
30-100 pc





A Milky Way-like galaxy
10 billion years ago

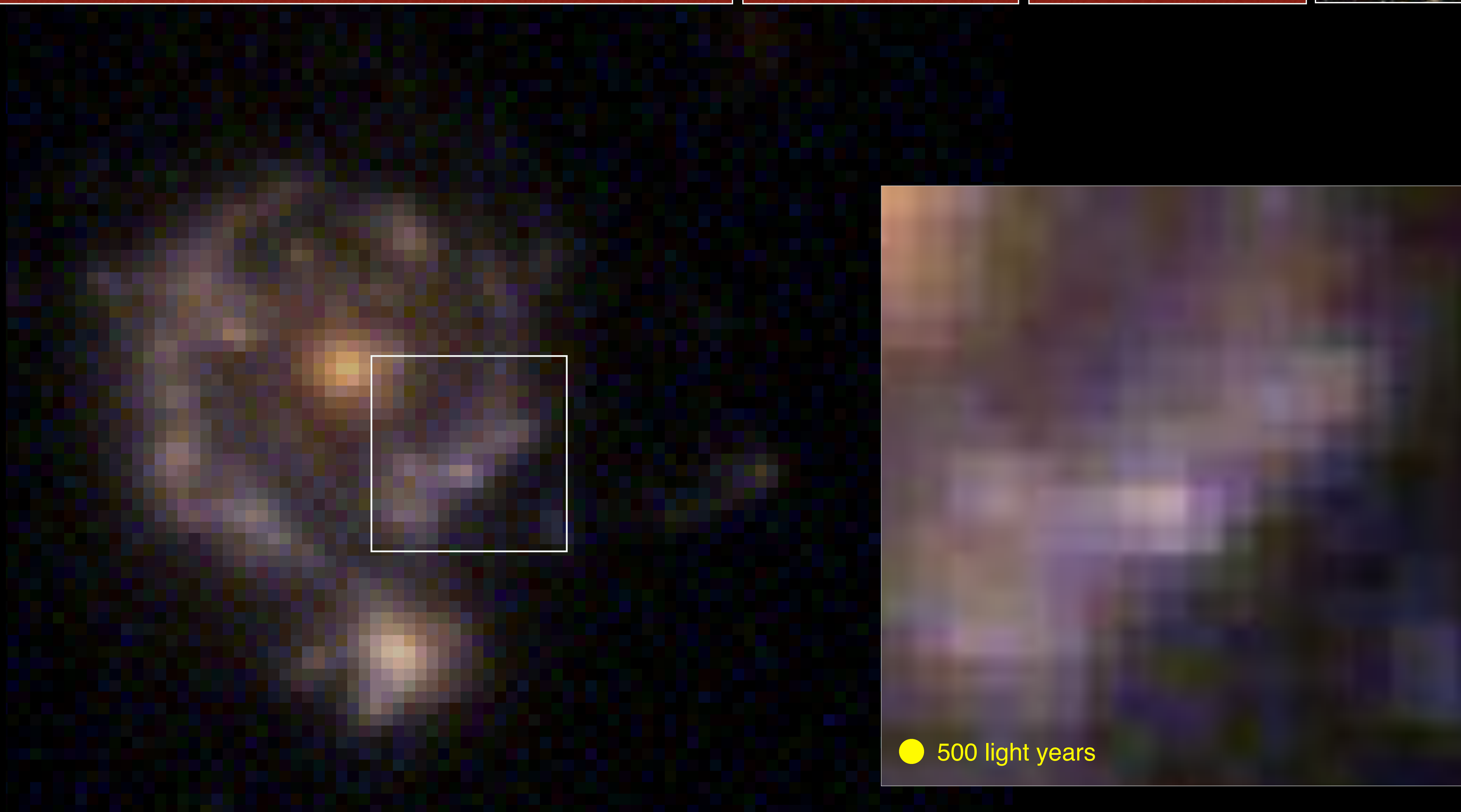
Image Credit: Ceverino/Moody/Snyder

Hubble

How Did the Milky Way Form from its Earliest Seeds?

Epoch
z = 1 - 4

Resolution
30-100 pc



A Milky Way-like galaxy
10 billion years ago

Webb

Image Credit: Ceverino/Moody/Snyder

How Did the Milky Way Form from its Earliest Seeds?

Epoch
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Resolution
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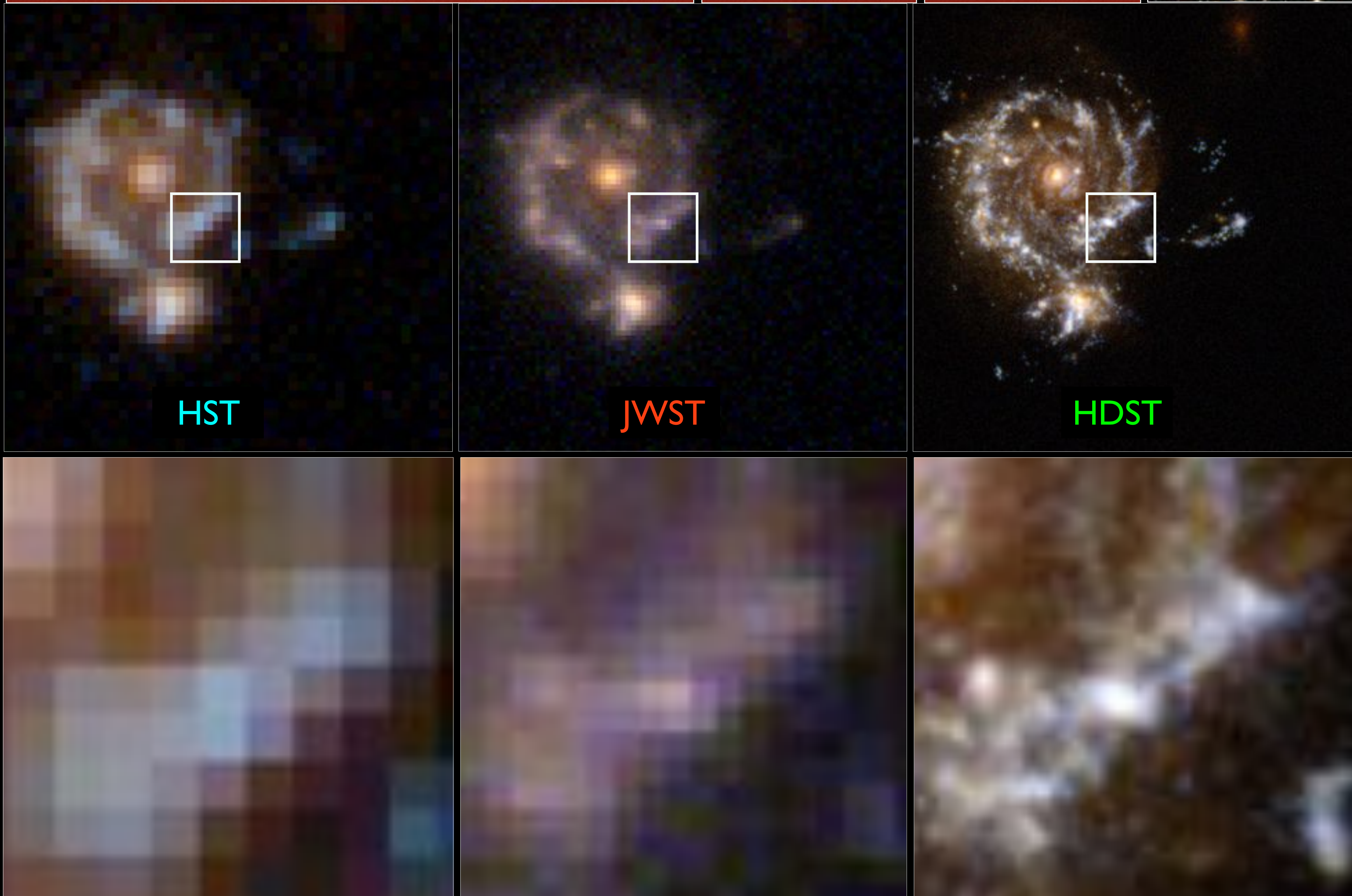
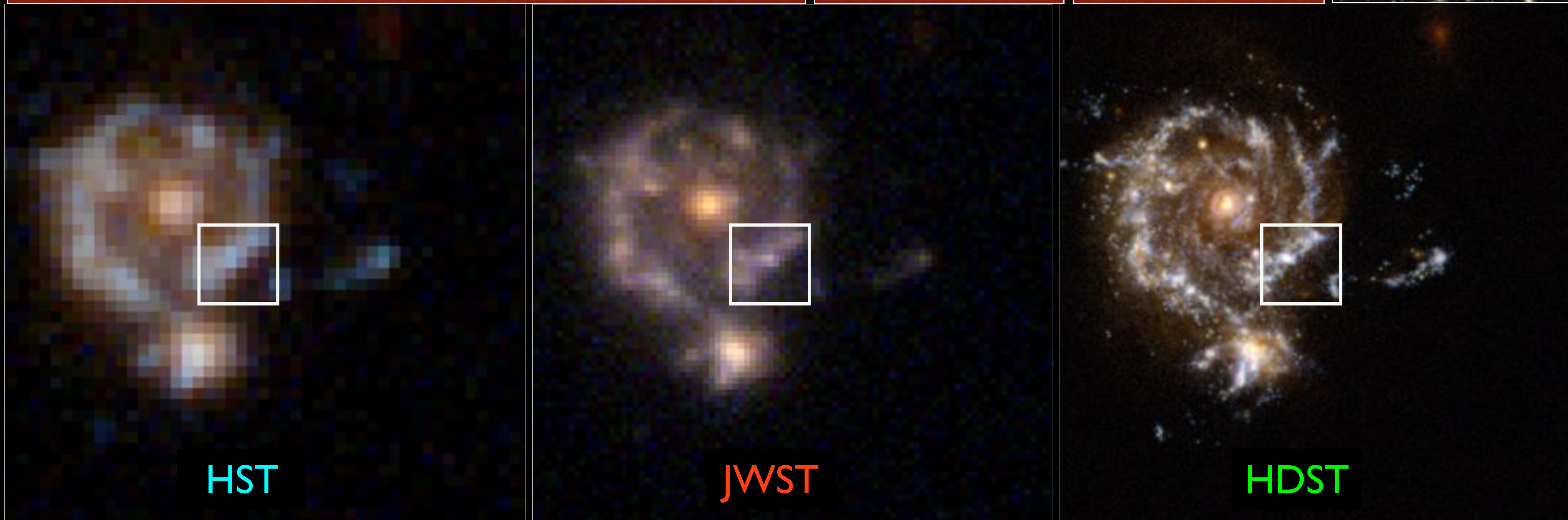


How Did the Milky Way Form from its Earliest Seeds?

Epoch z = 1 - 4

Resolution 30-100 pc



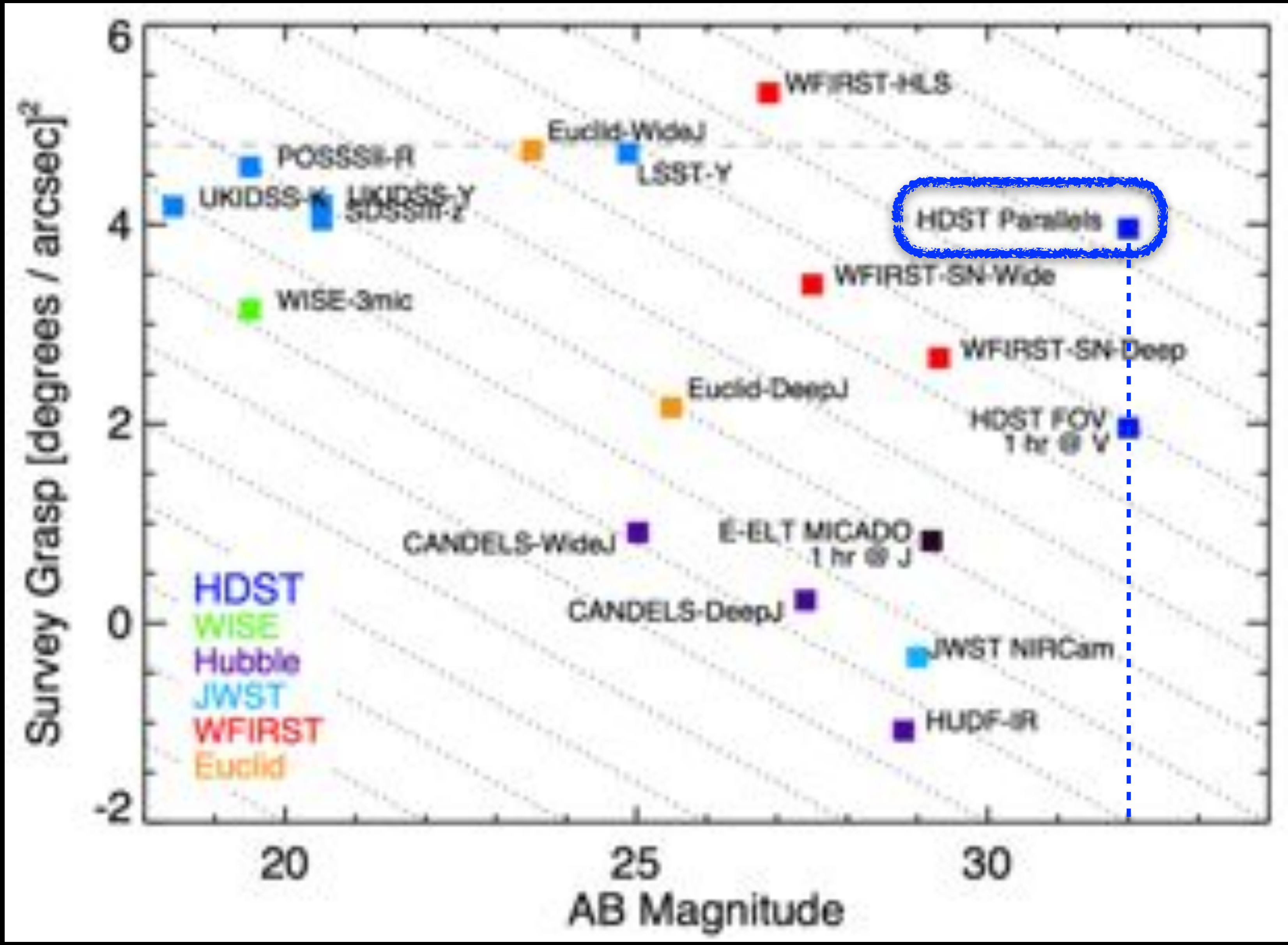
With <u>unique 100 parsec resolution</u> in the optical at all redshifts, HDST can resolve ALL the building blocks of galaxies: individual star forming regions and dwarf satellites, including progenitors of the present-day dwarf spheroidals.

These high-resolution images will complement spectroscopy from 30m class ground-based telescopes and ALMA of the galaxies and their molecular gas.

How Do Galaxies Grow, Evolve, and Die?

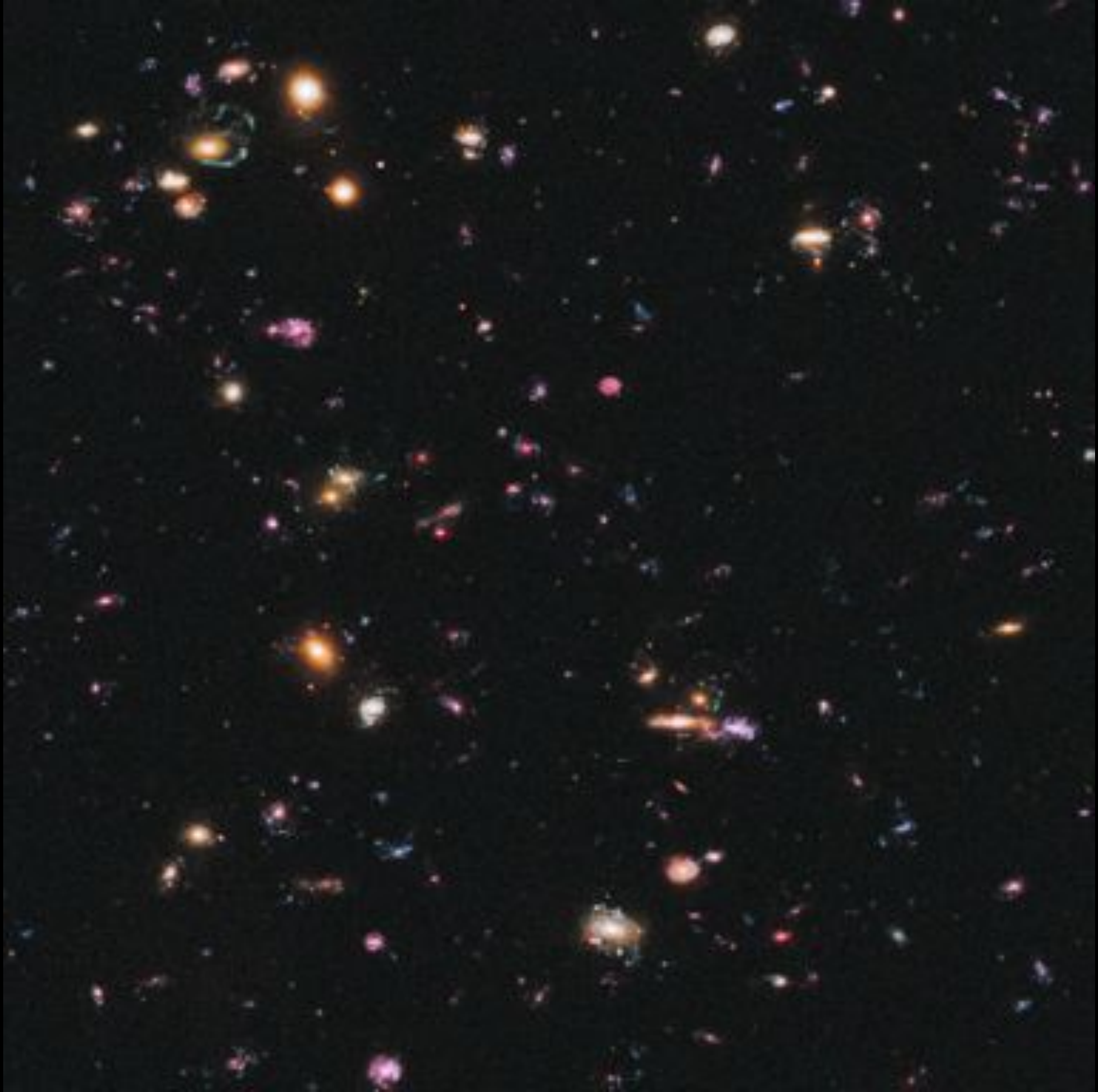
Epoch $z = 1 - 4$

Resolution 30-100 pc



Total area of sky in "exoplanet parallels" will approach ~ 1 deg^2, reaching ~ALL star forming galaxies and sees almost all star forming satellites.

Total comoving volume at $z = 2$-3 is roughly equivalent volume of entire SDSS, enabling robust comparisons across cosmic time.



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

Epoch
$z < 1$

Resolution
10-100 pc

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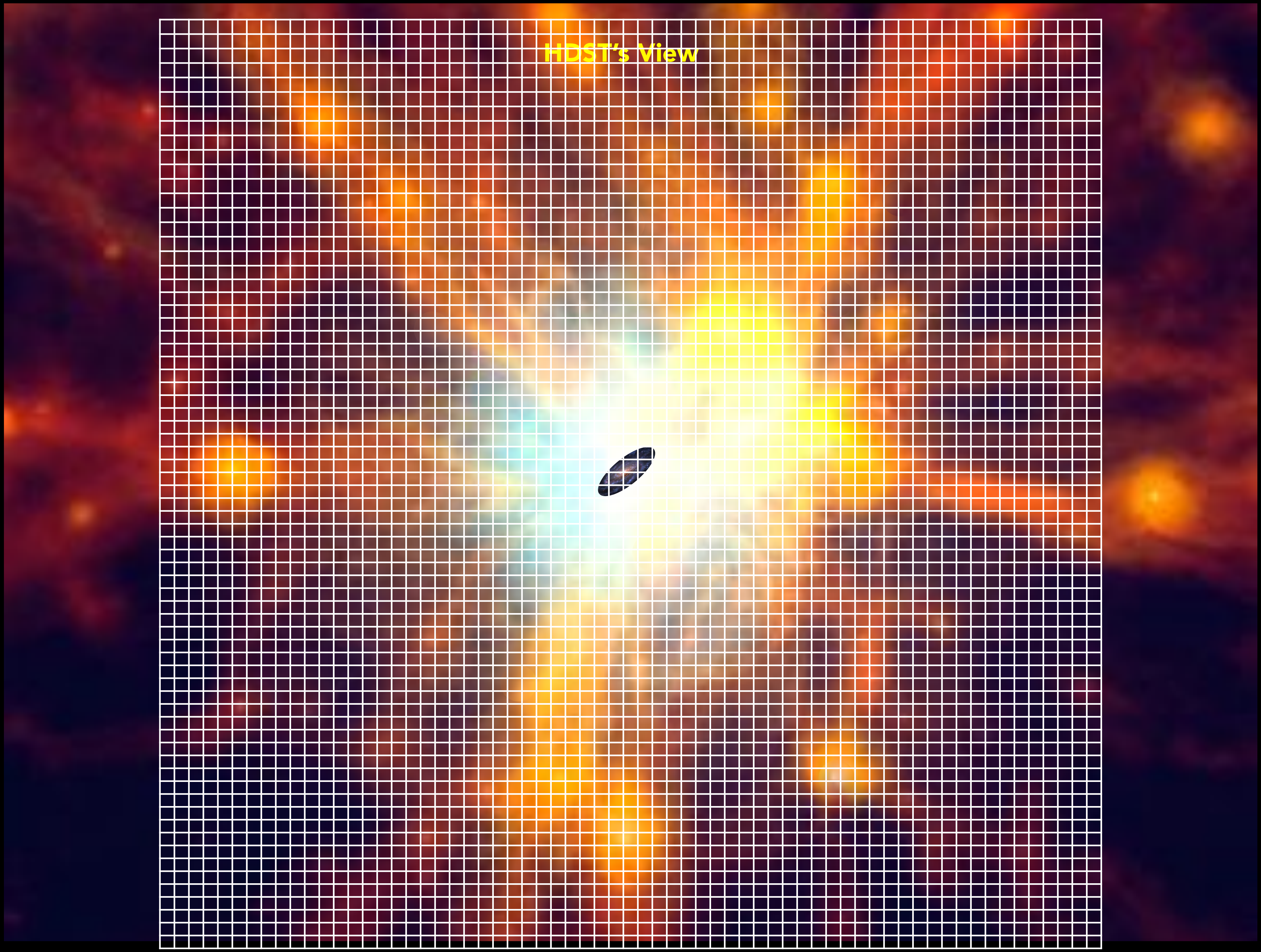
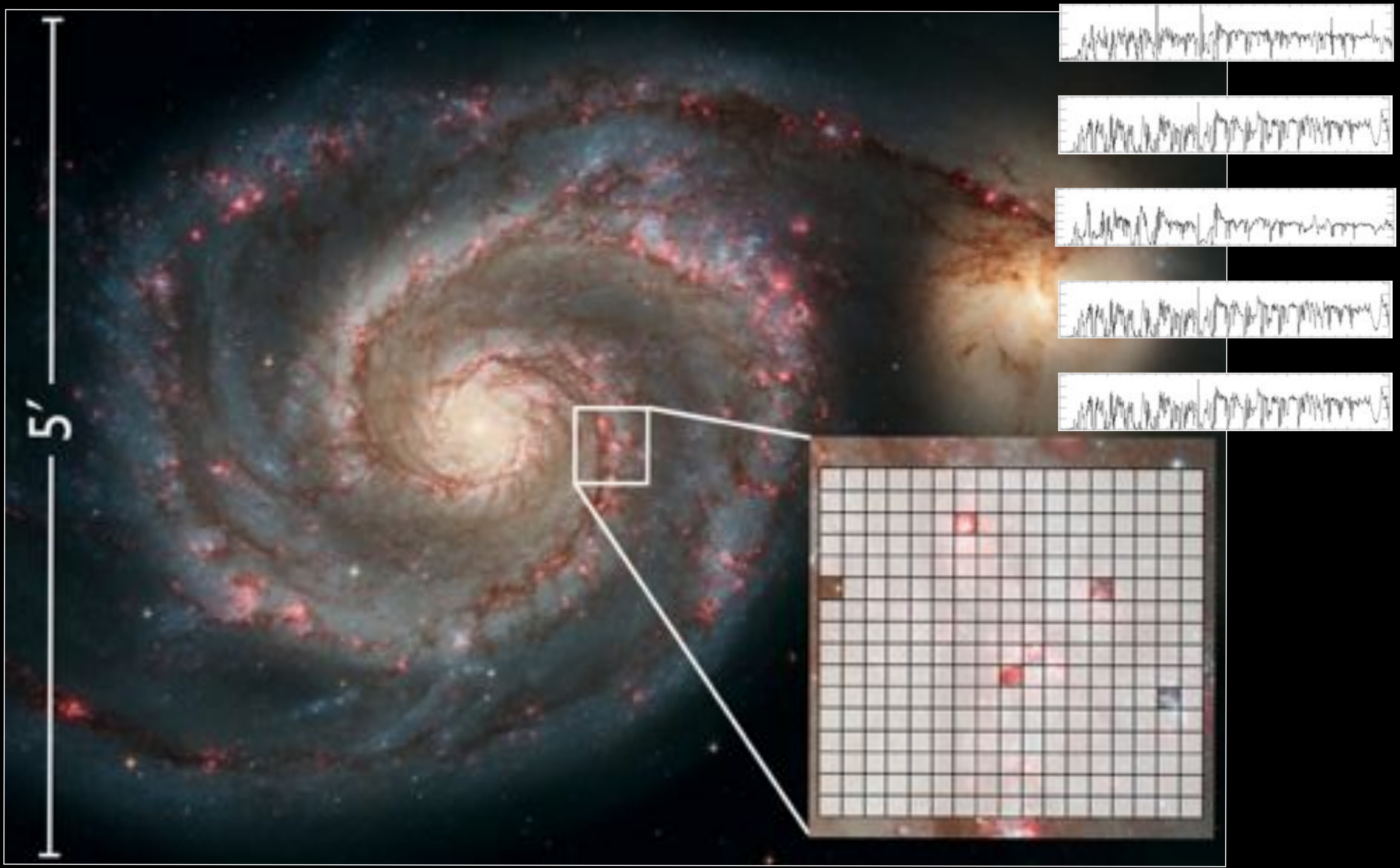


How Do Galaxies Acquire, Process, and Recycle Their Gas?

Epoch
z < 1

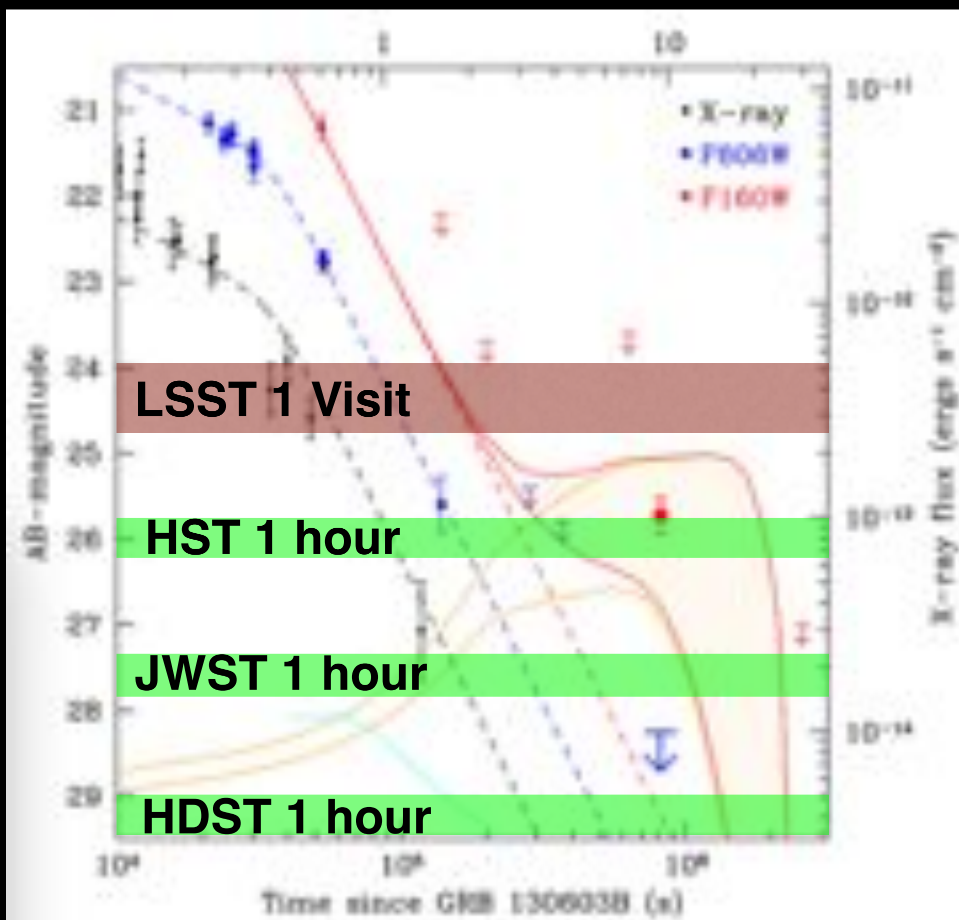
Resolution
10-100 pc

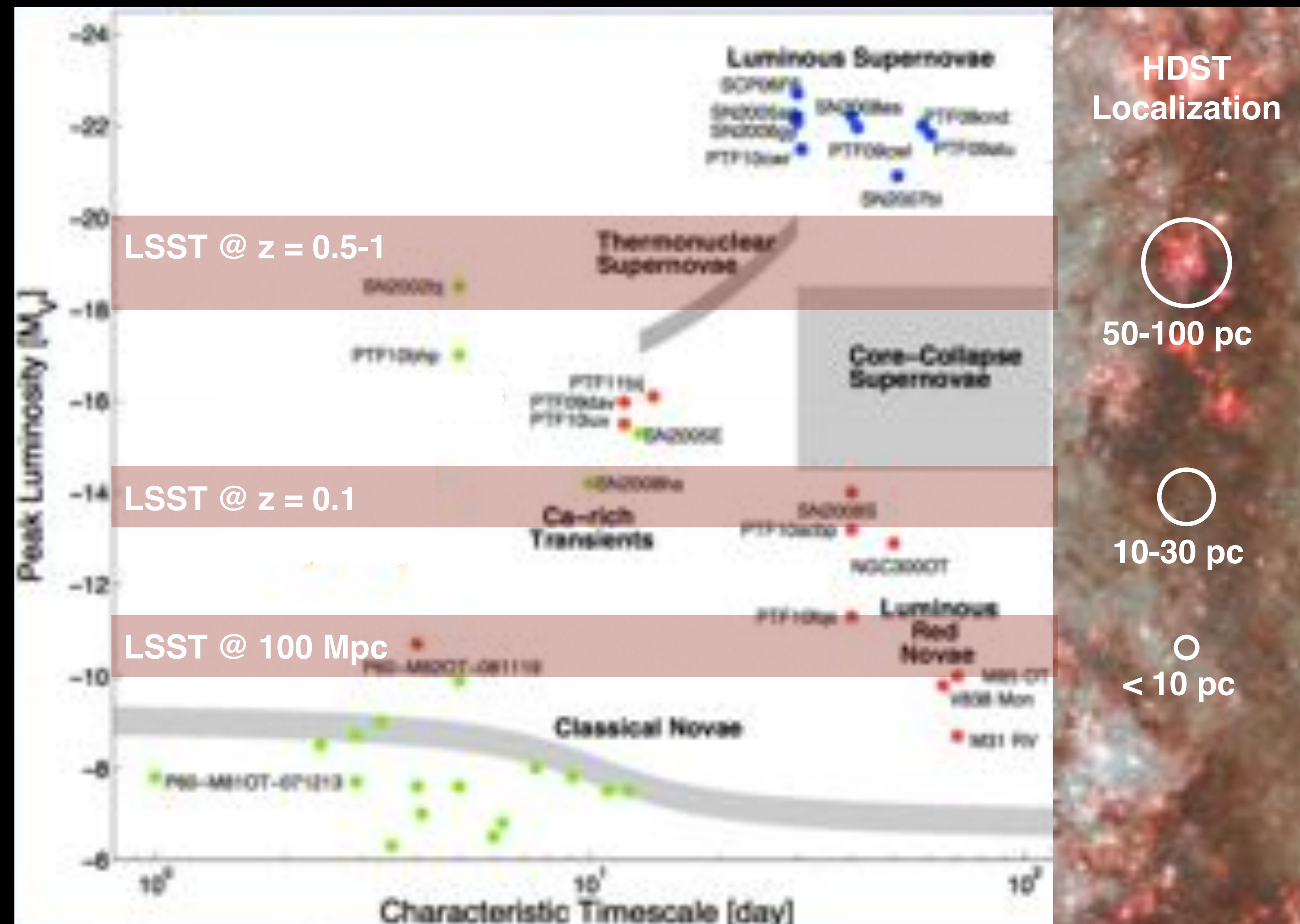


How do Stars End Their Lives?
How do they Disperse their Metals?

Epoch
z < 1

Resolution
10-100 pc





Wide-field synoptic surveys find a zoo of transients.

Aperture Driver: High resolution imaging identifies and characterizes their stellar progenitors and galactic hosts, both key to unraveling causes.

Many transients are very blue (early SNe, TDEs) and ground-based imaging is not always available.

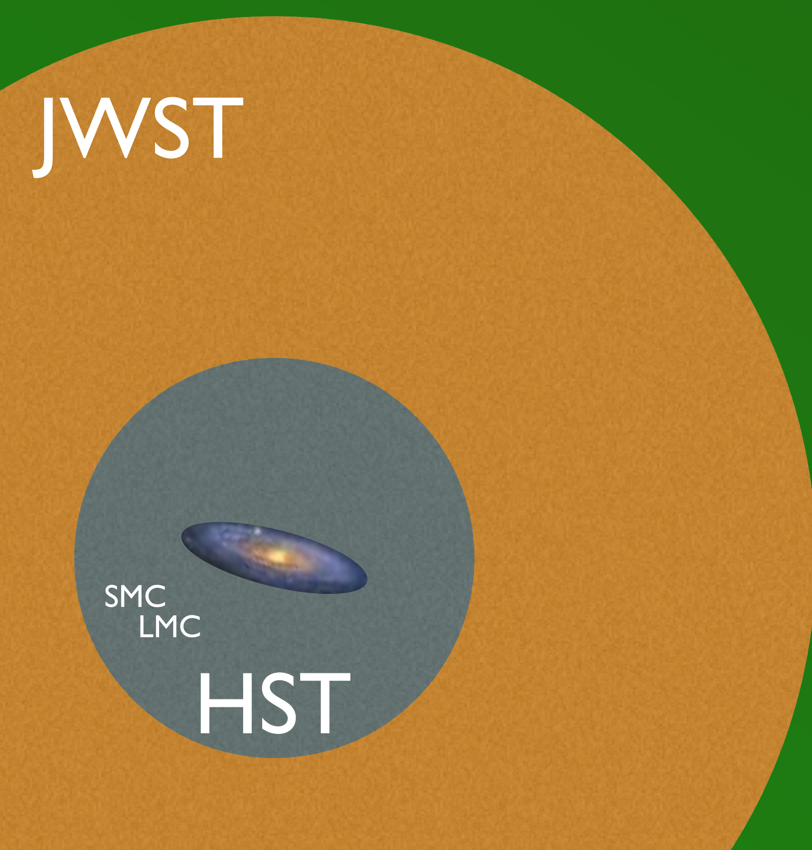
How Does the IMF Vary with Environment?
How and When is the IMF Established?

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.



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

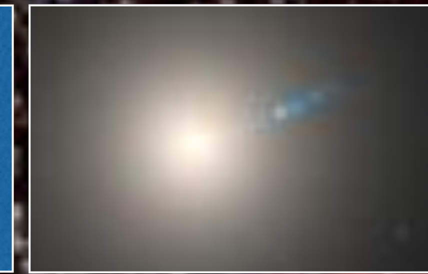
<u>UV light</u> provides a direct estimate of stellar accretion rate from the protostellar disk, but <u>only</u> if single stars can be resolved (<u>≥10 meter</u> aperture for the Magellanic Clouds).

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 is the Dark Matter? How Does Light Trace Mass? How Does Dark Mass Move?

Volume
< 10 Mpc

Resolution
0.1 - 1 pc



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Distance	Speed	Example	Goal
10 pc (nearest stars)	10 cm s 0.2 mph		planets
100 pc (nearest SF regions)	100 cm s 2.2 mph		planets in disks
10 kpc (entire MW disk)	0.1 km s 223 mph		dissipation of star clusters
100 kpc (MW halo)	1 km s 2200 mph		DM dynamics in dwarf sats.
1 Mpc (Local Group)	100 km s		3D motions of all LG galaxies
10 Mpc (Galactic Neighborhood	100 km s		cluster dynamics

A 10-meter telescope can measure proper motions to ~ microarcsec / year precision over a ten-year baseline.

At this level, **virtually everything on the sky moves** - every star in the Milky Way and Local Group and every galaxy in the Galactic Neighborhood.

Aperture driver: A 10+ m is required to reach the motions of virtually ANY Milky Way star, the internal motions of Local Group satellites, and the motions of giant ellipticals in the Virgo cluster (~15 Mpc).

System driver: Extremely stable PSF and low-noise detectors are needed to centroid objects to a few thousandths of a pixel.

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

Volume <50 AU

Resolution 20-100 km

HDST

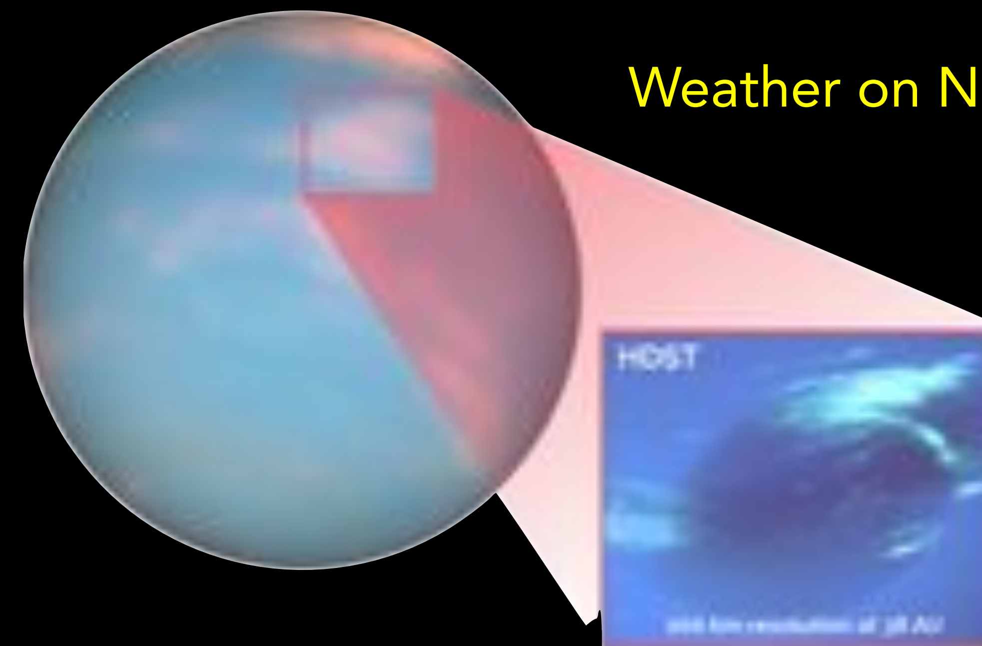
Pluto

Charon

Hubble

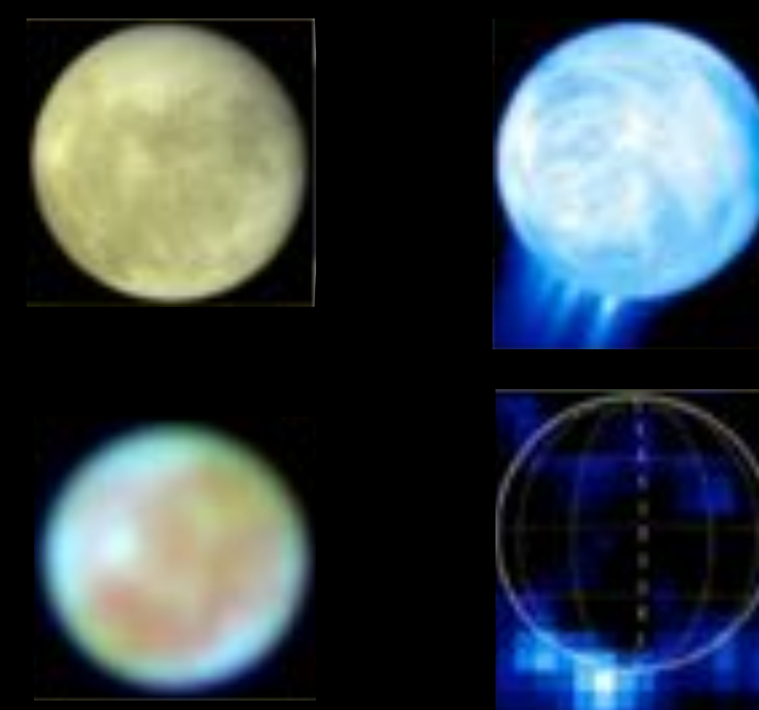
Surface features on Pluto

Weather on Neptune



HDST

Hubble



Geysers on Europa

HDST, with its unique optical/UV capability, will open new avenues in Solar System research, <u>in partnership with future *in situ* space missions.</u>

What can a >10 meter space telescope do?

.

. . . detect dozens of Earth-like planets and search for life there. . .

. . . unravel planet formation with hundreds of fully characterized systems. . .

. . resolve every galaxy in the Universe to its smallest building blocks (100 pc). . .

. . . detect every star-forming galaxy at the time when the Milky Way formed. . .

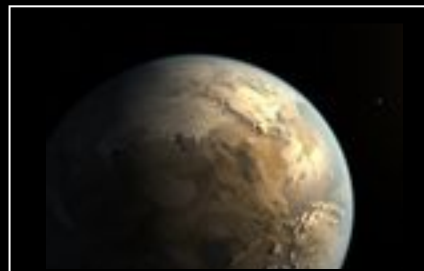
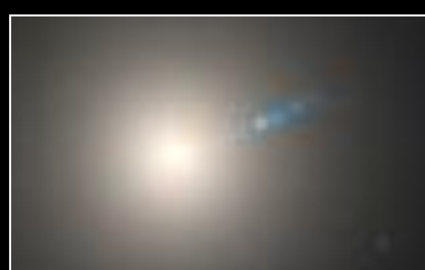
. . . observe individual supernovae at the dawn of cosmic time. . .

. . . 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 positives.
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!)

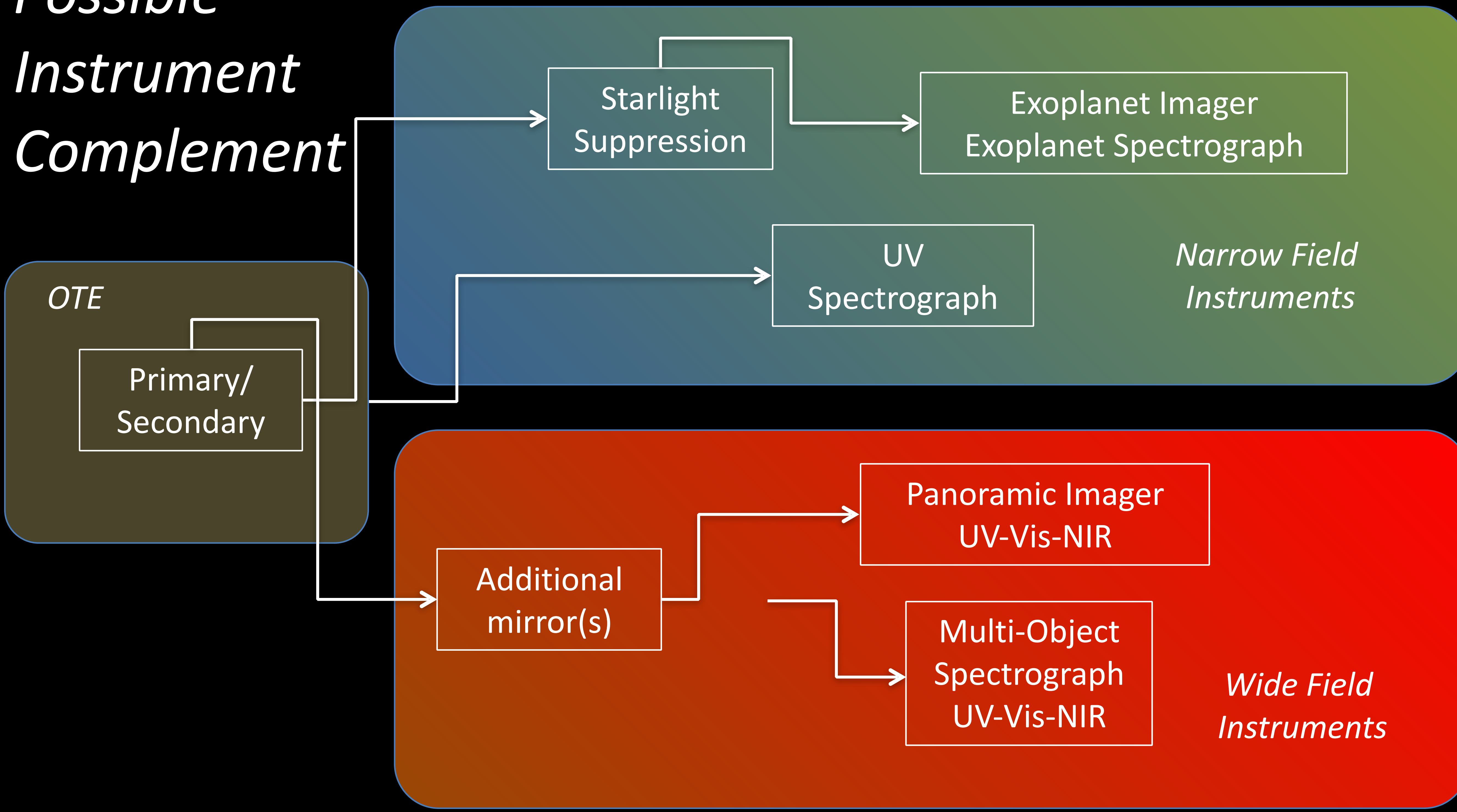
Your Idea Here!

HDST Requirements
as a Large Aperture Space Telescope

Capability		*HDST* Gain vs.	
Parameter	***Requirement***	***HST***	***JWST***
Aperture	***10-12 m***	***x5***	***x1.5-2***
Wavelength	***0.10 to 2 microns***	***Same***	***HDST: UV-vis***
Field of View	***6 arcminutes***	***x3***	***x3***
Pixel Count per Instrument Channel	***0.5-1 gigapixel***	***x30 (vs. Wide Field Camera 3)***	***x25 (vs. NIRCAM)***
Angular Resolution	***0.01” (Diff lim. @ 500 nm)***	***x5 @ 500 nm***	***x1.5-2 @ 1 um***

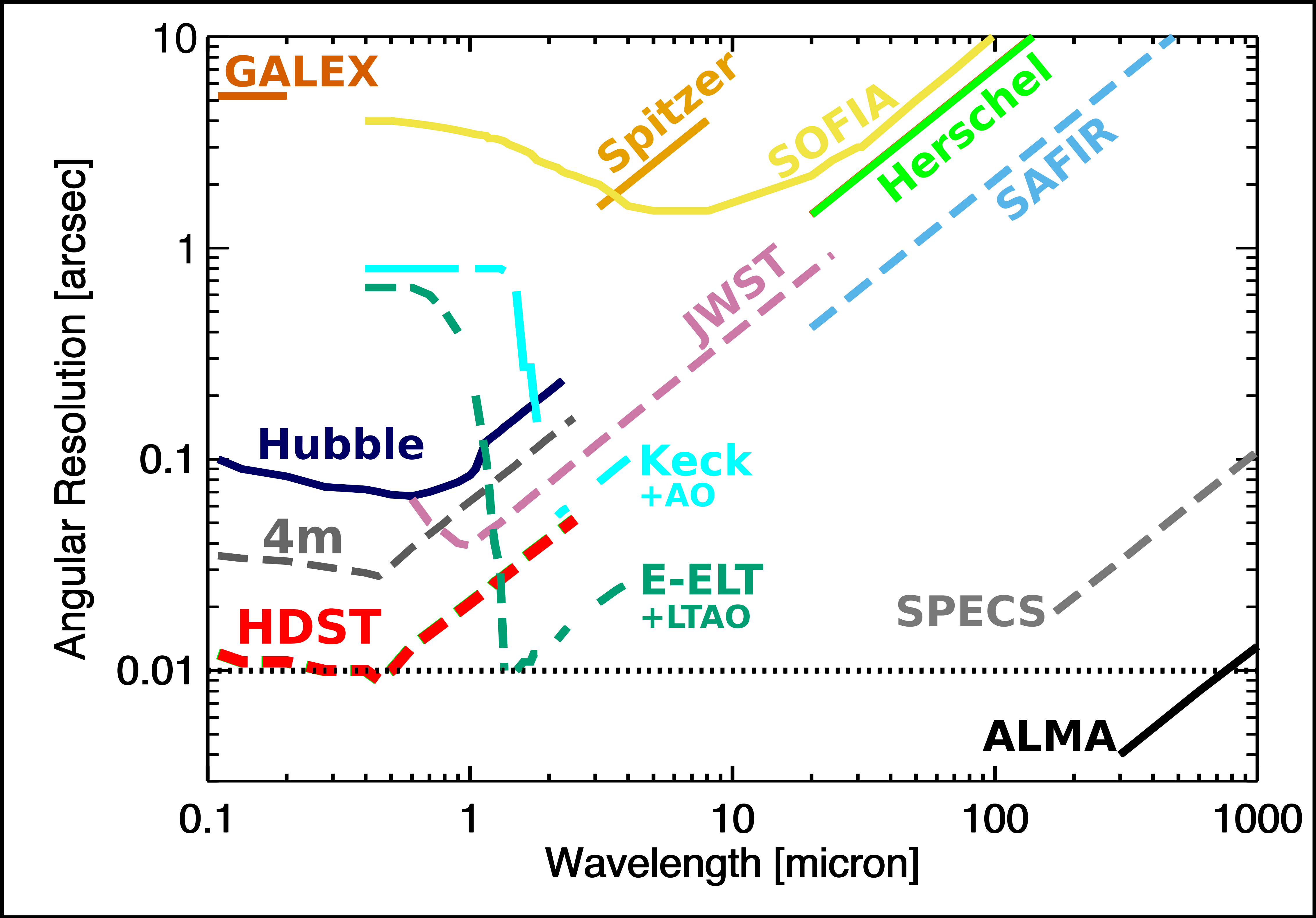
HDST Requirements

Possible Instrument Complement

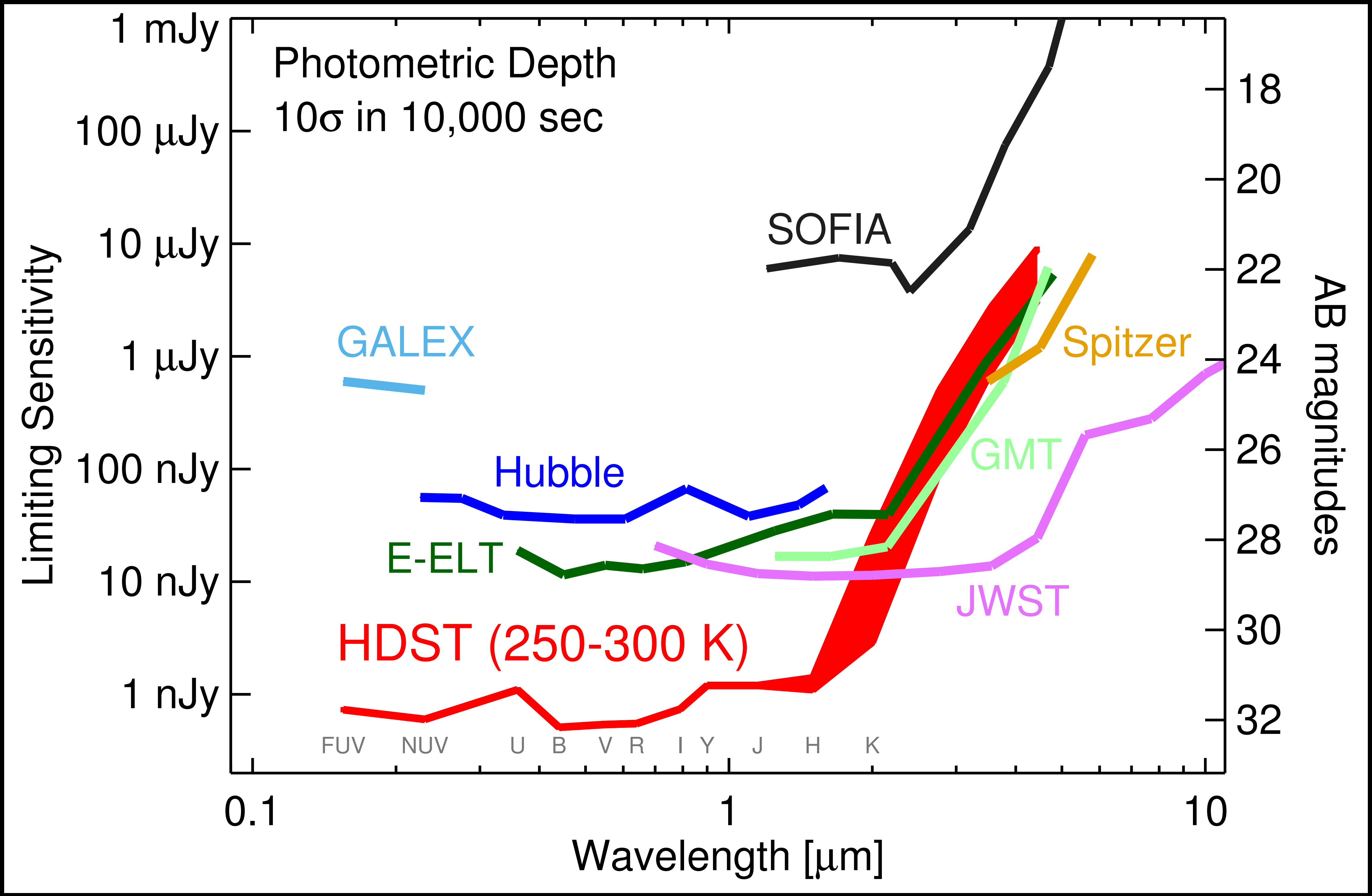


plus *Parallel Observing Capability*

HDST in Context: Angular Resolution



HDST in Context: Broadband Sensitivity



Capability and Technology Requirements

Aperture	*A segmented-mirror aperture of 10m - 12m*
Angular Resolution	*Diffraction limited angular resolution at 500 nm*
Precision (starlight suppression, stability)	*High stability required for telescope & coronagraph (~10 of picometers WFE over 10 - 20 minutes) to enable a 10^{-10} raw contrast ratio.*
Wavelength	*High throughput from UV (90 nm) to NIR (2 microns and possibly longer) will enable science that cannot be done from the ground.*
Temperature	*Room temperature (250-300 K) operation.*

See Chapters 5 and 6 of Report

Technology: Current Status

Tech Category	Current Maturity
Segmented Primary	Substrate TRL 4-6, System TRL 3
Low Noise Detectors	TRL 4-6
High-performance UV Coatings	TRL 4-5
WFE Stability (Thermal)	TRL 4
WFE Stability(Metrology)	TRL 3
High Performance Coronagraph	TRL 3-4
Starshade (external occulter)	TRL 2-3

All at TRL ~5 by 2019

"Thorough testing of prototyping in relevant environment."

Highest priority technologies address key performance issues, building on past and current NASA and non-NASA projects and investments.

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All at TRL6 by 2024

"Engineering feasibility fully demonstrated in actual system application."

i.e. ready to build the "real thing"

Highest priority technologies address key performance issues, building on past and current NASA and non-NASA projects and investments.

HDST is envisioned to be. . .

.

. . . a general purpose, flexible Flagship observatory. . . .

. . . with full community access via peer reviewed proposals. . .

. . . with a “killer app” for seeking Earth 2.0 and resolving the cosmos to 100 pc . . .

. . . and with a diverse, powerful instrument complement. . .

. . . that will make factor of 10-1000x gains over present instruments. . .

. . . and will be a leader in the astronomical landscape in the 2030s. . .

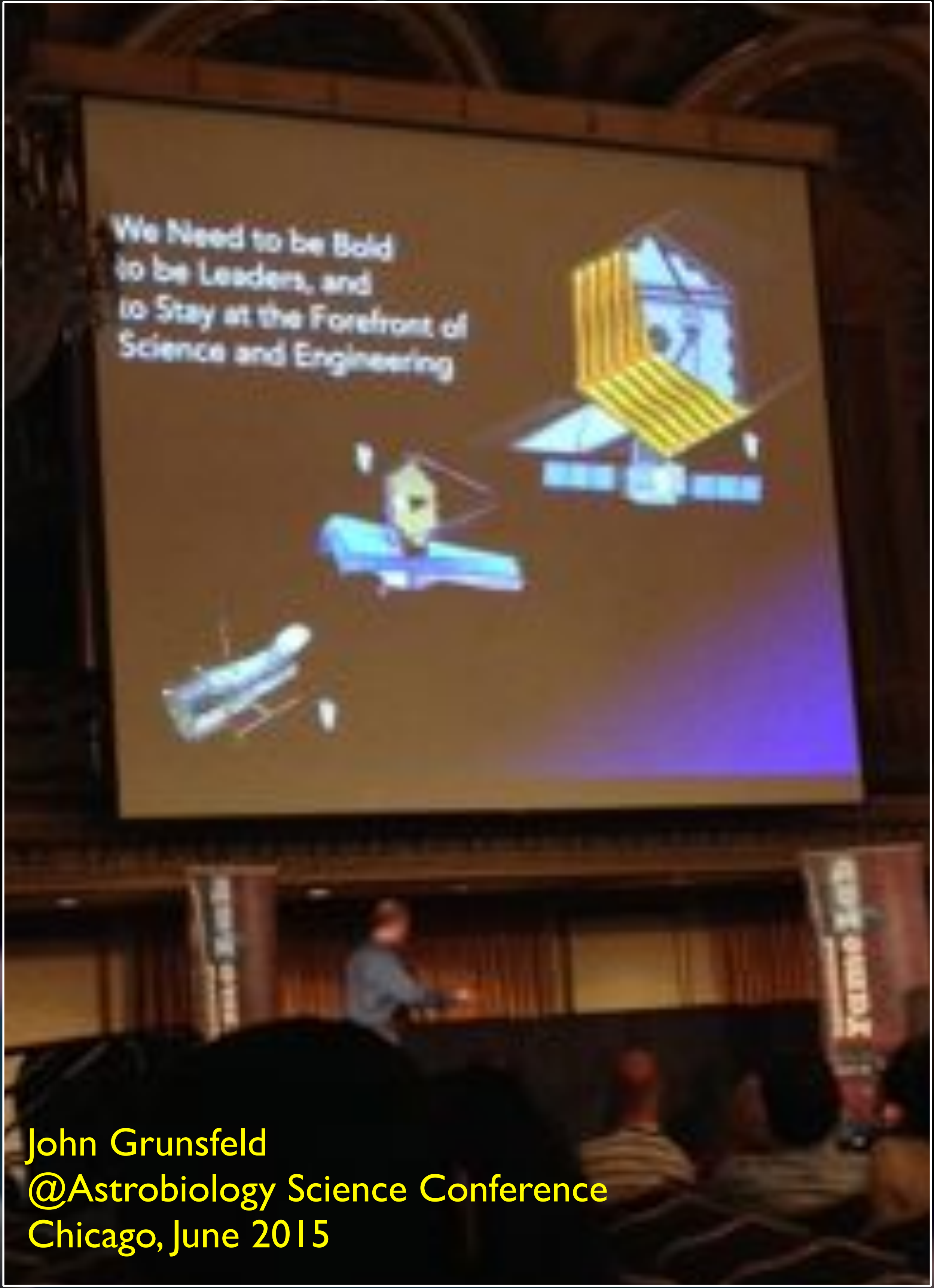
. . . and a vital UVOIR complement to other facilities of that era.

WHY A BIG FLAGSHIP?

(1)
SCIENCE!
dozens of Earth-like planets, the Cosmos at < 100 pc, and 100x Hubble in the UV

(2)
Strategy
A Large Telescope fits better into the anticipated astronomical era of the 2030s (after JWST and WFIRST, with the ELTs).

(3)
Leadership
. . .



John Grunsfeld
@Astrobiology Science Conference
Chicago, June 2015

WHY COMBINE SCIENCE CASES?

(1)

SCIENCE!

a single 12 meter filled aperture telescope provides enough collecting area and resolution to enable searches for dozens of Earth-like planets and revolutionize multiple areas of astronomy.

(2)

Compatibility

to the limits of our current knowledge, there are no high-level requirements on architecture, telescope, or instruments that make high-contrast imaging and panchromatic high-def astronomy incompatible.

(2)

Strategy

An astronomical community speaking with one voice about compelling science will be heard in a way that two groups will not.

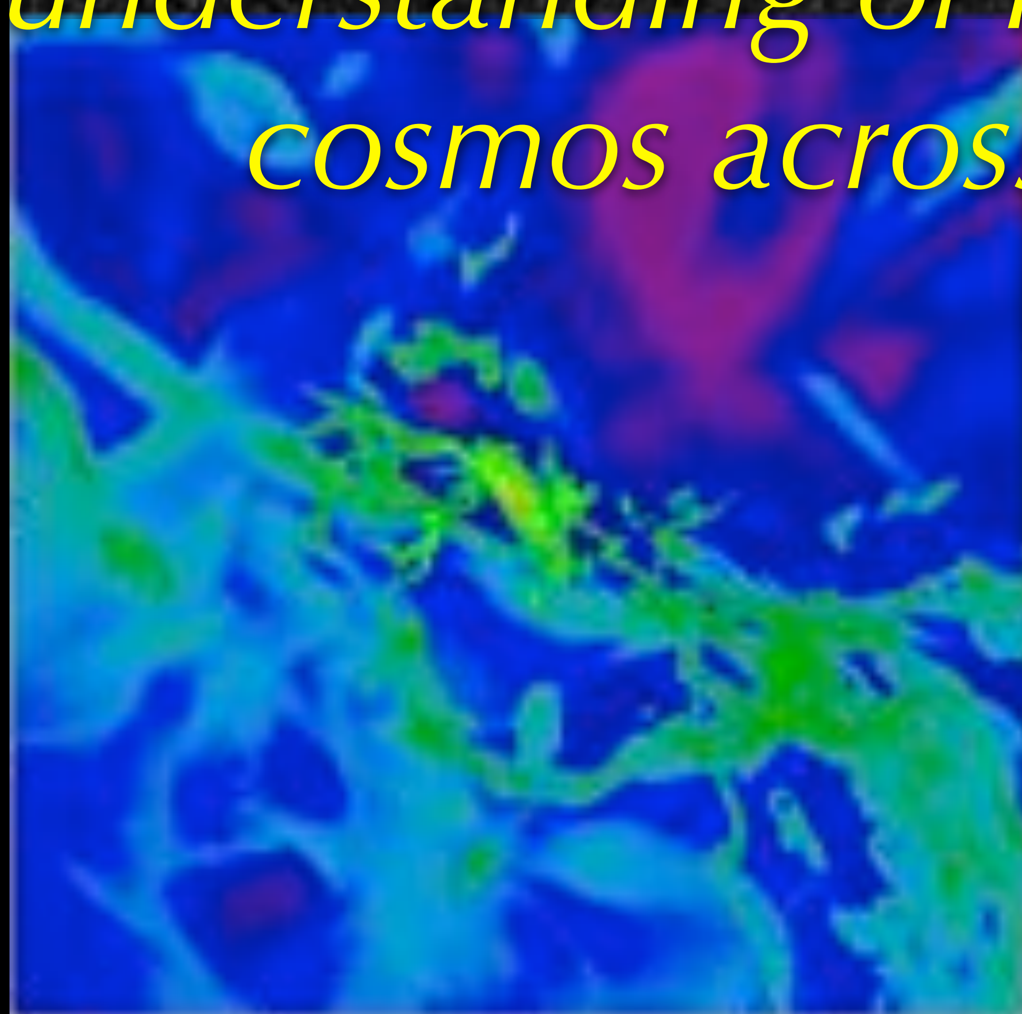
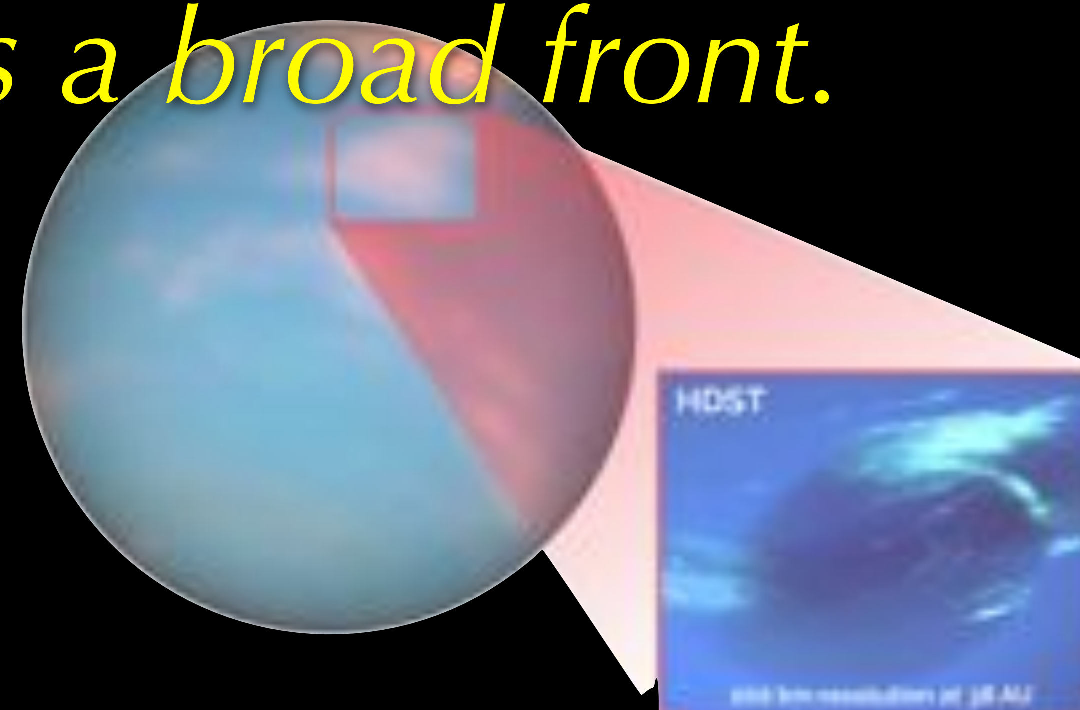
From Cosmic Birth to Living Earths

There is an exciting future for UVOIR Space Astronomy. To realize it will require bold, innovative steps. These steps are within reach.

We will be able to survey hundreds of planetary systems and detect dozens of Earth-like planets in the habitable zones around their stars, including stars similar to the sun. If any of these exoEarths have biosignatures, we'll have the sensitivity to detect them.

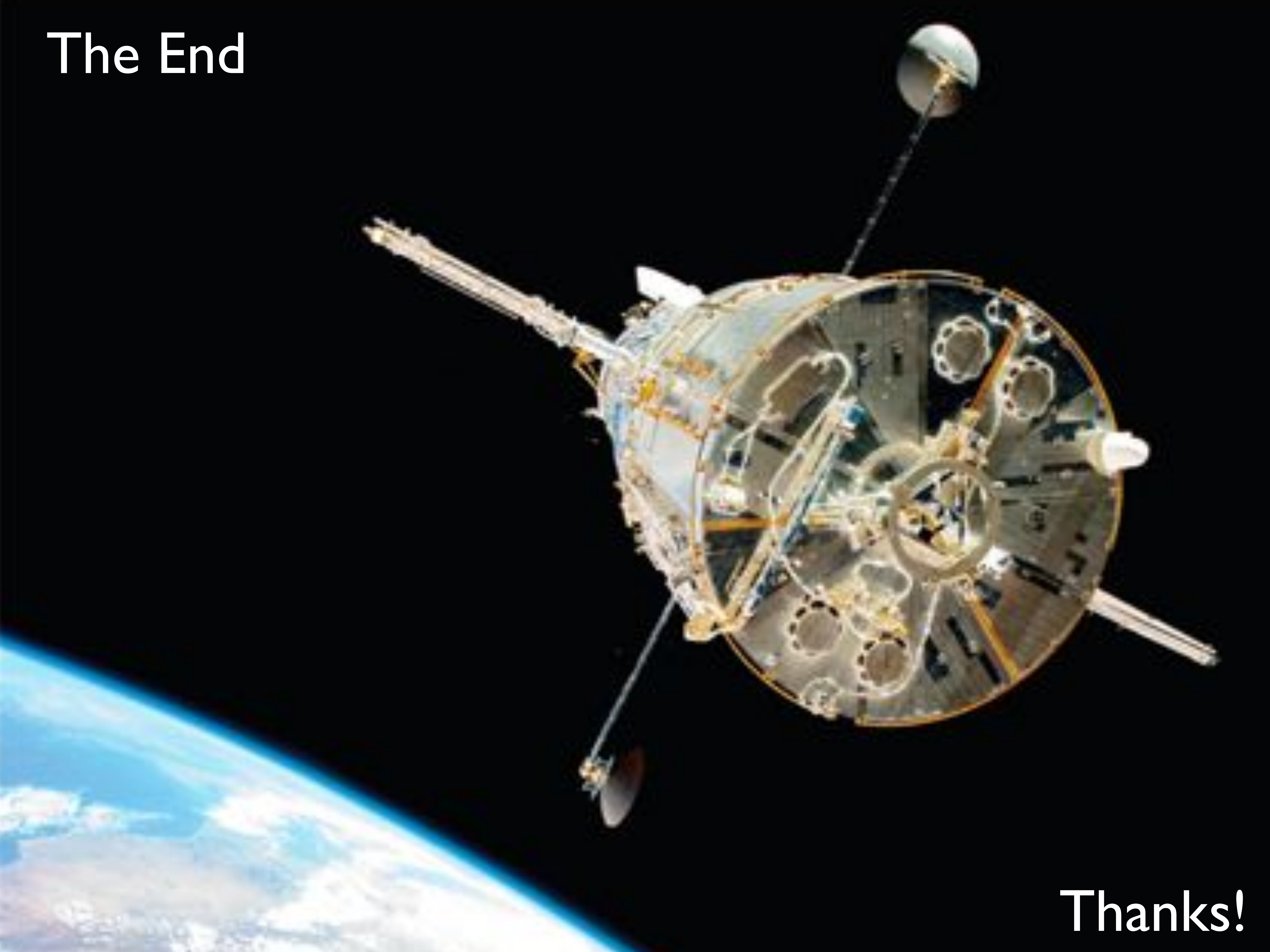
We will radically advance every area of astronomy from galaxy formation to star and planet formation, and from black hole physics to long term studies of solar system objects.

A 12m space 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.

A single Great Observatory can revolutionize our understanding of life and its origins in the cosmos across a broad front.

The End



Thanks!