From HST to JWST and Beyond: The Science Drivers for Large Apertures in Space

Keck Institute for Space Studies
Large Space Apertures Workshop
9-10 November 2008

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The Johns Hopkins University

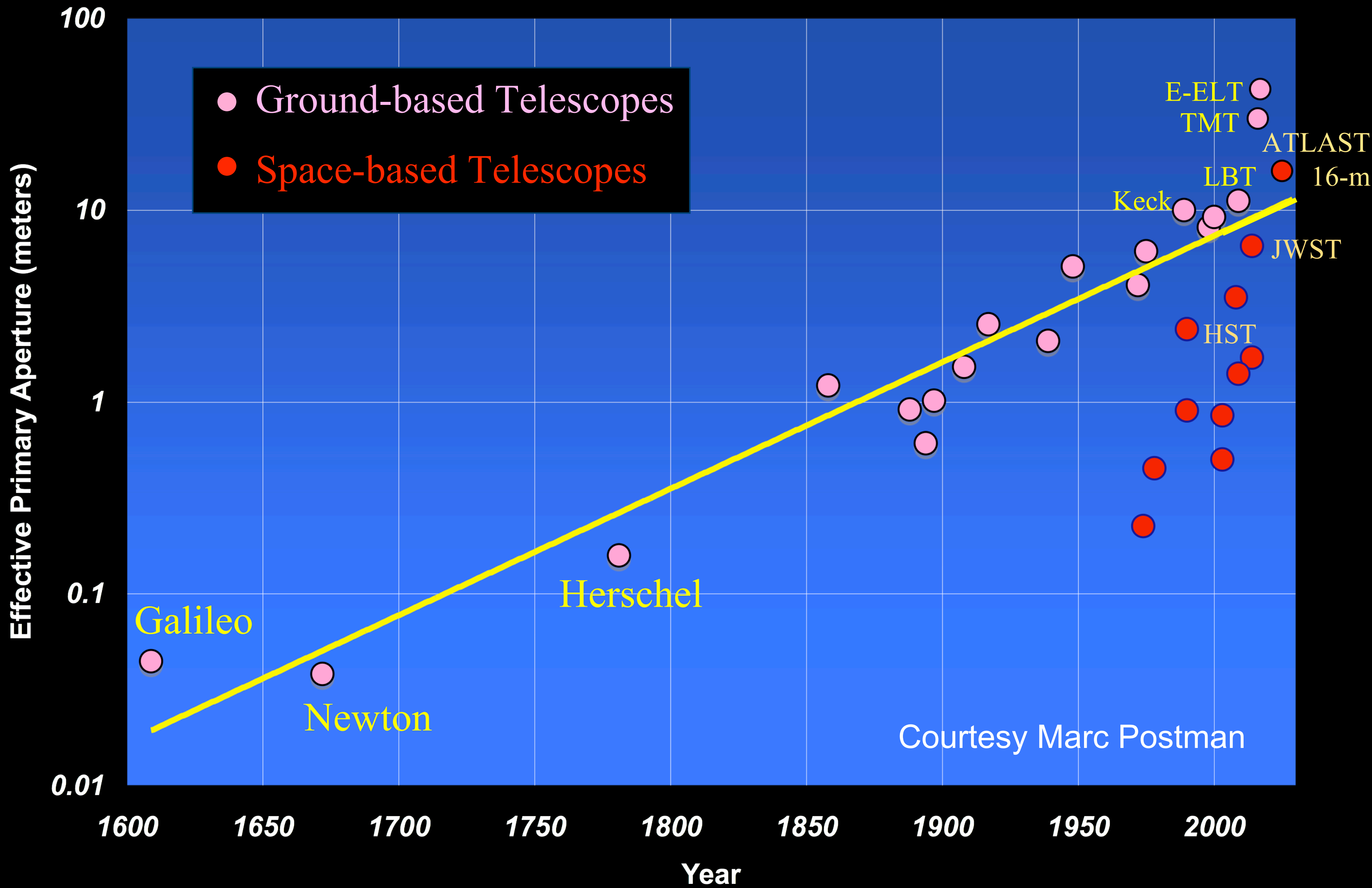
The Large Apertures Workshop has the following objectives:

1. What are the community's needs for
(a) optical apertures or
(b) RF apertures in the next 10-20 years?
2. What is the state of the art in optical and RF apertures?
3. What are the roadblocks that prevent us from meeting the community's needs, given the state of the art?
4. What approaches could be followed to address these roadblocks?

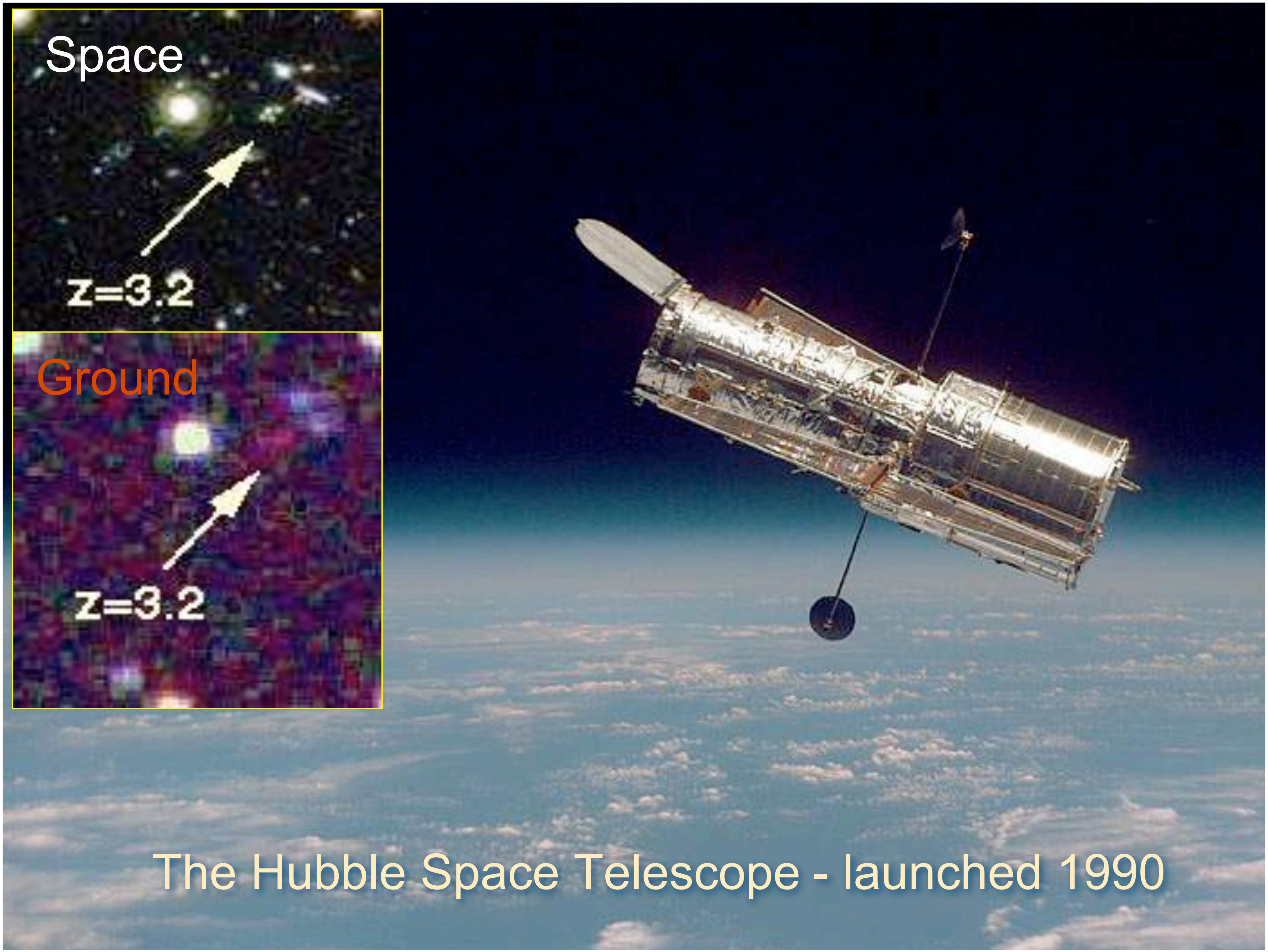
Outline:

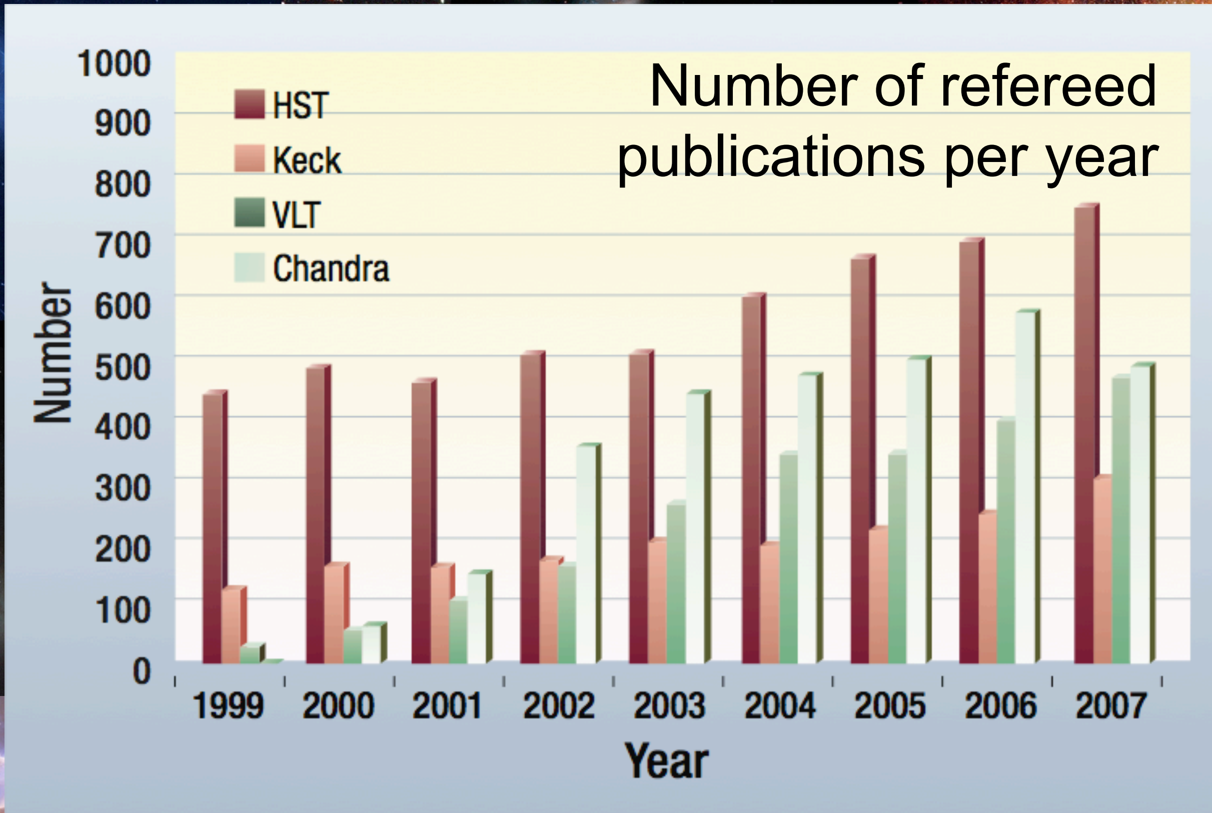
- The growth of "aperture" in observational astrophysics
- The Hubble Space Telescope and the James Webb ST
    - *the role of groundbased Adaptive Optics*
- Science drivers for future spacebased UV/Optical/NIR telescopes
- Are there lessons from groundbased telescopes?
    - *future challenges*
- Summary

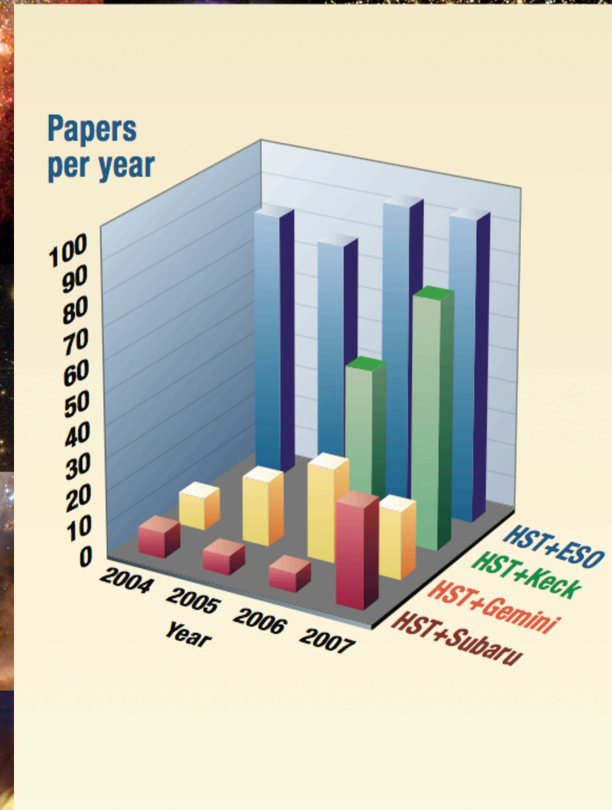
Growth in aperture driven by science *and* technology

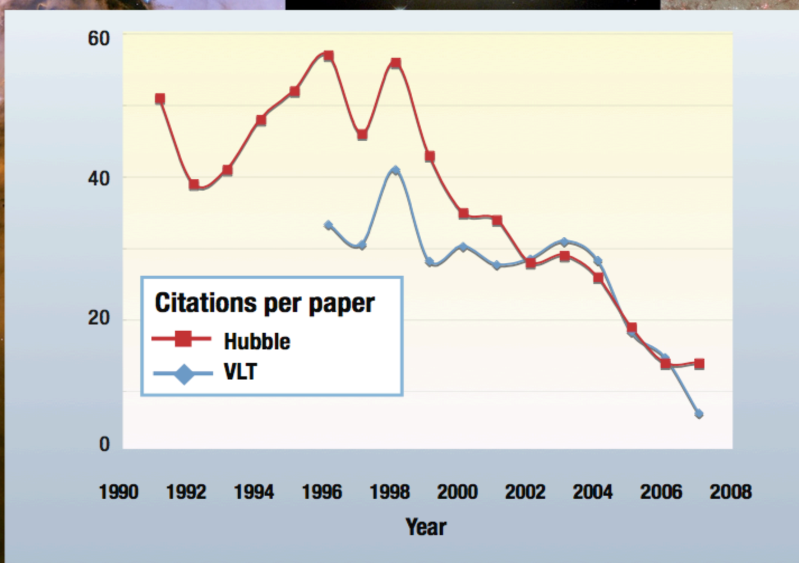


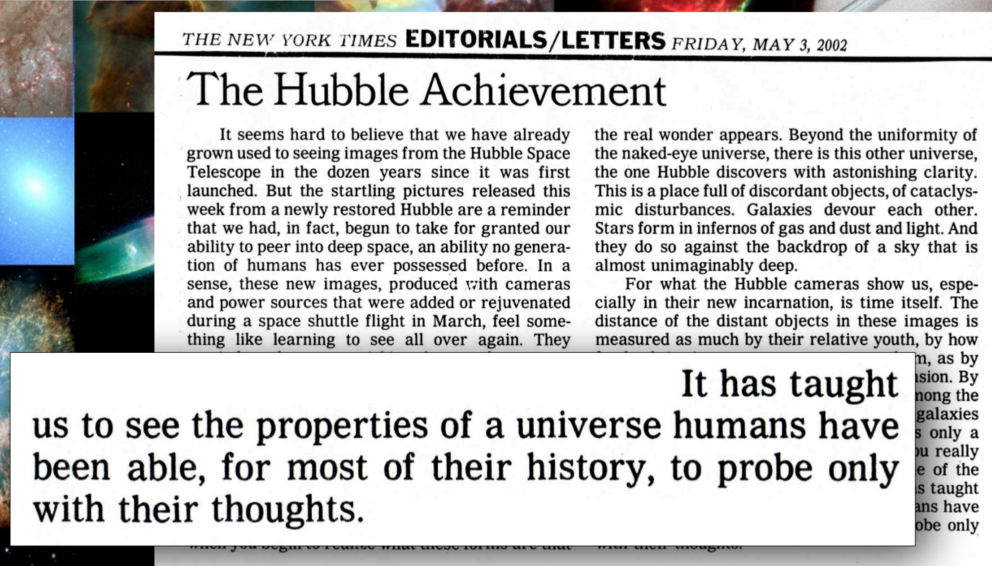
Primary Telescope Aperture vs. Time


Space
z=3.2
Ground
z=3.2
The Hubble Space Telescope - launched 1990








THE NEW YORK TIMES **EDITORIALS/LETTERS** FRIDAY, MAY 3, 2002

The Hubble Achievement

It seems hard to believe that we have already grown used to seeing images from the Hubble Space Telescope in the dozen years since it was first launched. But the startling pictures released this week from a newly restored Hubble are a reminder that we had, in fact, begun to take for granted our ability to peer into deep space, an ability no generation of humans has ever possessed before. In a sense, these new images, produced with cameras and power sources that were added or rejuvenated during a space shuttle flight in March, feel something like learning to see all over again. They

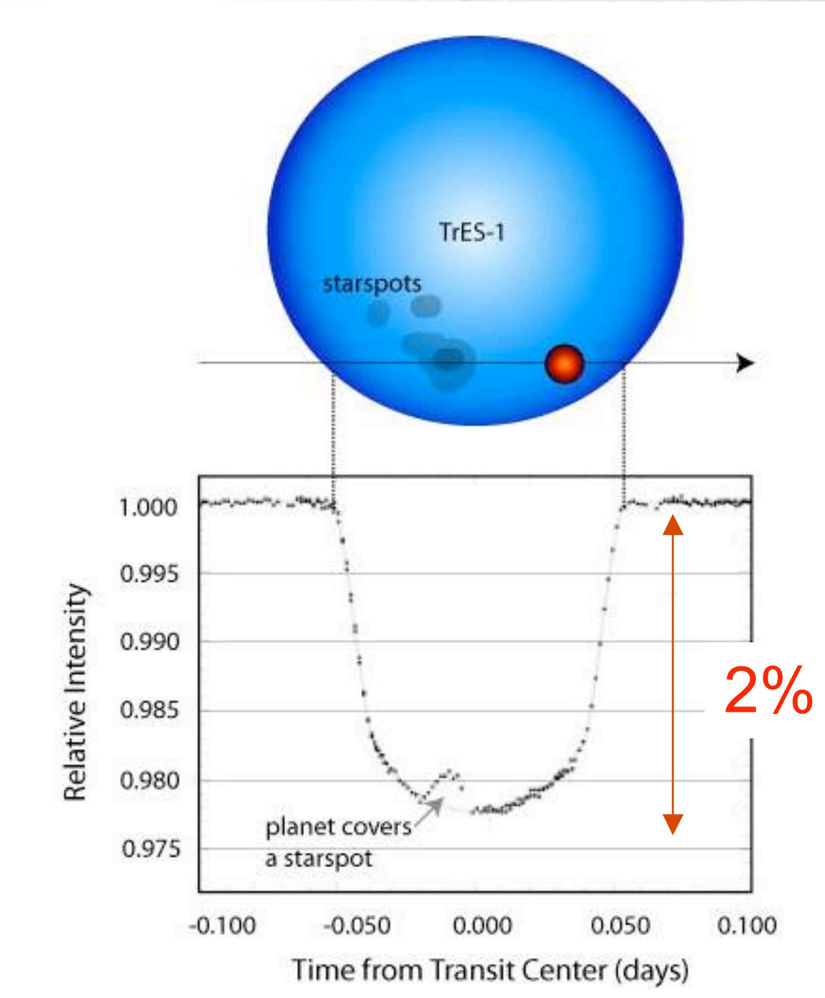
the real wonder appears. Beyond the uniformity of the naked-eye universe, there is this other universe, the one Hubble discovers with astonishing clarity. This is a place full of discordant objects, of cataclysmic disturbances. Galaxies devour each other. Stars form in infernos of gas and dust and light. And they do so against the backdrop of a sky that is almost unimaginably deep.

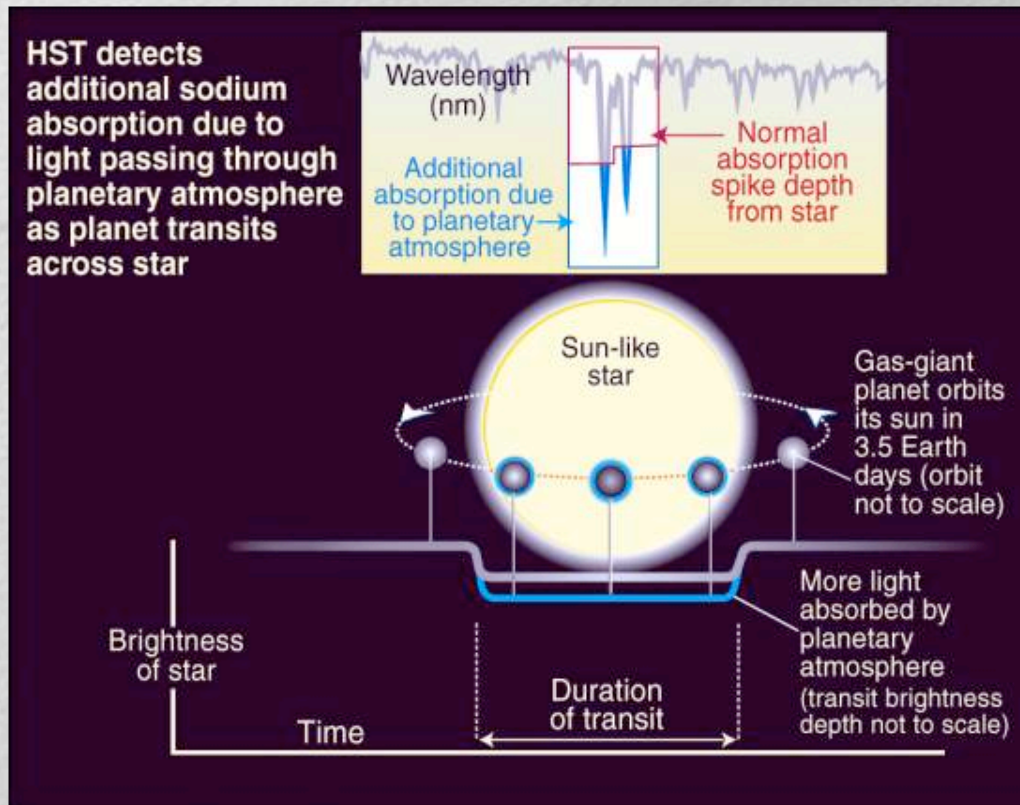
For what the Hubble cameras show us, especially in their new incarnation, is time itself. The distance of the distant objects in these images is measured as much by their relative youth, by how

It has taught us to see the properties of a universe humans have been able, for most of their history, to probe only with their thoughts.

There are some things that are hard to do from the ground….

Space is a very stable place…



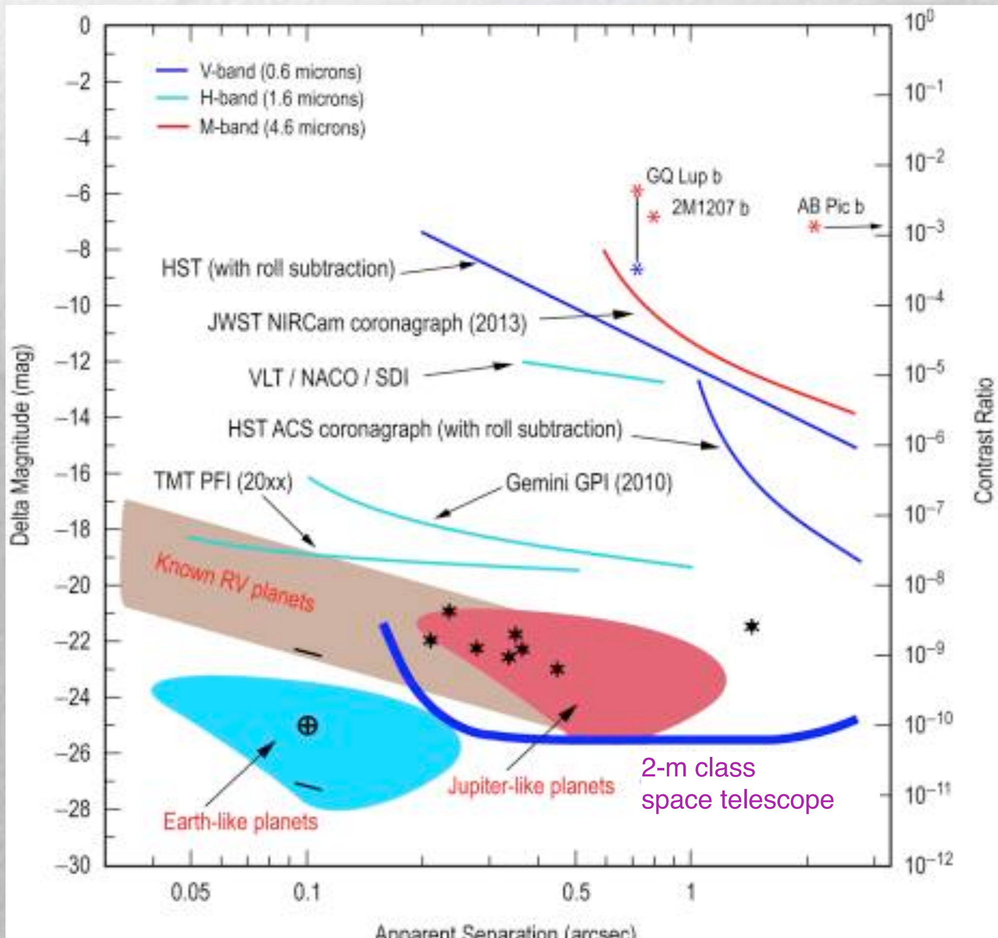


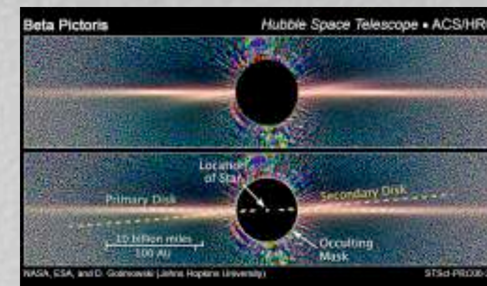
High precision, time dependent HST transit observations: exoplanet diameters and atmospheric composition

Progress requires stable space environment and increased collecting area

Direct imaging of extra-solar planets limited by atmospheric turbulence: a floor on contrast

- Even to image “normal” Jupiters in known extrasolar planetary systems requires contrast ratio’s 1:10^{10}
- Advance the spacebased coronagraphic technology needed for tackling Earth-like planets, *and large collecting area*





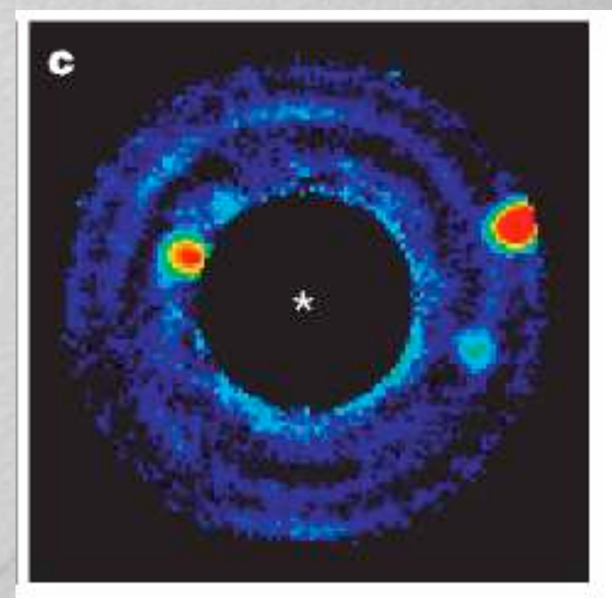


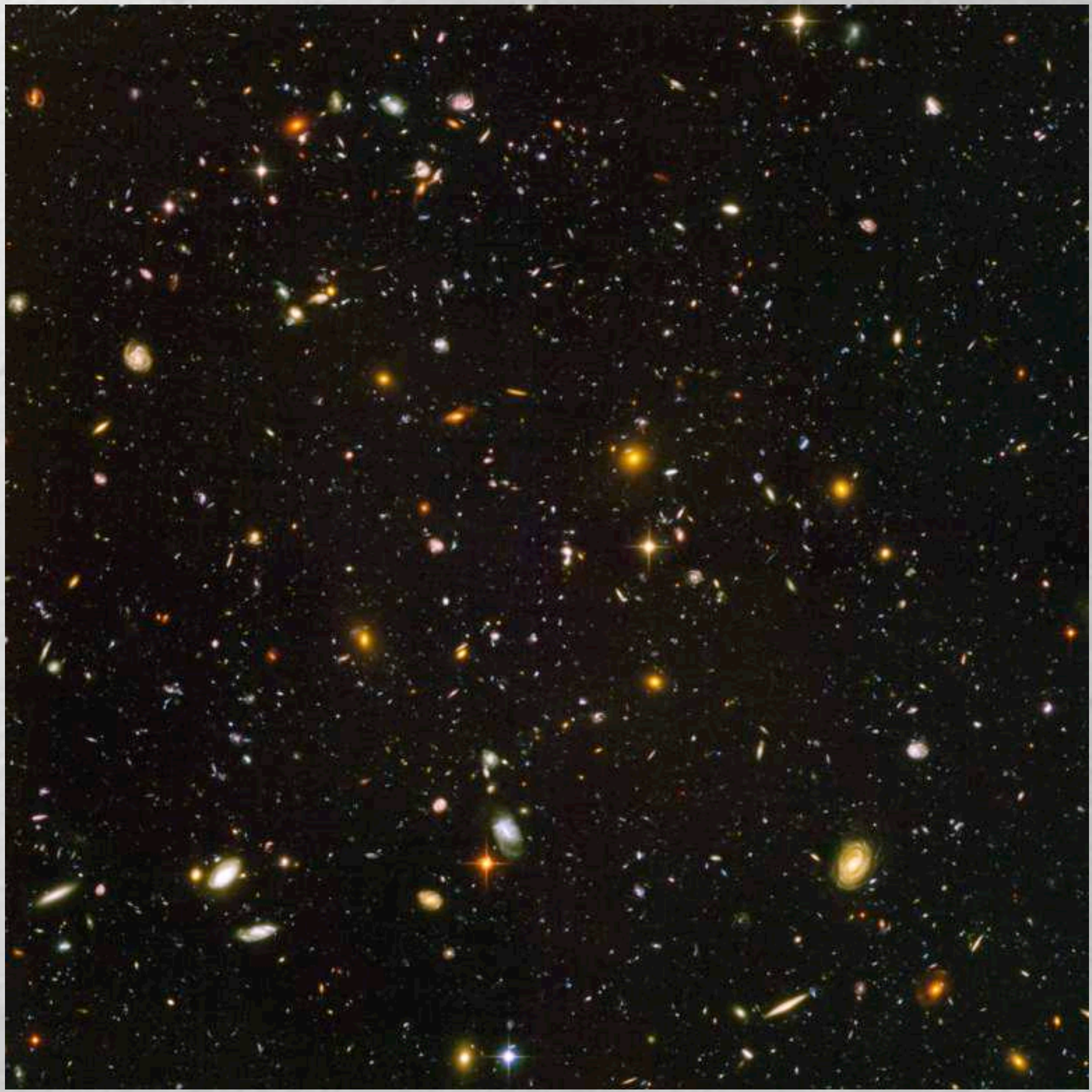
Figure 2 | Laboratory images demonstrate contrast at levels required to detect an Earth-twin. a, Three planet images are shown on the sky. The planets are copies of the measured star but reduced in intensity by factors of (10, 5 and 1) × 10^{-10}, corresponding to the typical intensities of Jupiter, half-Jupiter and Earth, respectively. The Earth-twin is at about 4 o’clock, and the Jupiter-twin at 2 o’clock. The D-shaped field of view rotates on the sky as

From Trauger & Traub Nature Letters, April 2007

Deep, high-resolution images of the distant universe

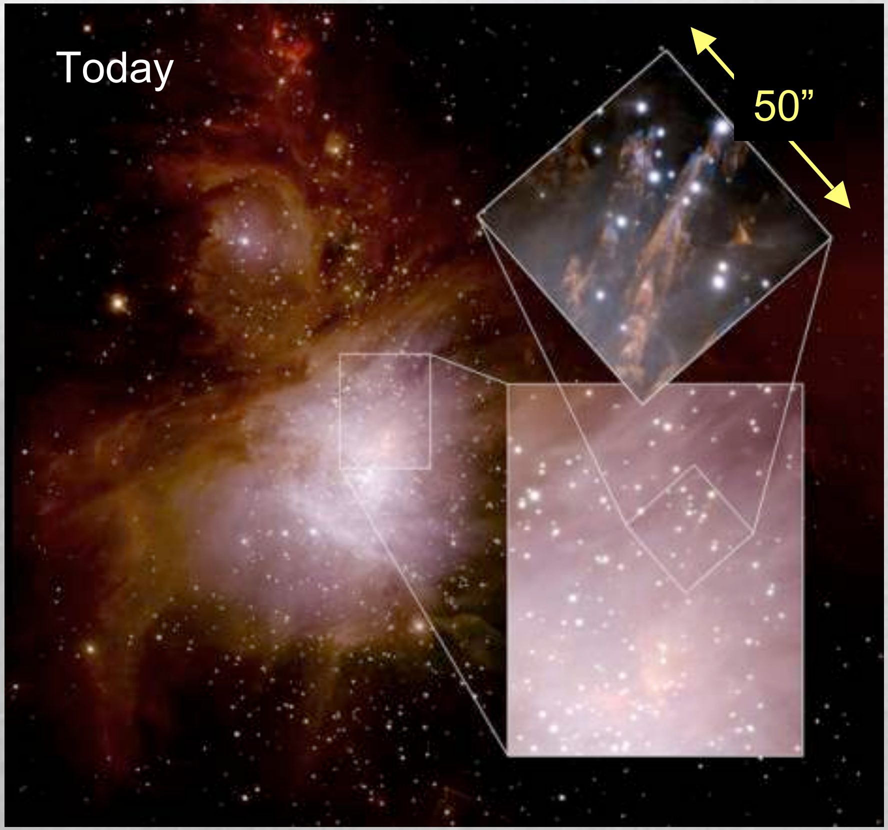
Current state of the art for deep observations:

- Hubble Ultradeep Field (Beckwith et al. 2006)
- 11 day exposure
- 11 square arcminutes, subtends 1.6 Mpc at z~3
- Resolution 0.7 kpc at z~3

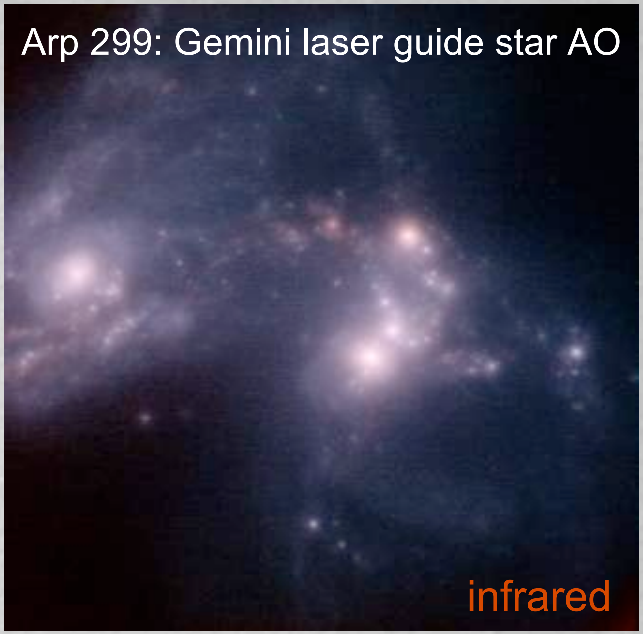


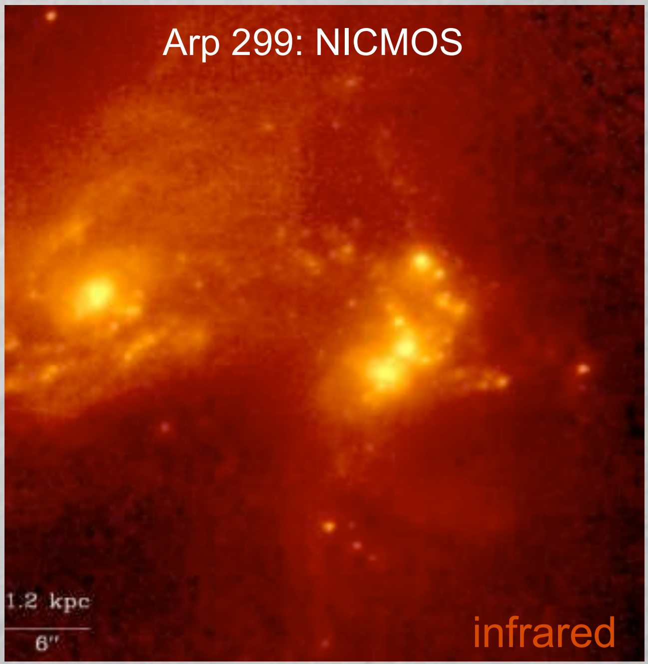
Progress demands resolution, depth, sky area, and broad wavelength coverage

Adaptive Optics is a developing groundbased technology



Corrected IR image quality ~0.1 arcsec
Courtesy Gemini Observatory





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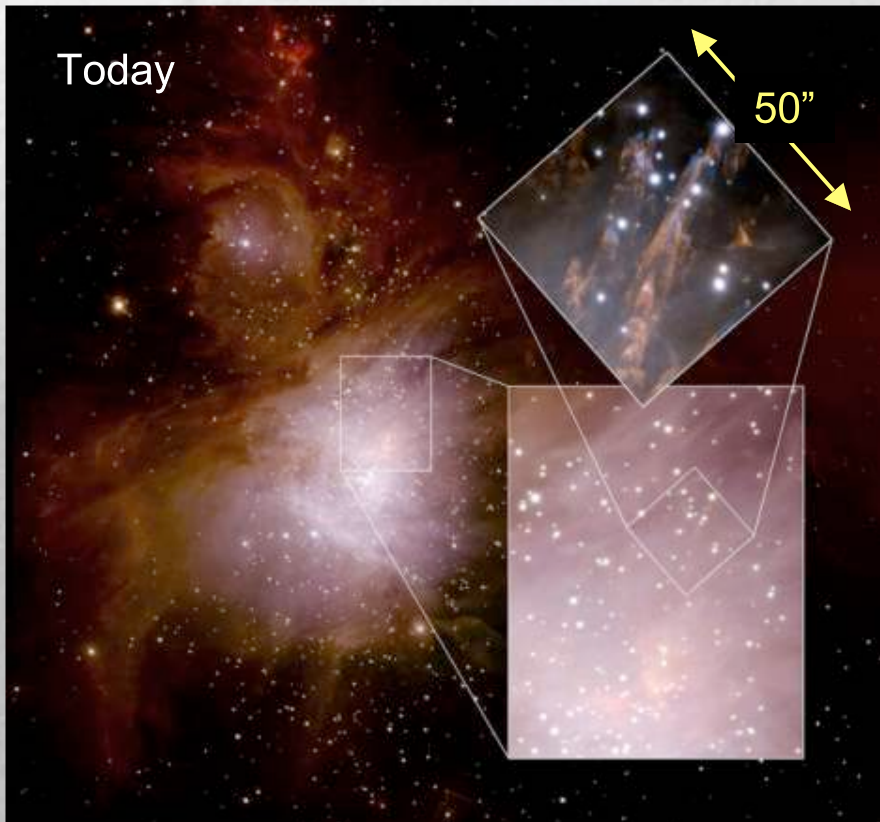

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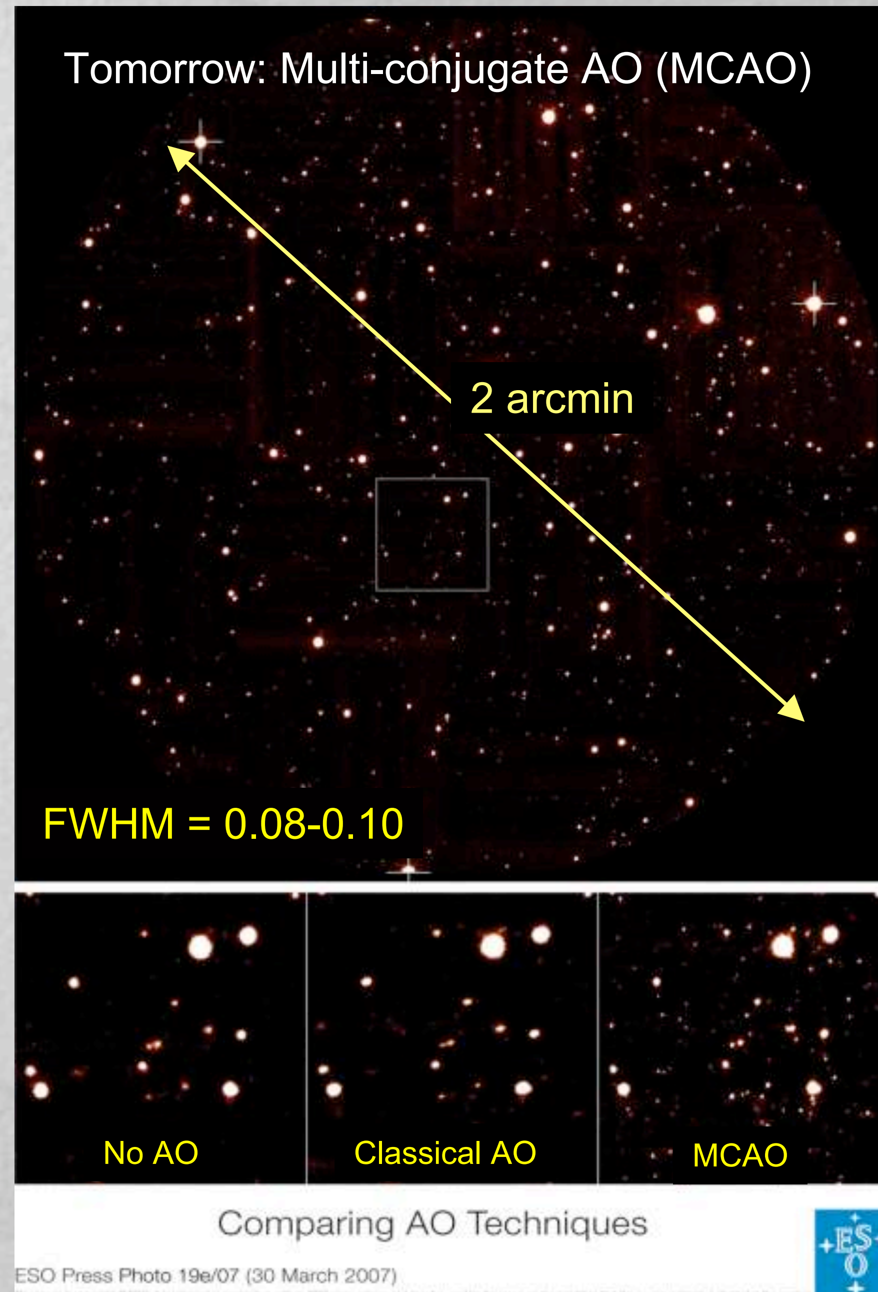
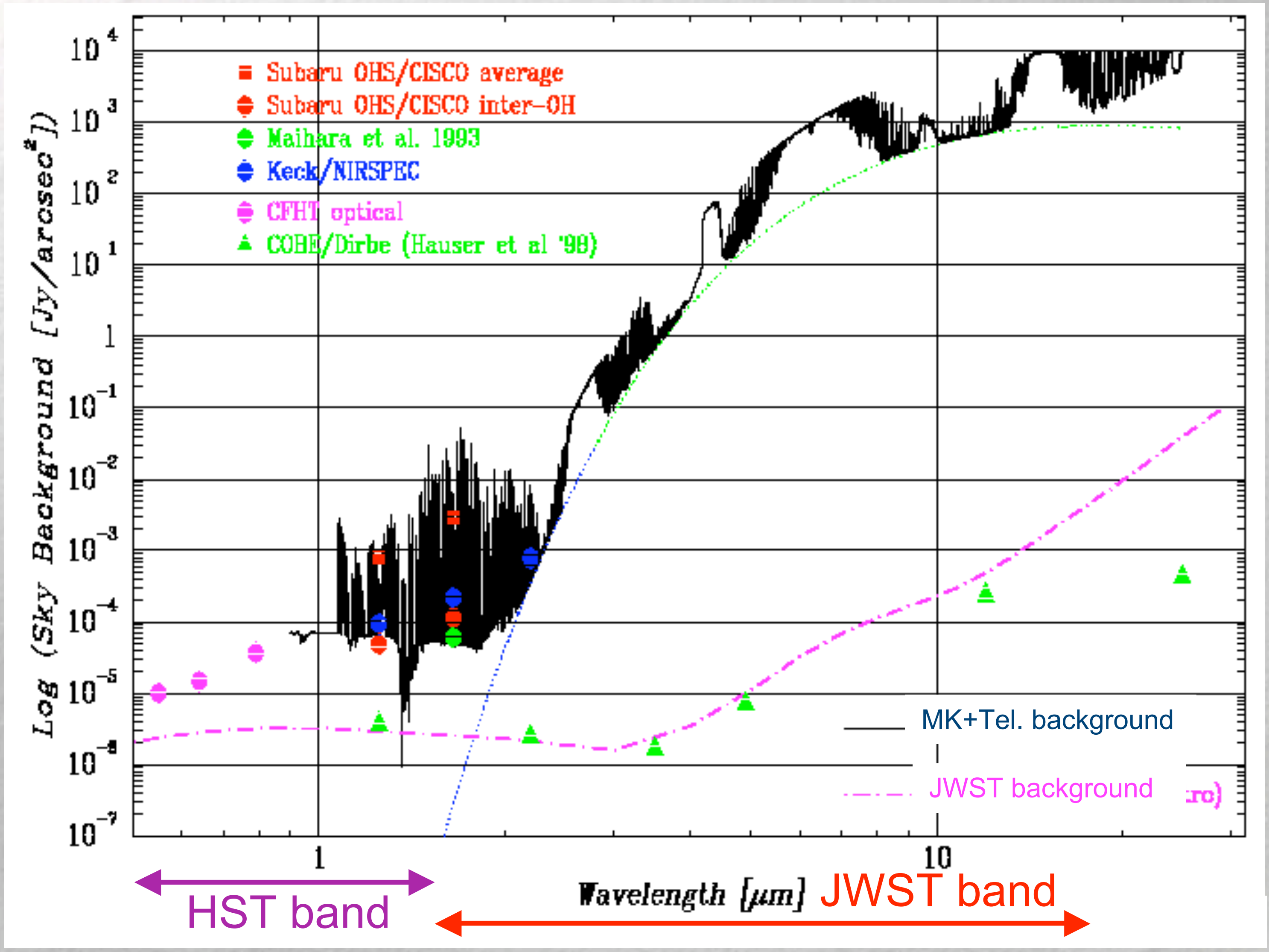
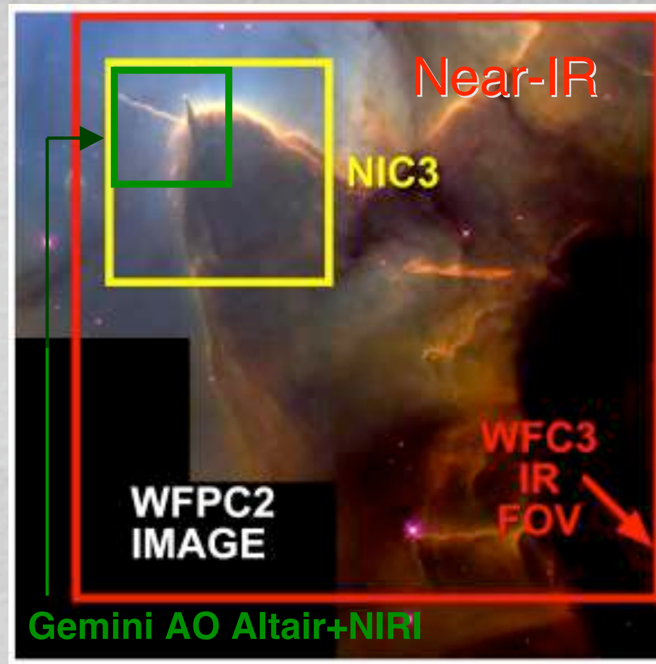


Example of the advantages of Space lower background



Complementarity with AO

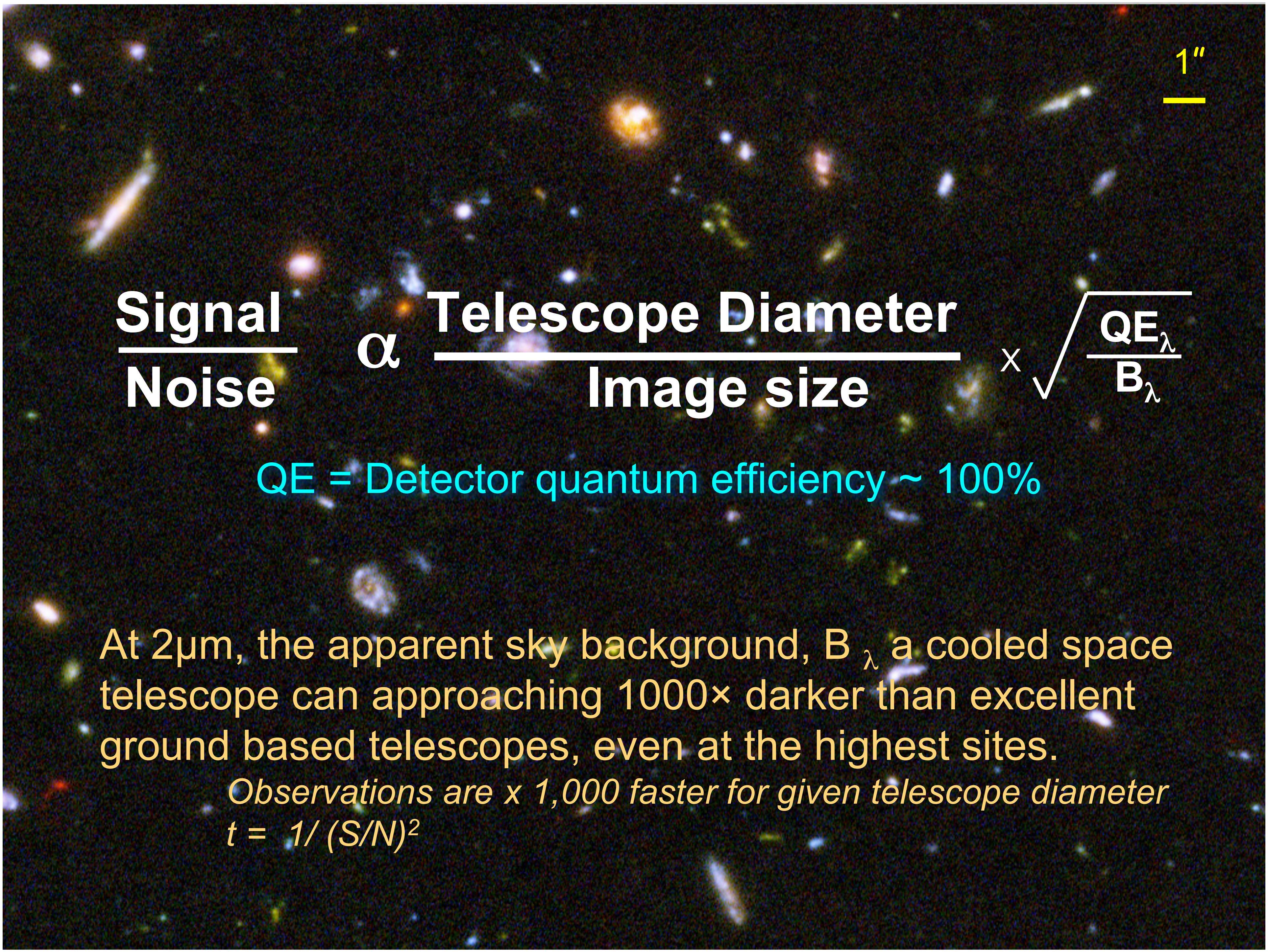


- Ground-based 30-m telescopes *will* achieve higher resolution in the NIR
- Space has much lower background
  - Exposure times for faint objects for a space 2-m are comparable to an AO-corrected 30-m shortward of 2 μm.
- Starlight suppression much better from space
  - 2-m space telescope outperforms a 30-m with AO
- Space provides a wider corrected field than AO, or even MCAO
- At optical wavelengths, AO fields on a 30-m will subtend just a few arcseconds.

Exposure times for S/N=5 point source AO in typical conditions:

	J=25.2	H=24.5	K=23.2
Instrument	1.2 μm	1.6 μm	2.1 μm
HST+WFC3	8 min	20 min	-
8-m VLT NAOS+Conica	640 min	730 min	260 min
30-m + MCAO	6 min	6 min	0.06min

Even a 2.4m space telescope can be competitive with a 30m groundbased telescope



$$\frac{\textbf{Signal}}{\textbf{Noise}} \; \alpha \; \frac{\textbf{Telescope Diameter}}{\textbf{Image size}} \times \sqrt{\frac{QE_\lambda}{B_\lambda}}$$

QE = Detector quantum efficiency ~ 100%

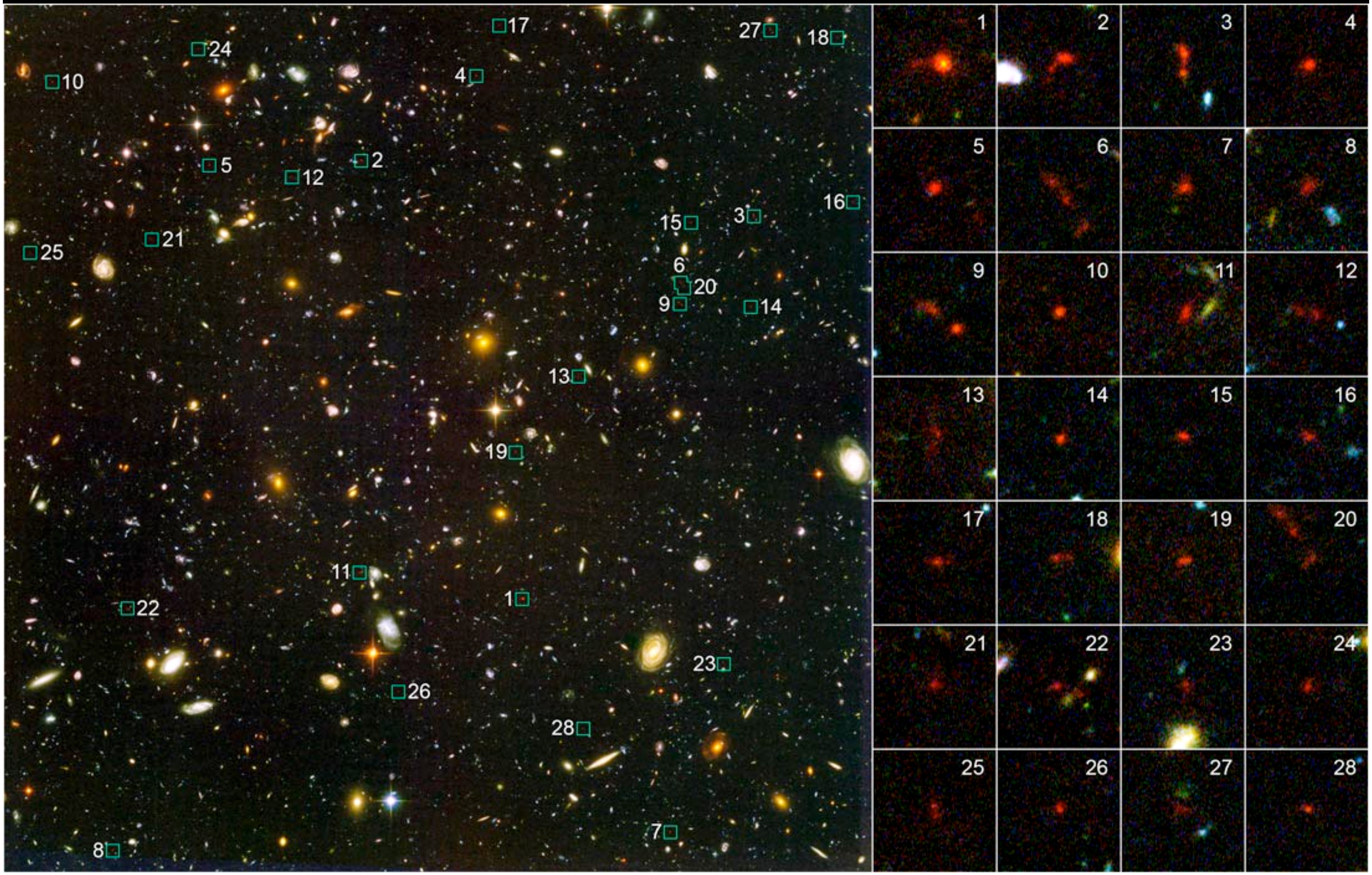
At 2µm, the apparent sky background, B_λ a cooled space telescope can approaching 1000× darker than excellent ground based telescopes, even at the highest sites.

Observations are x 1,000 faster for given telescope diameter

$t = 1/(S/N)^2$

Peering into the high z Universe

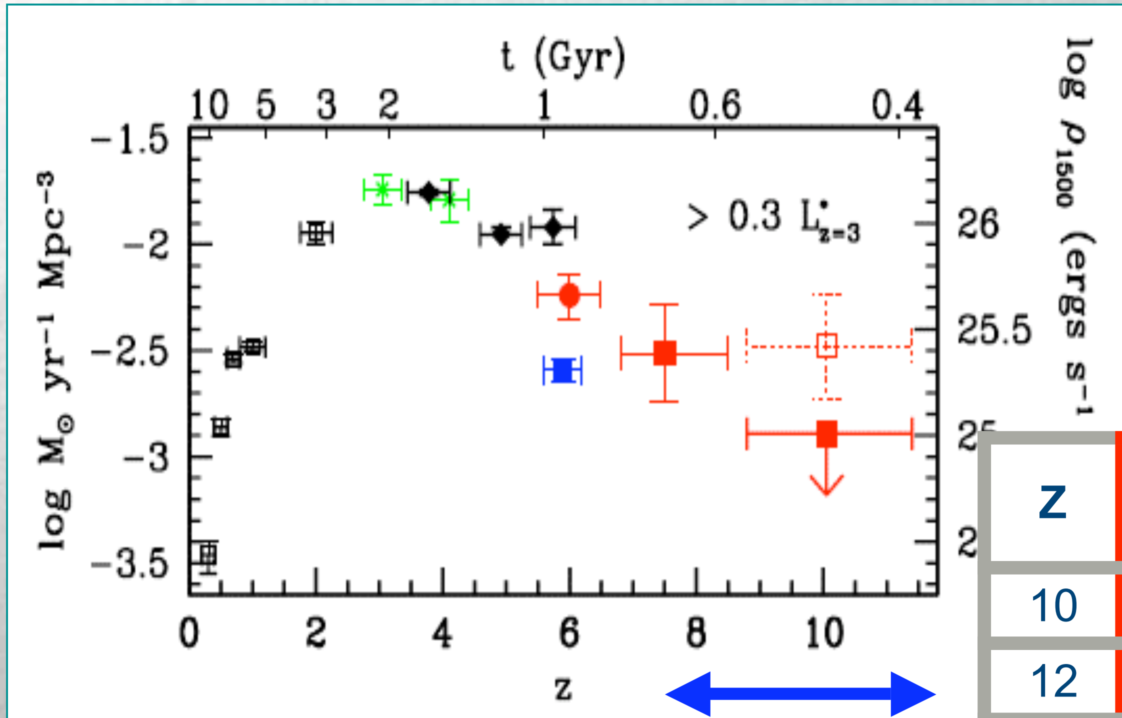
Bouwens et al.: 506 galaxies with z>6 assembled from ACS data (HUDF, GOODS)



Star-formation History

Bouwens et al.: 506 galaxies with z>6 assembled from ACS data (HUDF, GOODS) ~ several 10^6 second observations

Starformation rate



Look back time

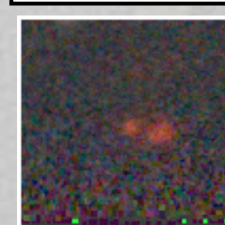
Z	AB (1350)	Fυ (nJy)	λ (nm)
10	30.3	2.80	1.34
12	30.6	2.19	1.58
15	30.9	1.63	1.95
20	31.3	1.13	2.55

Stiavelli 2005

8.8 Gyr

3.3

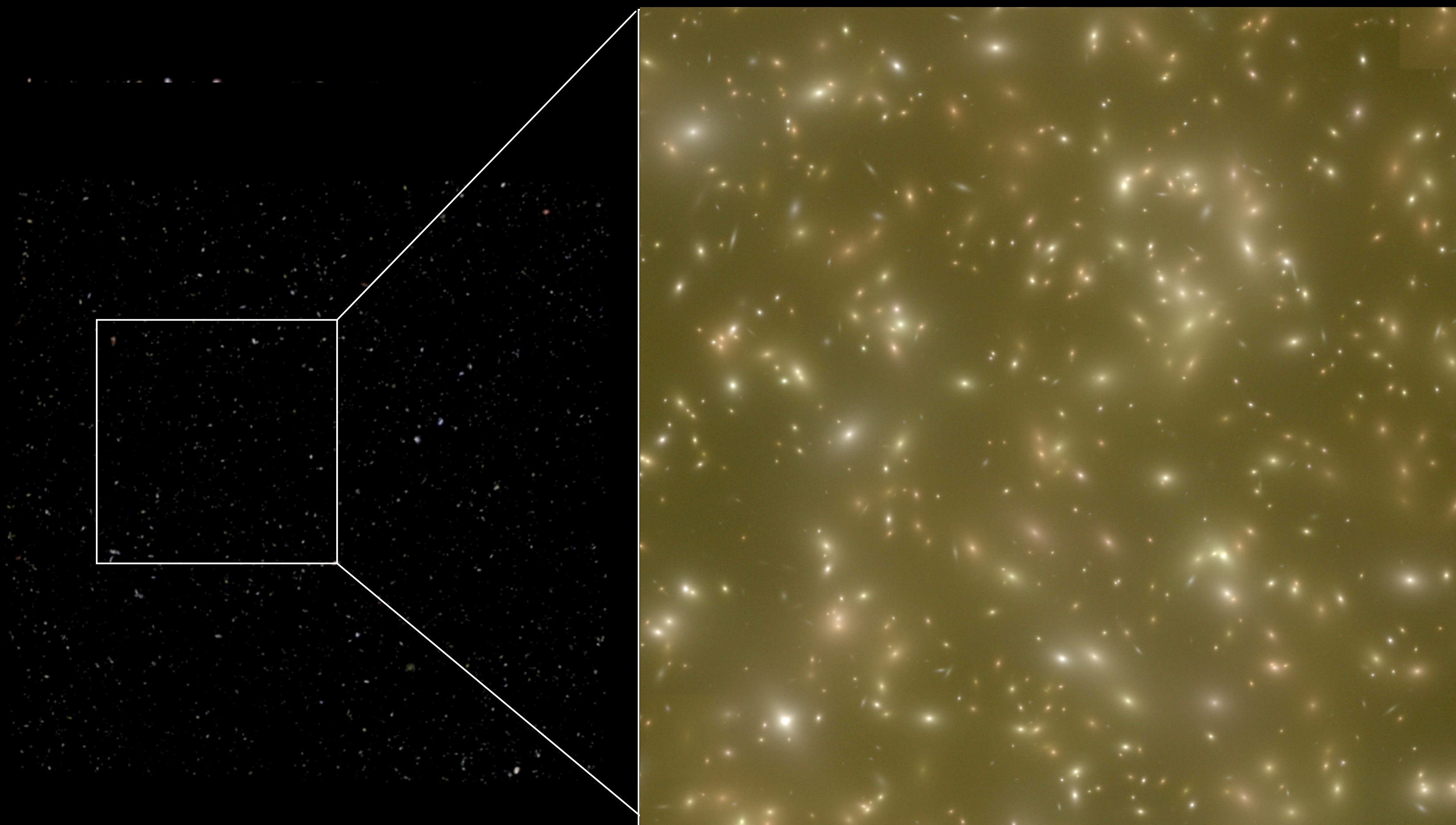
2.2



1.1

The earliest galaxies are faint and small: unraveling high z universe beyond z > 6 challenges HST

Probing the Early Universe in the Infrared with a 6m Space Telescope



z = 1.6 – 6.0

1,000,000 seconds integration with HST

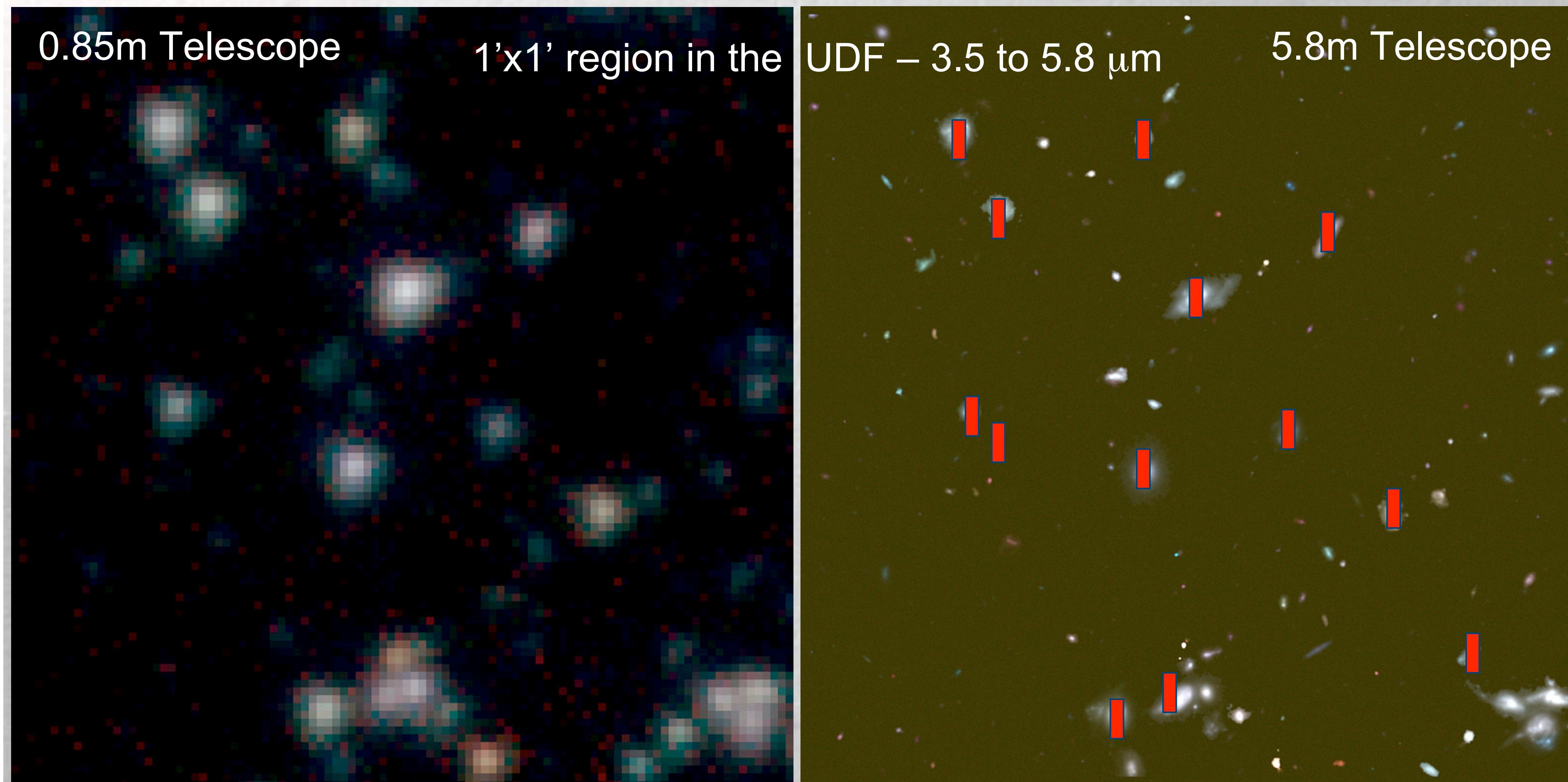
Age = > 7 Byrs 7 - 4 Byrs 4 - 1 Byrs

z = 1.6 – 6.0 JWST simulation, 10,000 seconds per infrared band, 2.2µm, 3.5µm, 5.8µm

JWST-Spitzer Space Telescope image comparison

Spitzer, 25 hour per IR band

JWST, 1000s per band (simulated)

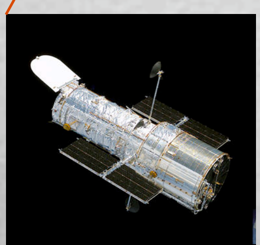


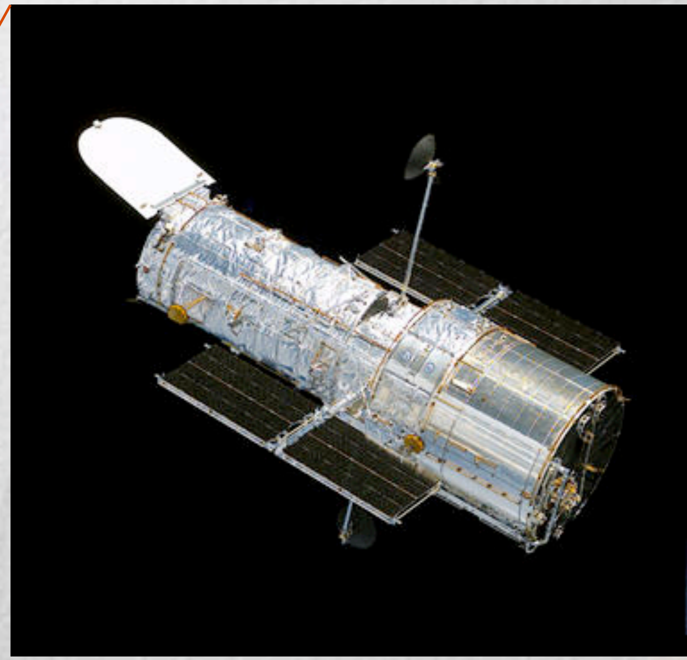
Sensitivity *and* resolution required to probe the early Universe

Time to reach given S/N ~ $1/D^4$

6.5m James Webb Space Telescope

Building more powerful telescopes than Hubble takes more than simple scaling





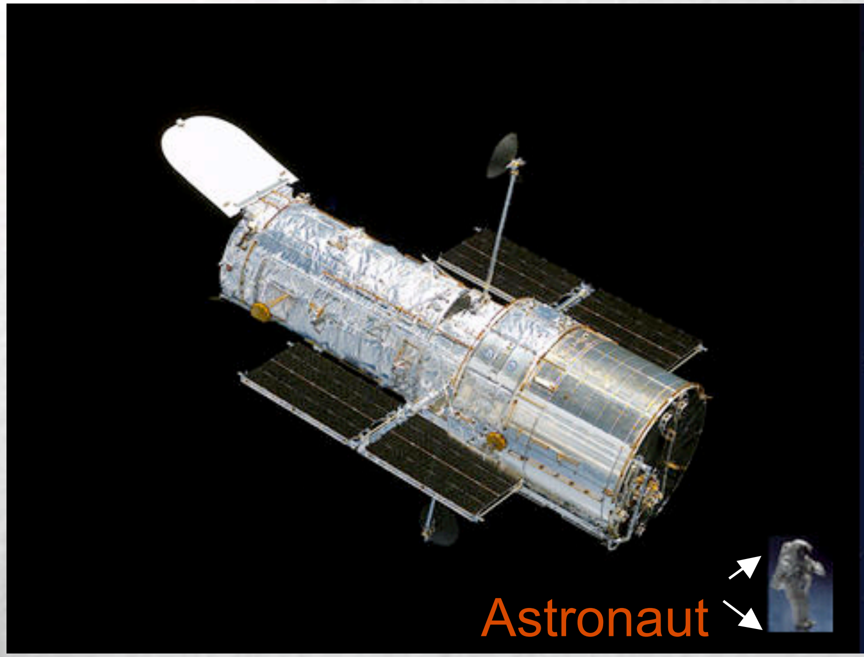
Hubble
2.4 m primary
12 tons

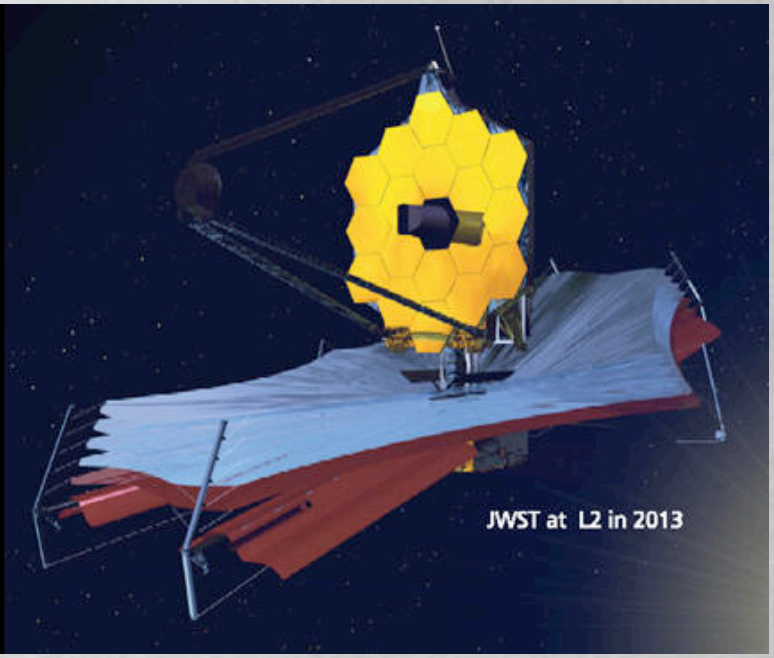
Beyond Hubble
6.5 m primary
~150 tons
(scales like $D^{2.5}$)

Skylab
Saturn V Launch
~100 tons

Courtesy Peter Stockman, STScI

The James Webb & Hubble to same scale





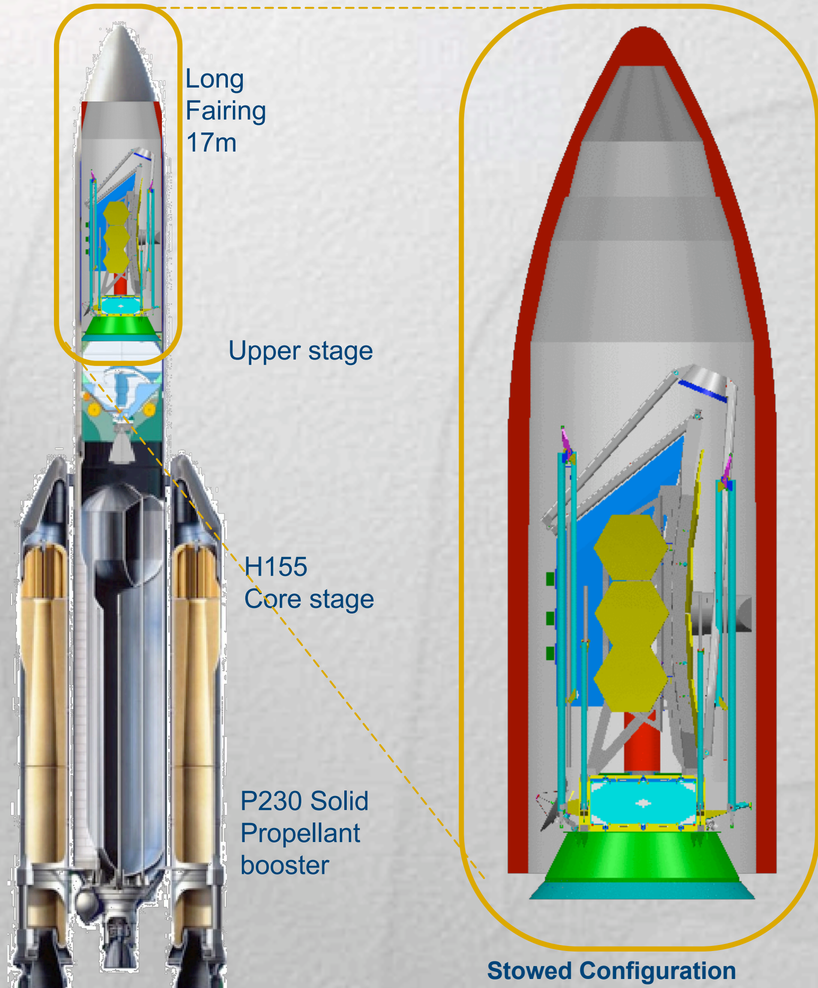
JWST is 7 tons and fits inside an Ariane V shroud

This remarkable feat is enabled by:

- Ultra-lightweight optics (~25 kg/m^2)
- Deployed, segmented, actively controlled primary
- Multi-layered, deployed sunshade
- *L2 Orbit allowing open design/passive cooling*

Courtesy Peter Stockman, STScI

JWST Launch Configuration

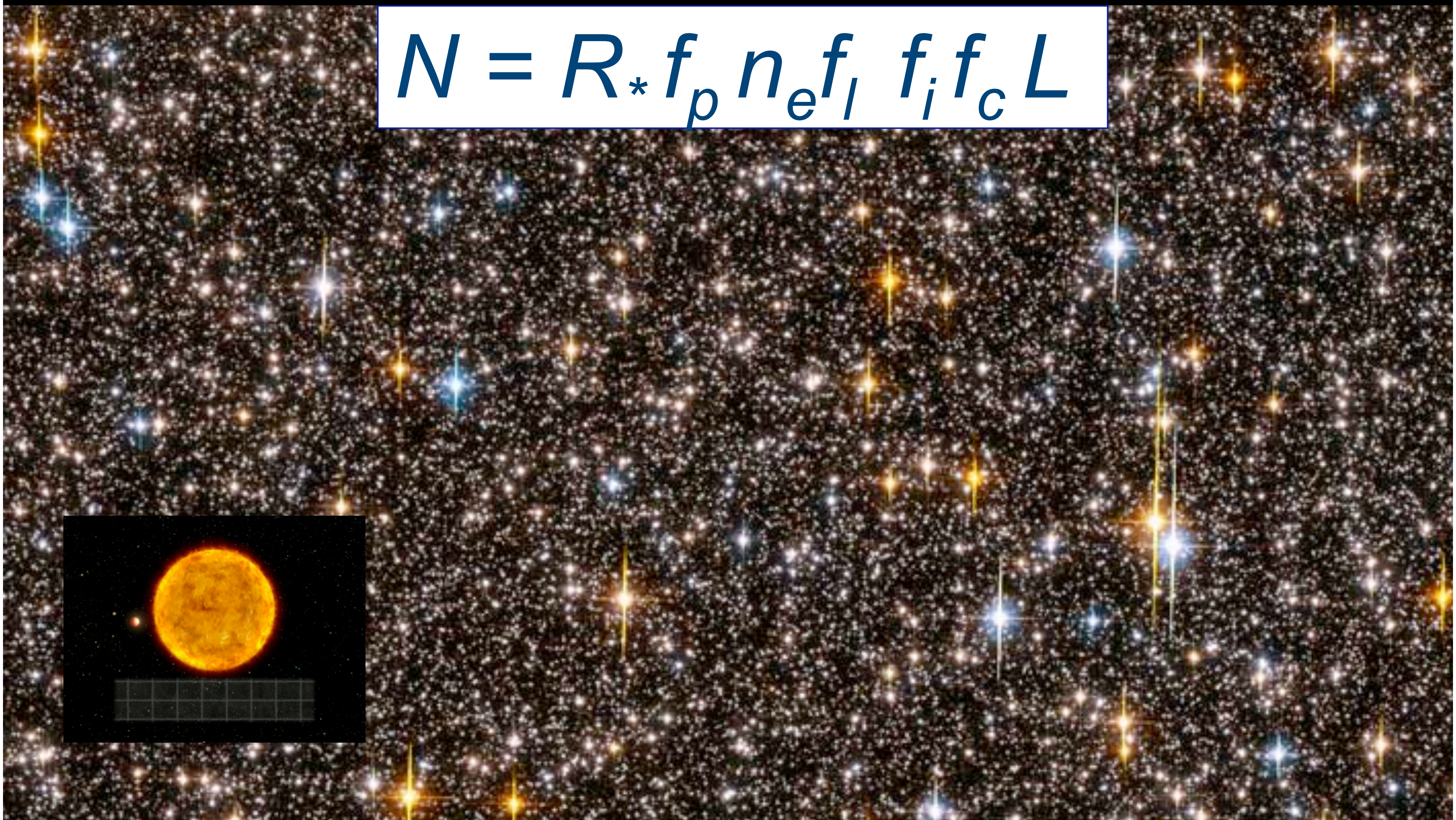


- JWST is folded into stowed position to fit into the payload fairing of the Ariane V launch vehicle

Astrophysics in 2020^+

A new frontier: The Drake Equation?

$$N = R_* f_p n_e f_l \; f_i f_c L$$



Preliminary observations of planet system density implies > 10^8 systems in our Galaxy

The Drake Equation?

$$N = R_* f_p n_e f_l f_i f_c L$$

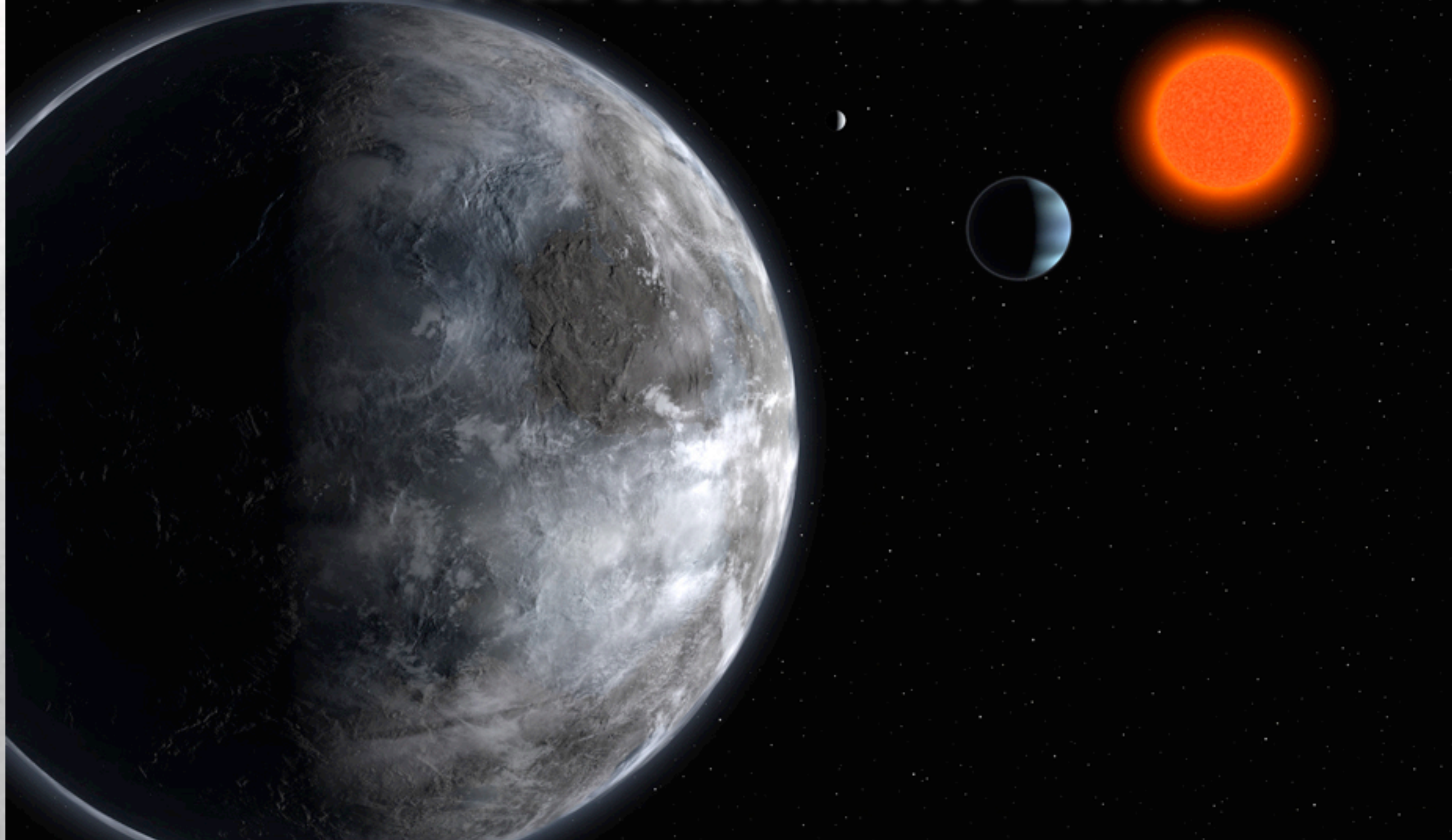
Observable Drake Equation *- after Reid & Hawley*

$N_{L,T}$ is the number of life bearing planets at time T

$$N_{L,T} = N_{*,T} p_p n_e p_w p_l$$

		Observable
Number of stars @ T:	$N_{*,T} = SRF(t) * \Psi(m) * \Lambda(m,t)$	✓
Prob. of planet system:	$p_p = f(Z, m)$	✓
No. of terrestrial planets	$n_e = n\ (0.1 m_e < m_p < 10\ m_e)$	✓
Prob. of liquid water	$p_w = f(\bar{n}_b, \varepsilon, r_{orbit}, L_*)$	✓
Prob. of life	p_l	?

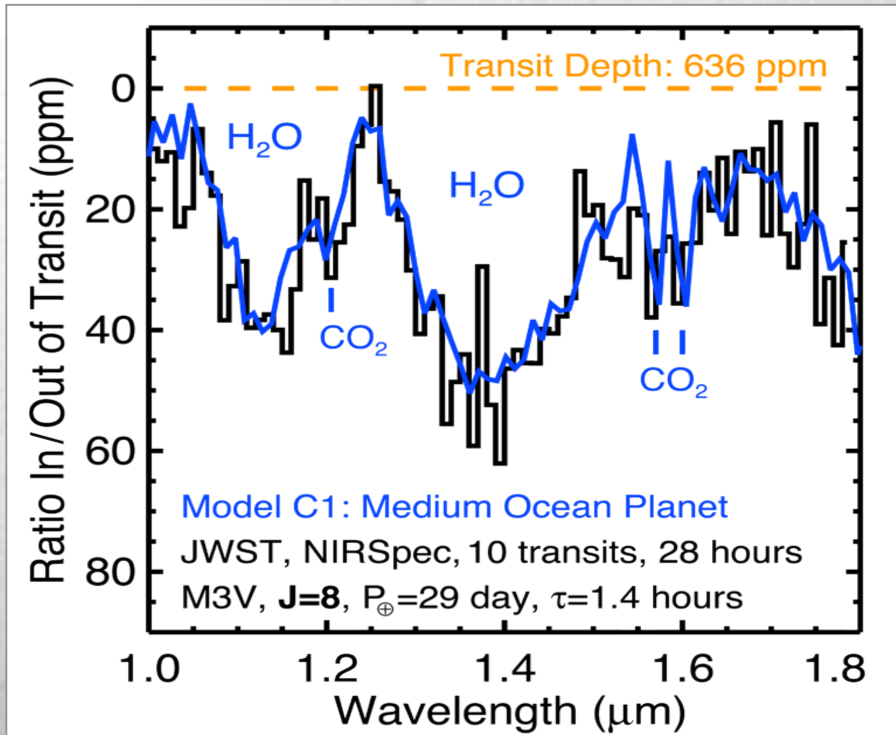
Astronomers Find First Earth-like Planet in Habitable Zone

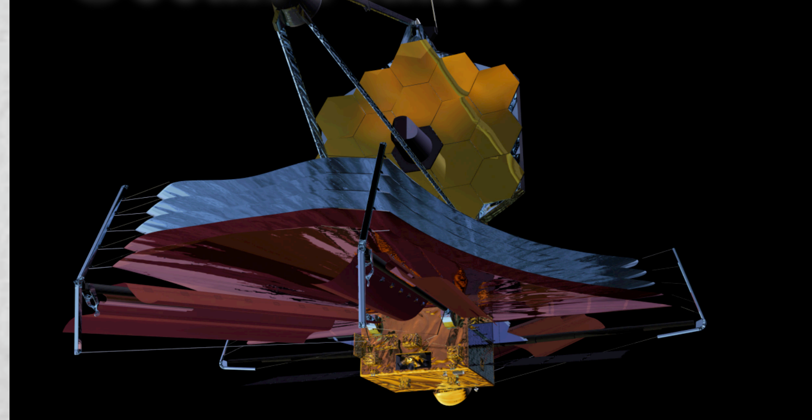


The Planetary System in Gliese 581
(Artist's Impression)

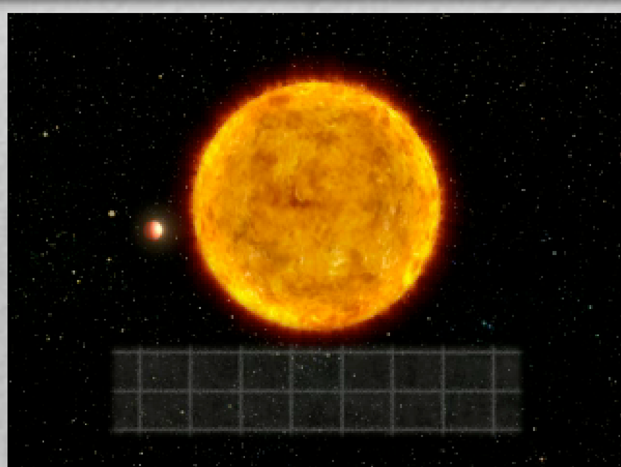
ESO Press Photo 22a/07 (25 April 2007)

Transcrit Spectra of a Habitable Ocean Planet



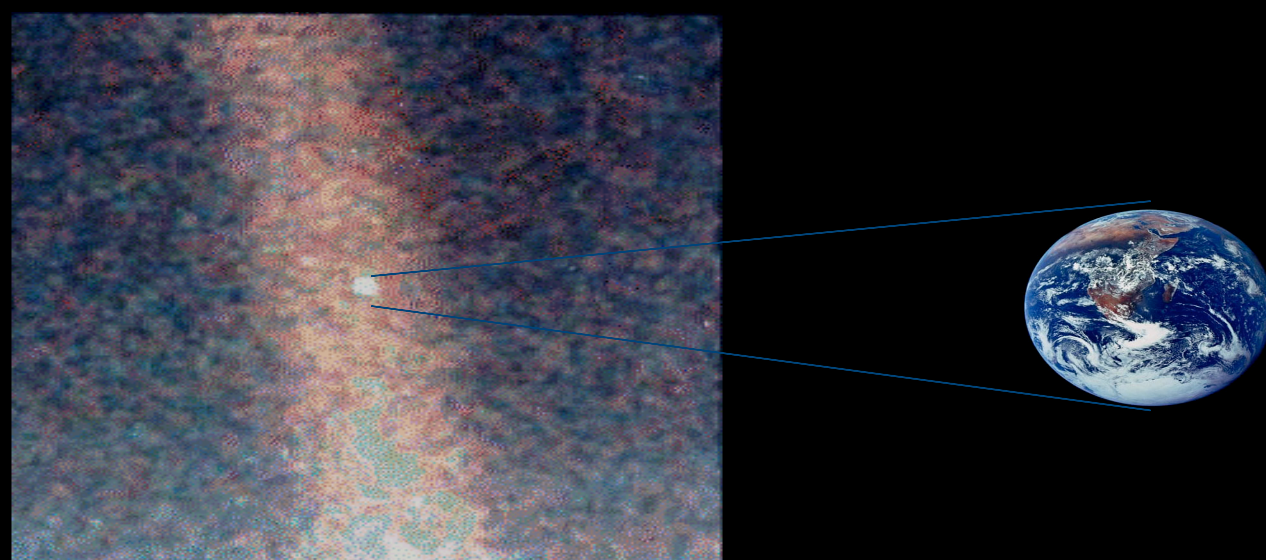


- JWST may detect water



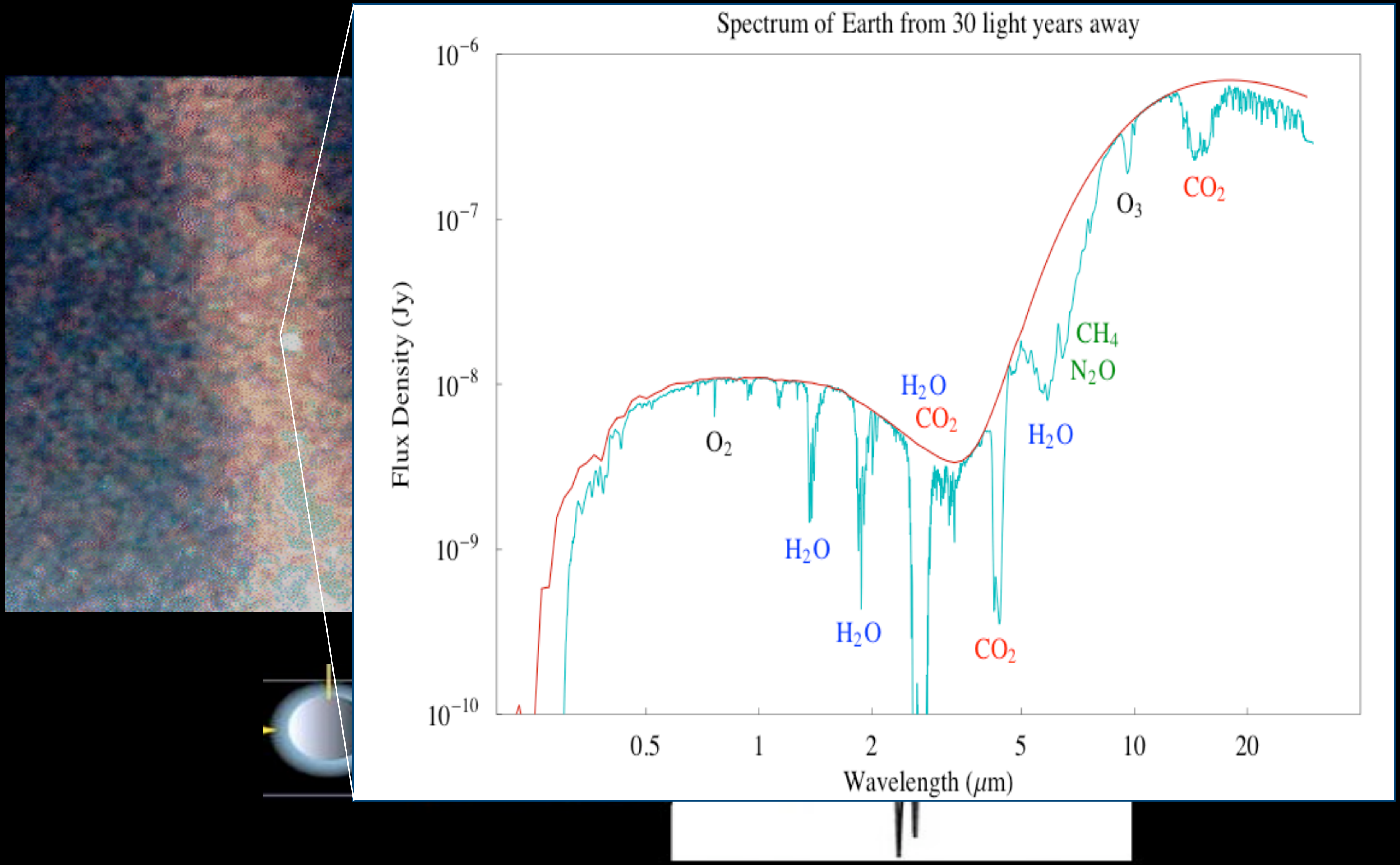
- Gliese 581 (M3V, J=6.7)
  - b: 5.4 days, 15.6 $M_\oplus$
  - c: 12.9 days, 5.1 $M_\oplus$
  - d: 83.4 days, 8.3 $M_\oplus$
- Find one that transits…
  - 6000 M dwarfs with J<10
  - Habitable → 11% transit
  - Up to 70 transits for J<10

A journey to one of the Frontiers

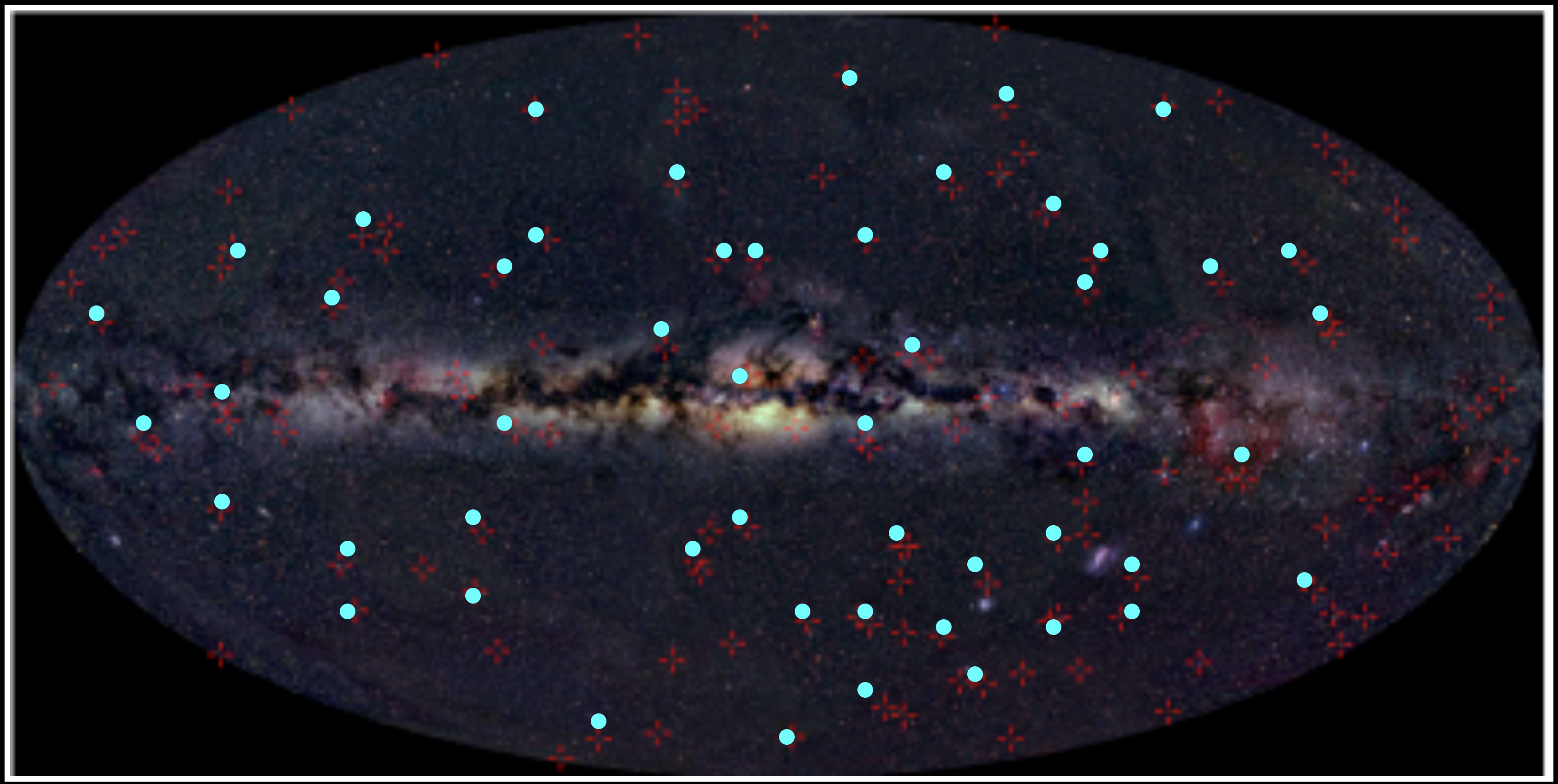


- Is there life on this planet?

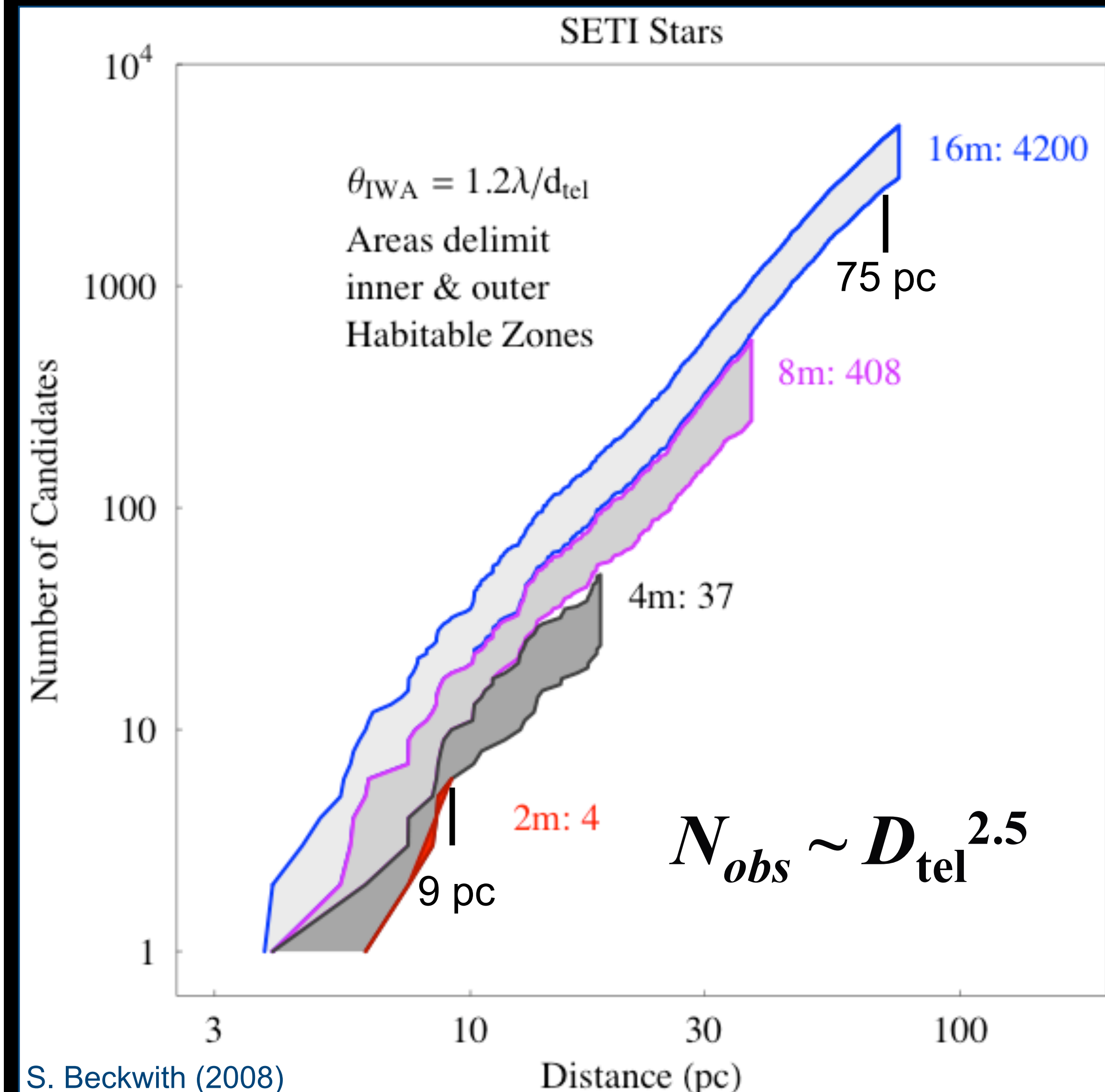
A journey to one of the Frontiers

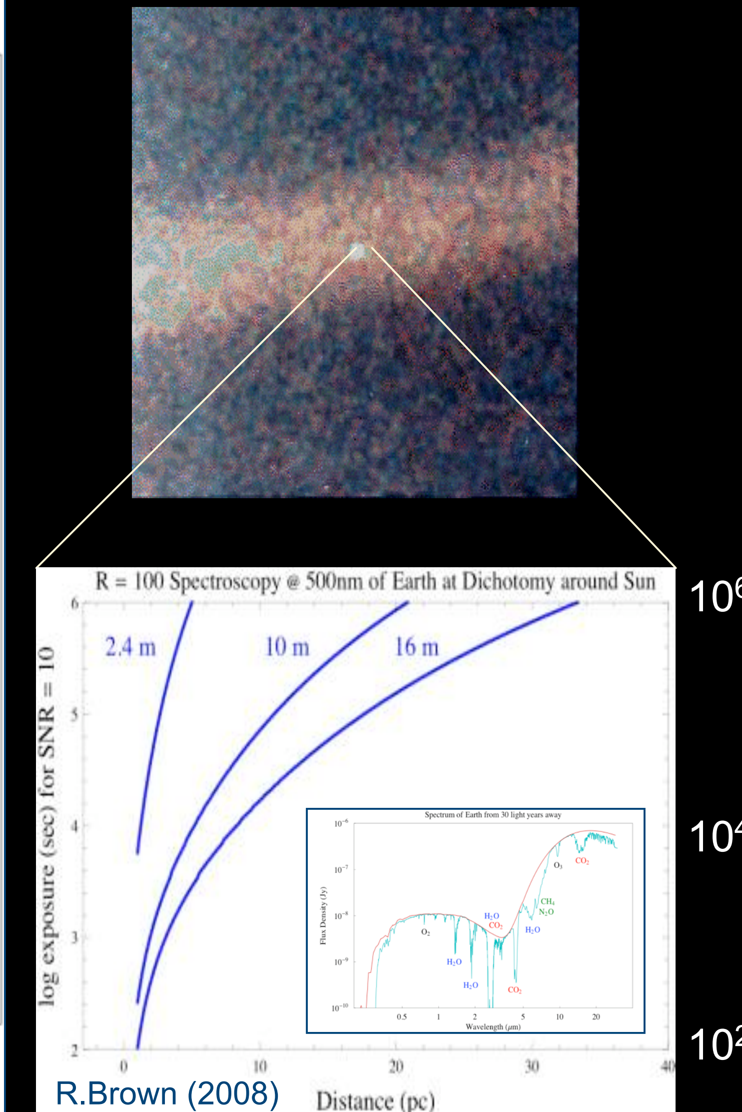


136 most favorable nearby stars for HZ planets



Measuring Exo-Planet Atmospheres from Space as a function of Telescope Size



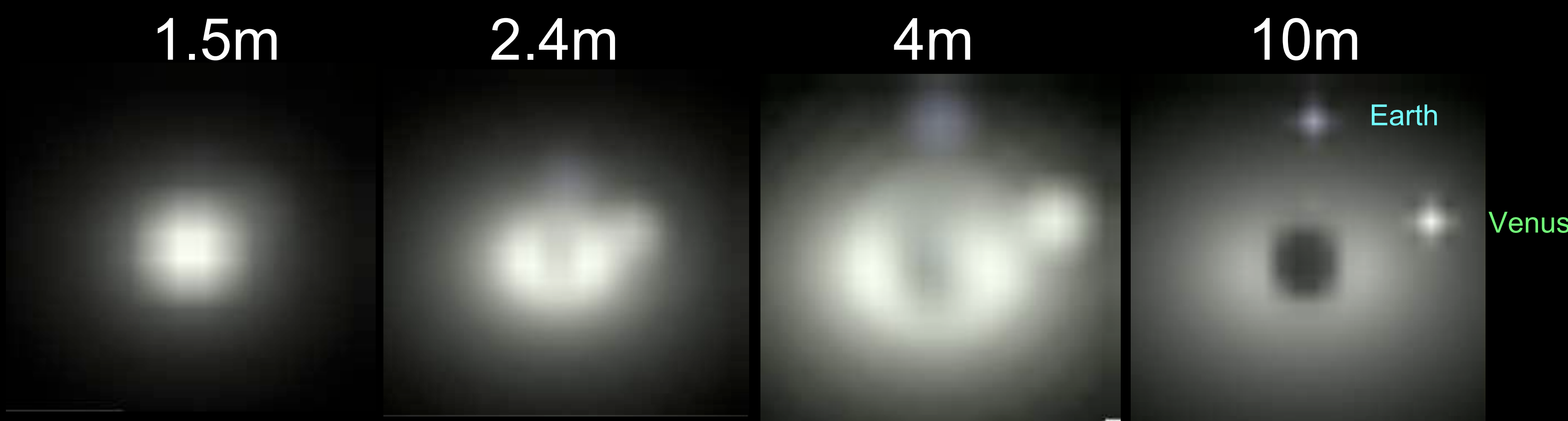


Number vs Distance

Time vs Distance.

Characterizing Exoplanets from Space

Credit: Web Cash 2008

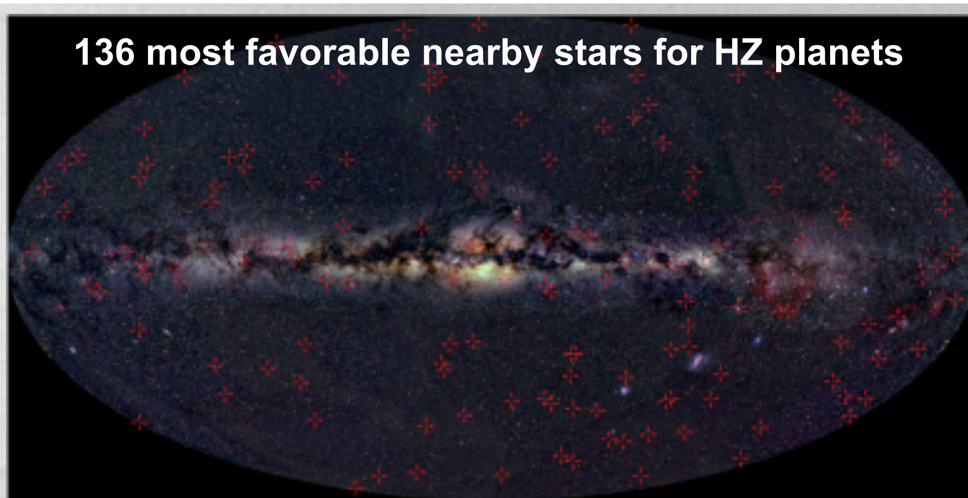


Above: a simulation of our solar system at a distance of 10 pc observed with an external occulter and a telescope with the indicated aperture size. The two planets are Earth and Venus.

Discriminating and characterizing terrestrial scale planets requires angular resolution *and* sensitivity

Courtesy ATLAST Team

How big a telescope do we need to solve the Observable Drake Equation?



$$N_{L,T} = N_{*,T}\, p_p\, n_e\, p_w\; p_l$$

Observable

Number of stars @ T:	$N_{*,T} = SRF(t) * \Psi(m) * \Lambda(m,t)$	✓
Prob. of planet system:	$p_p = f(Z, m)$	✓
No. of terrestrial planets	$n_e = n\,(0.1 m_e < m_p < 10\, m_e)$	✓
Prob. of liquid water	$p_w = f(\bar{n}_b, \varepsilon, r_{orbit}, L_*)$	✓

$$N_{L,T} = N_{*,Observed} \cdot \eta_{\,earth} \cdot\; p_l$$

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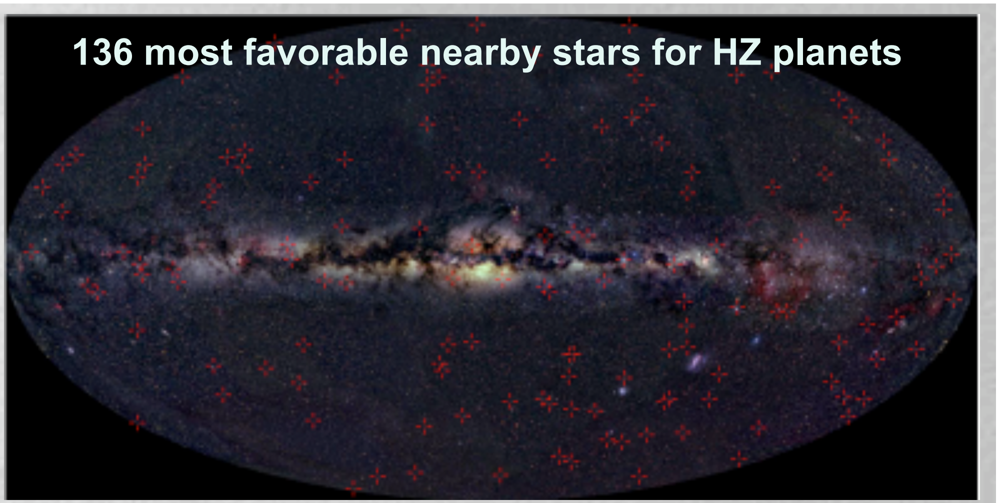
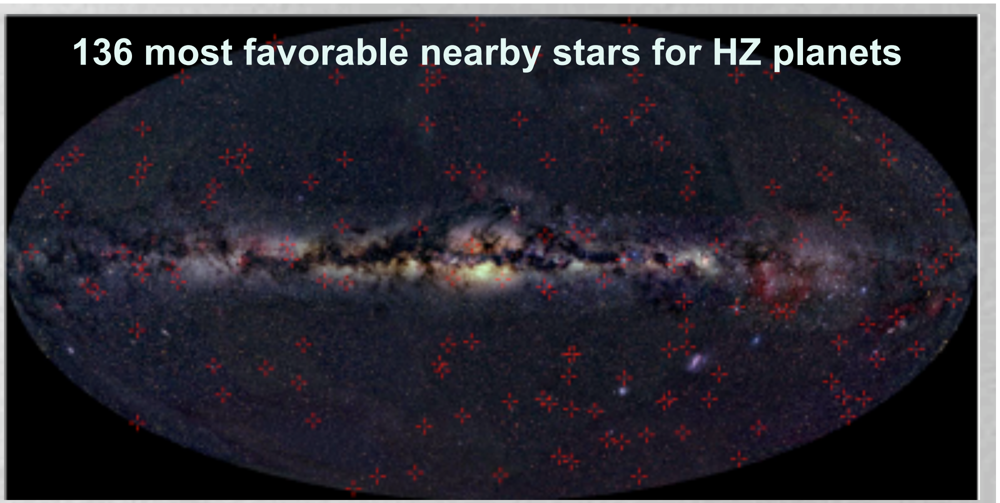


$$N_{L,t} \sim D_{Tel}^{\;2.5} \cdot \eta_{\,earth} \cdot \; p_L$$

EXOPLANET HOST STAR SAMPLE SIZE vs. TELESCOPE DIAMETER (For Realistic Telescope Performance)		
Primary Mirror Diameter (Meters)	# Coronagraphic Candidates	
	All Stellar Types	Solar Type Stars
2	4	0
4	35	13
8	280	101
16	2240	1417

From Beckwith 2008

How big a telescope do we need to solve the Observable Drake Equation?



$$N_{L,t} \sim D_{Tel}^{\ 2.5} \cdot \eta_{\ earth} \cdot \ p_L$$

If: $p_L * \eta_{\ earth} \sim 1$ then $D_{tel} \sim 4m$

$p_L * \eta_{\ earth} < 1$ then $D_{tel} \sim 8m$

$p_L * \eta_{\ earth} << 1$ then $D_{tel} \sim 16m$

Multi-wavelength Angular Resolution

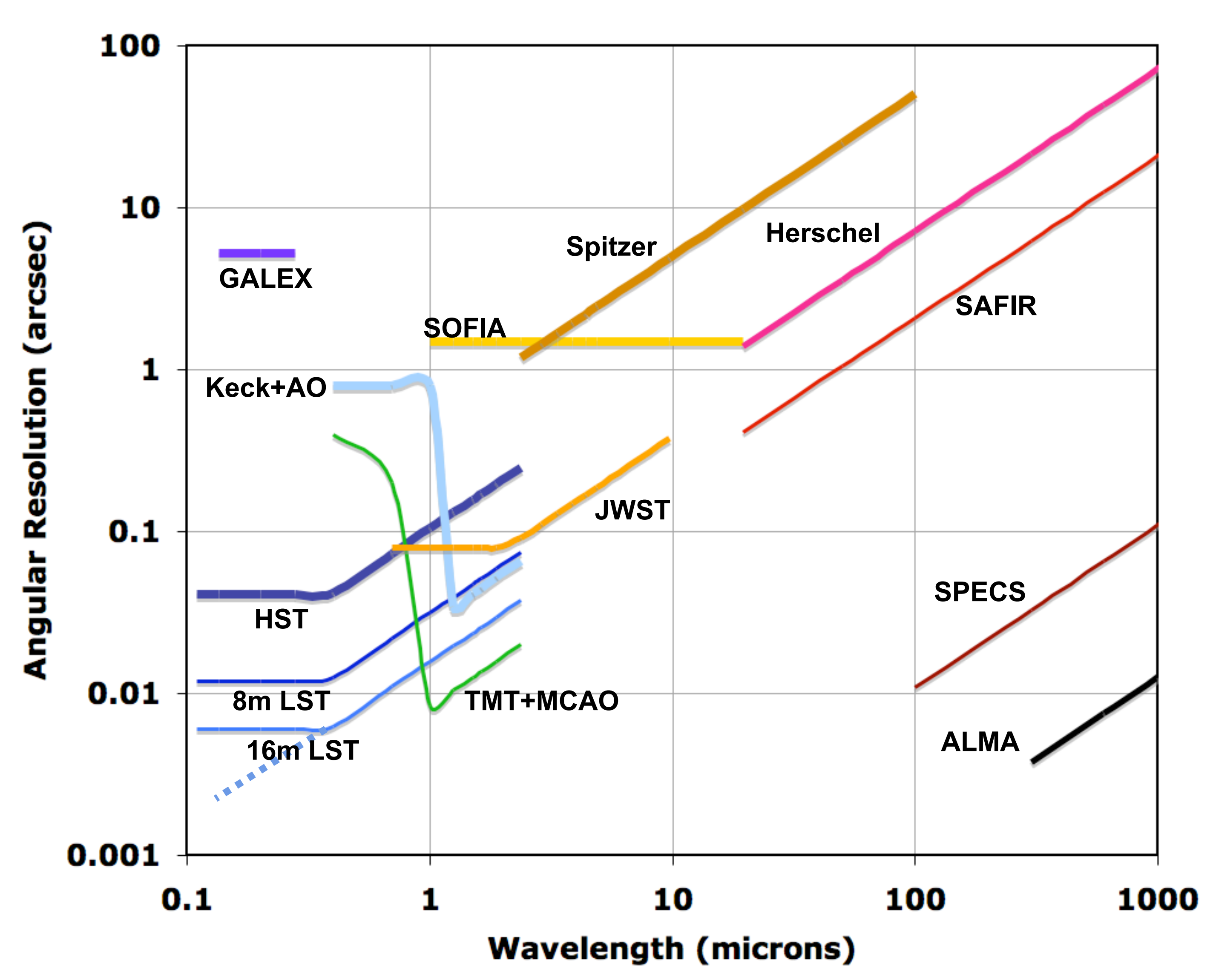
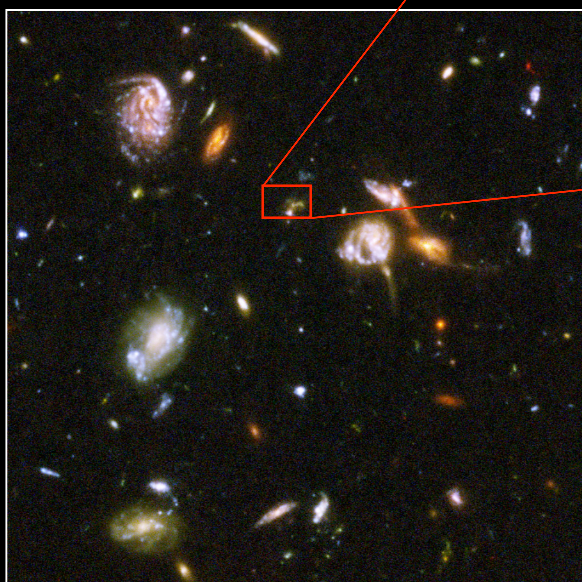


Figure derived from ExoPTF (Lunine et al. 2008)

“Modern” Galaxy Evolution



HST Ultra Deep Field

Faint Galaxy:

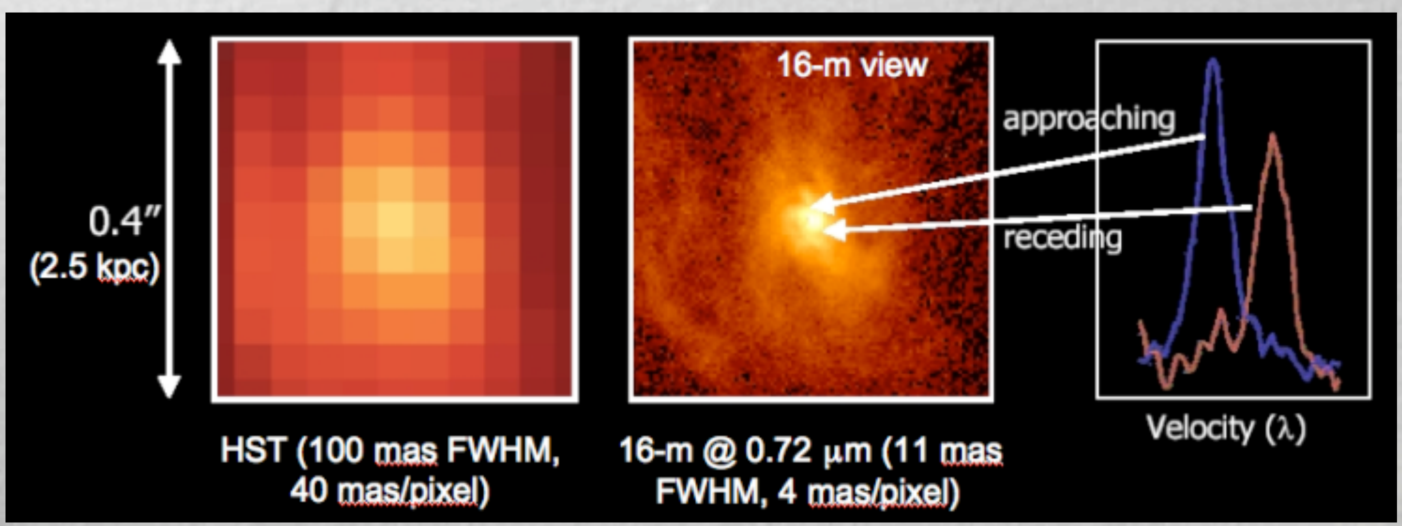
- 25.1 AB mag (330 nJy) in I-band
- 0.75 arc seconds across
- 2 “peaks” in light distribution
- Morphology unknown

Angular Resolution and Sensitivity enables new science

Probing Super Massive Black Holes Across Cosmic Time

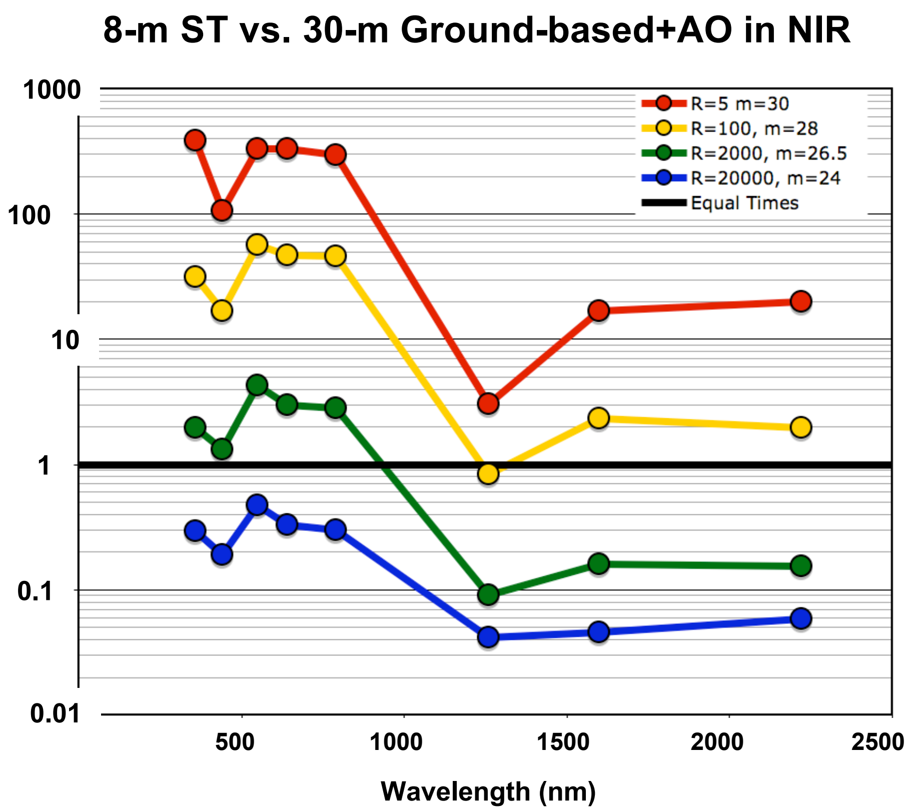
Courtesy A.Koekemoer

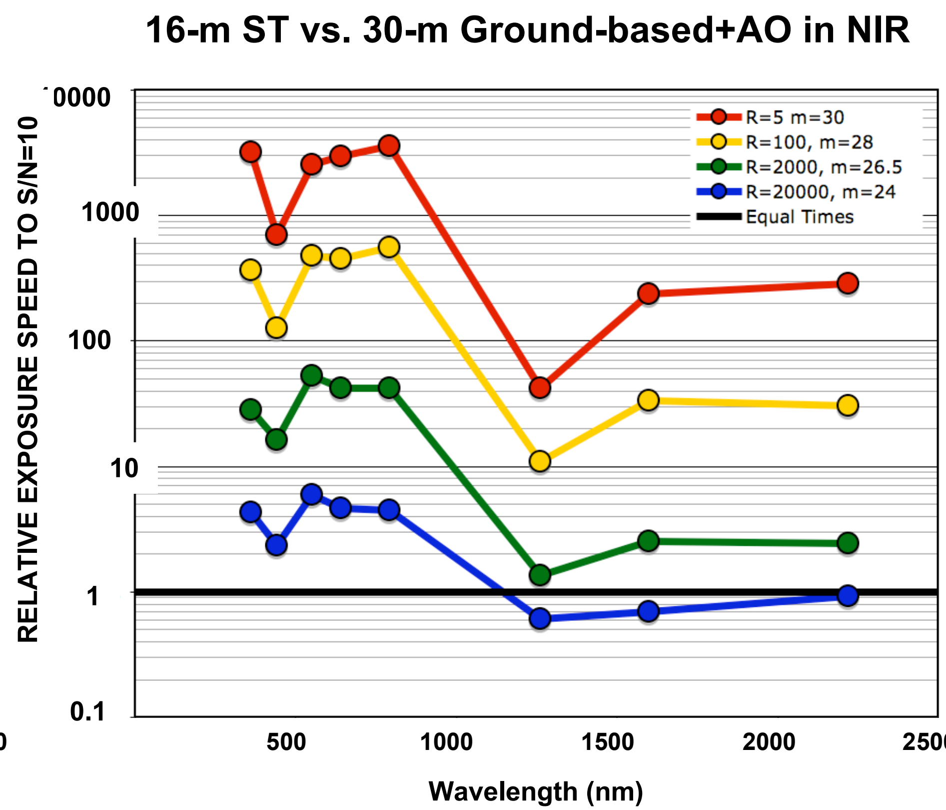
SMBH Candidates vs. Telescope Aperture		
D_{TEL} (meters)	Highest z at which 100 pc can be resolved in UV/Opt	Number of SMBH Candidates
2	0.06	10
4	0.10	50
8	0.36	1,740
16	7.00	43,500



Shown above is a galactic nuclear disk of radius 190 parsecs (30 mas) at redshift 5, observed in rest-frame Lyα emission. This figure is based on a real image of a gas disk around a supermassive black hole in a nearby active galaxy, placed at redshift 5 and scaled appropriately.

Time Gain Factor

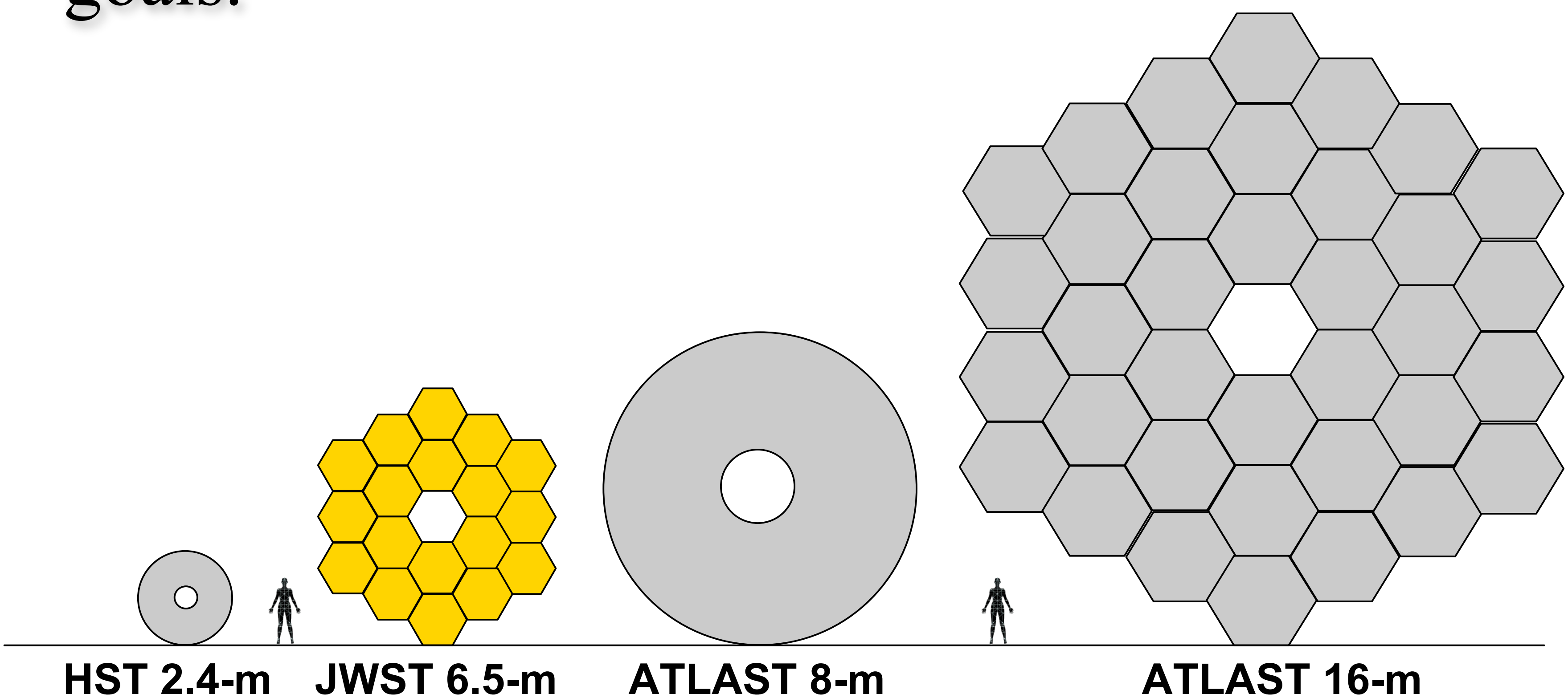




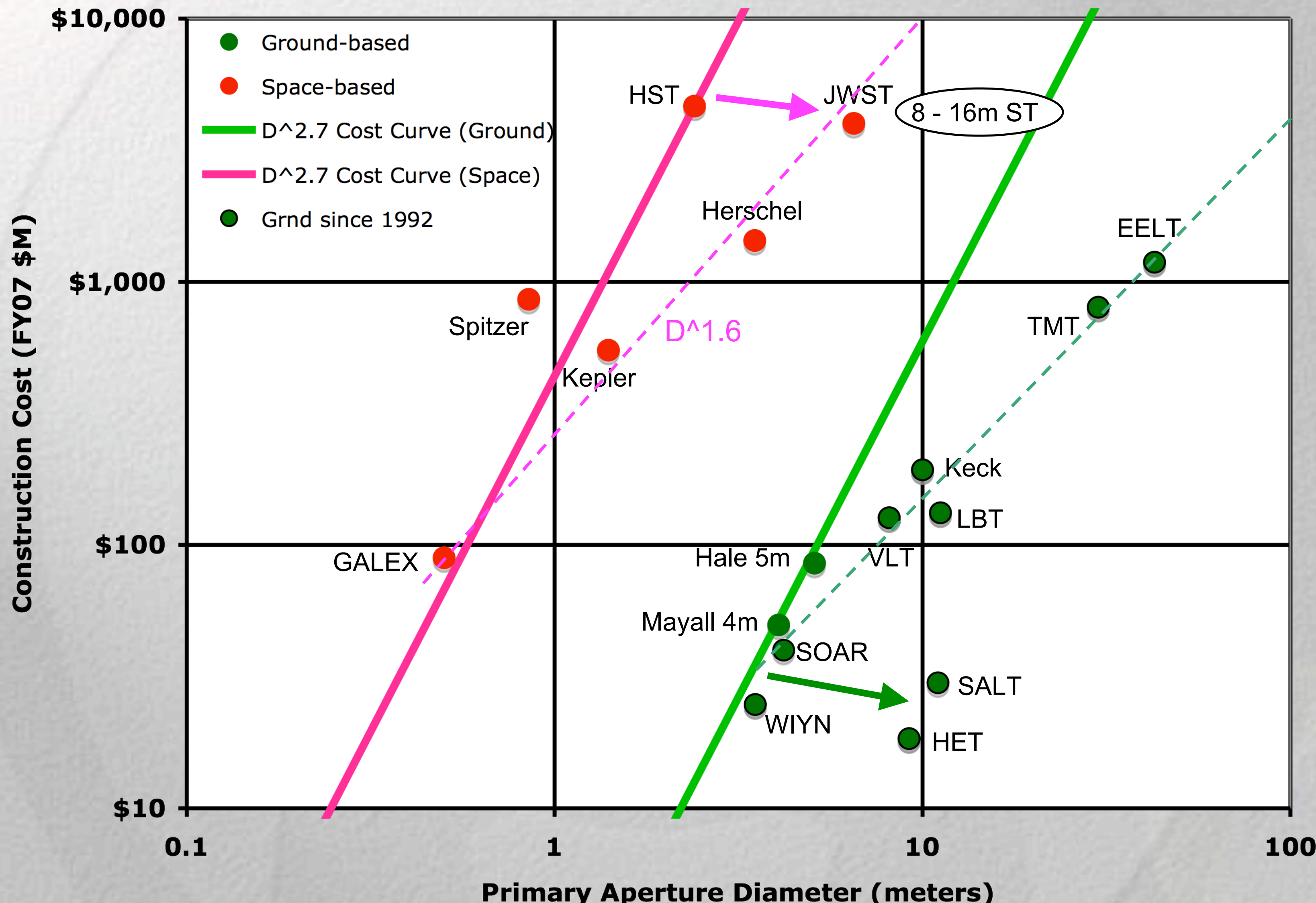
8-m ST faster than 30-m on ground for all imaging and for most R=100 low-res spectroscopy. 8-m also faster for med-resolution spectroscopy in optical band.

16-m ST faster than 30-m on ground for all imaging and spectroscopy except when R > few x 1000 in the NIR. Unique parameter space for hi-res spectroscopy in optical band.

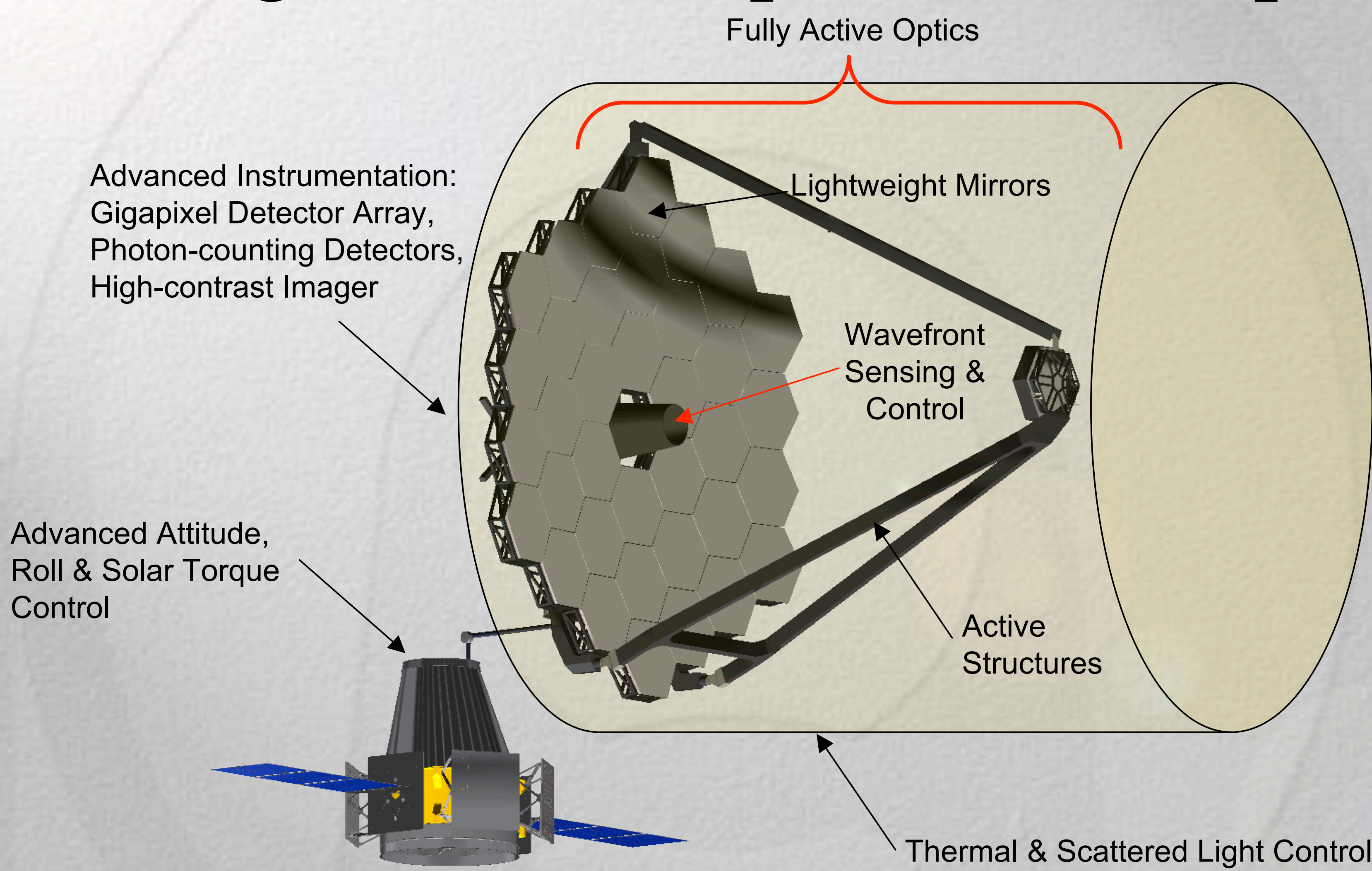
A UV/Optical space telescope with an aperture of at least 8-meters and, for some key problems, closer to 16-meters will be required to achieve a broad range of ambitious scientific goals.



Cost does NOT follow a fixed scaling relation with aperture as technology or architecture advance

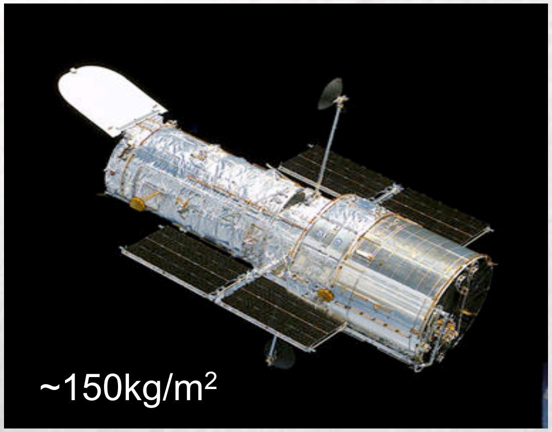


Key Technologies Needed for Large UVOIR Space Telescopes

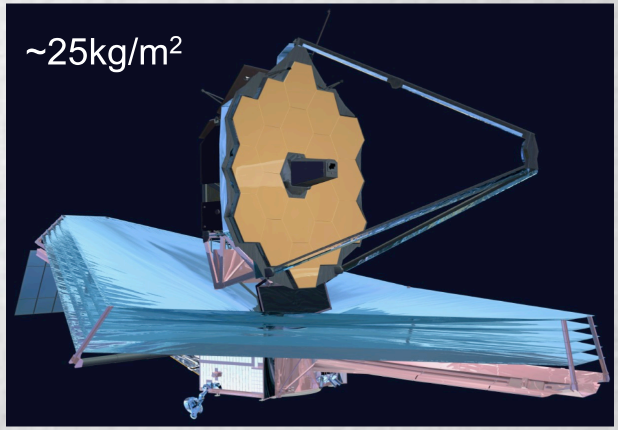


Space Telescope design and control philosophies

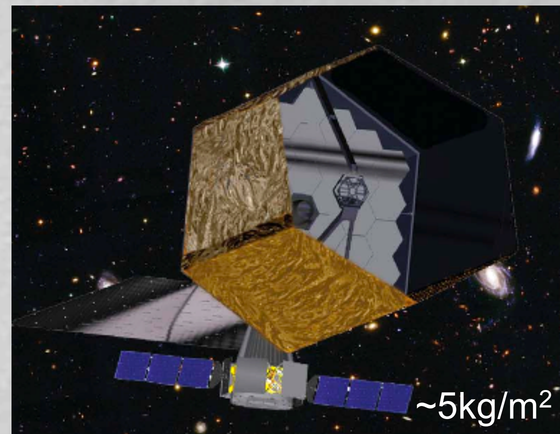
HST 2.4m



JWST 6m



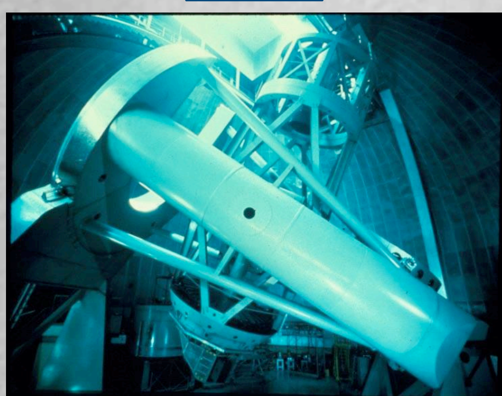
8m~16m LST



Passive control

Active control

Fully active and adaptive control



Palomar 5m

Keck 10m

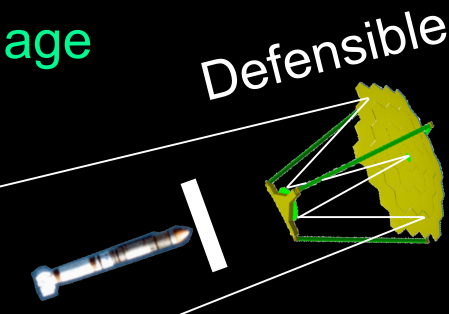
Earth Observations from Space

"How [have] we in astronomy come so far? … By standing on the shoulders of military/industrial giants. … These larger scale efforts have been central to our success. … Where military or industrial support did not exist and we had to go ahead on our own, progress has been much slower."

Martin Harwit,
March 1999

ntinuous coverage
high information / image
e
FOV
km FOV

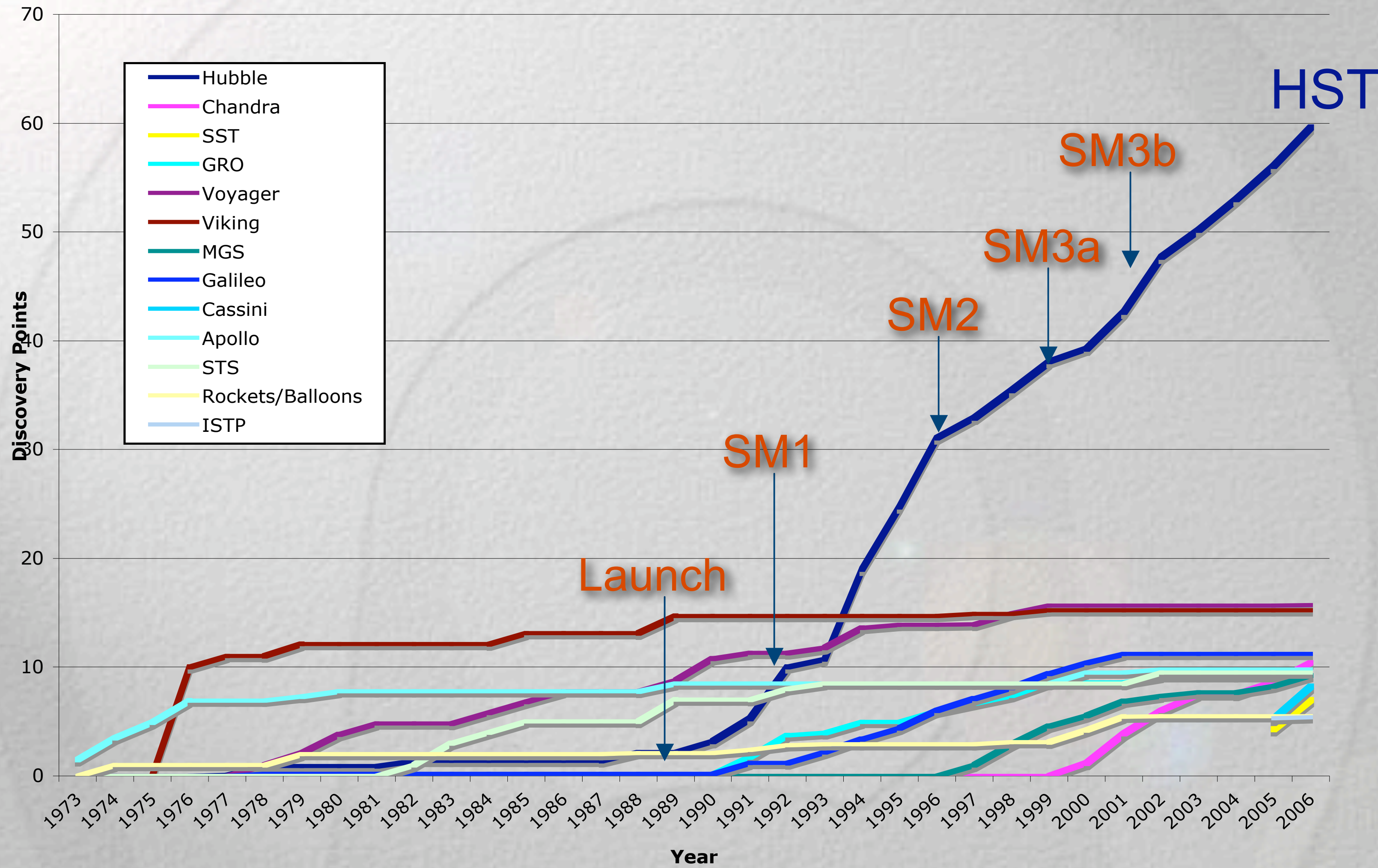
0 μm



- Surveillance: 10 cm (r_0)
  - 41 mas @ LEO: ~2m (KH series)
  - 0.5 mas @ GEO: 160m (0.5 μm)
- Earth Science: 5m
  - 28 mas @ GEO: 7m (1 μm)
  - 7 mas @ Moon: 14m (0.5 μm)

Courtesy S.Beckwith

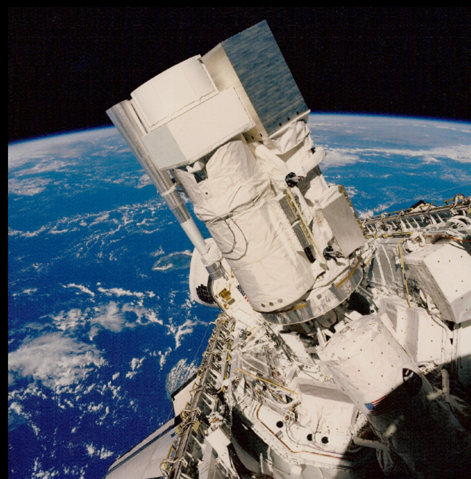
Science News Cumulative Impact of Hubble with each successive Servicing Mission



Servicing has repaired and upgraded the Hubble Space Telescope over the last 18 years -- making it the most productive telescope in History

NASA's Human Exploration Infrastructure Has And Will Continue To Enable UVOIR Astronomy

Past and Present:

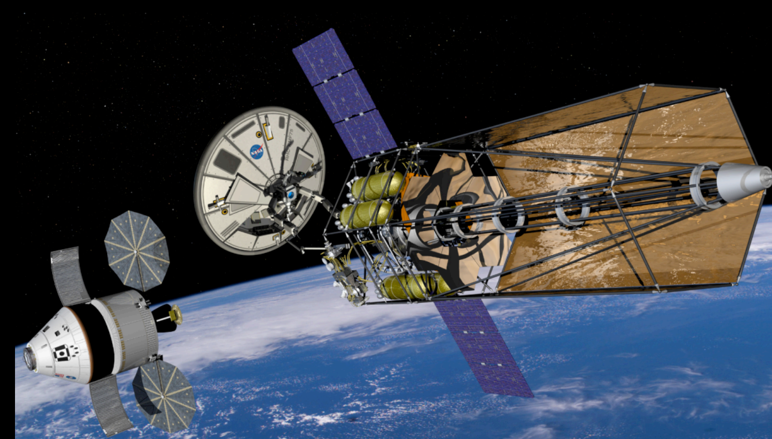


Astro-1 and 2

HST

Future:

Ares V Launch Vehicle: Very Large UVOIR telescope or multiple formation-flying telescopes (e.g., Stellar Imager) deployed in a single launch

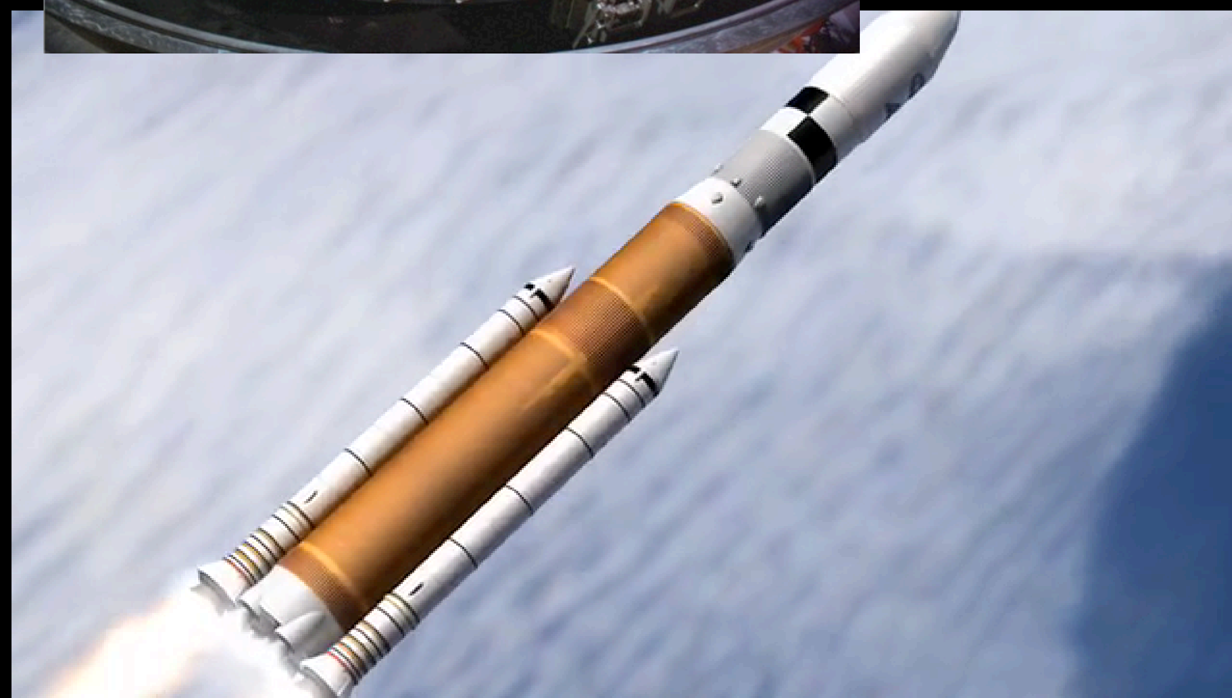


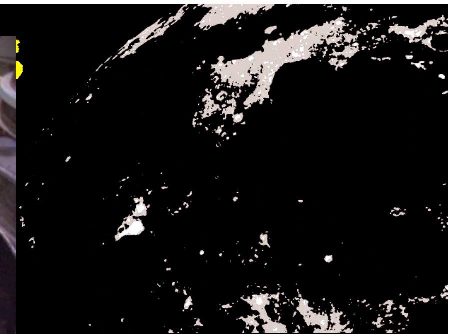
Tele-robotic observatory assembly and servicing in LEO or EM-L1

Ares V enables a new science paradigm:

- to save cost maybe we can optimize the telescope design to simply I&T?

- maybe we can take some risk and rely on adaptive optics technologies to deliver final on-orbit performance?





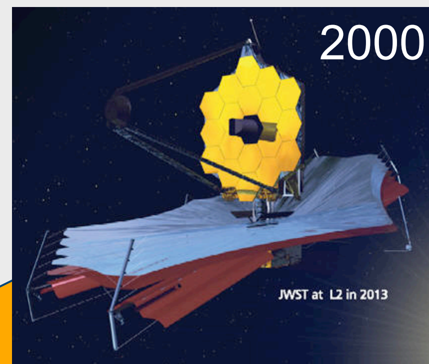
- perhaps we could launch with a simplified science capability and rely on future servicing to upgrade the telescope's scientific performance?

The Challenge

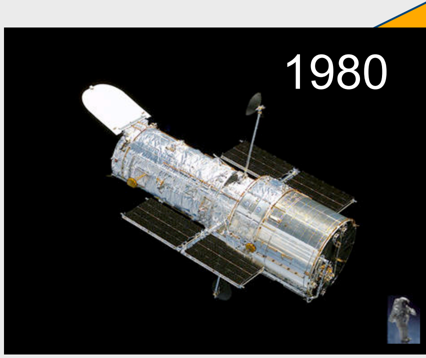
"Incrementalism is innovation's worst enemy. We don't want continuous improvement, we want radical change."
- Sam Walton

2020

16m ~ $4.5B (FY07)



6.5m ~ $4B (FY07)



2.4m ~ $4.5B (FY07)

Summary

- Observational astrophysics remains a photon limited science and hence there is a compelling case for large aperture UV, Optical & Near-infrared space telescopes in the 10m ~ 20m class today
  - We are poised to answer the question, “are we alone” with 10m~20m telescopes in space.

$$\frac{\text{Signal}}{\text{Noise}} \propto \frac{\text{Telescope Diameter}}{\text{Image size}} \times \sqrt{\frac{QE_\lambda}{B_\lambda}}$$

QE = Detector quantum efficiency ~ 100%

Summary

- Observational astrophysics remains a photon limited science and hence there is a compelling case for large aperture UV, Optical & Near-infrared space telescopes in the 10m ~ 20m class today
  - We are poised to answer the question, "are we alone" with 10m~20m telescopes in space.
- To launch large telescopes to orbits such as GEO or L2 will require a new generation of heavy launch vehicles
  - The requirements for such missions can be aligned with NASA's Vision for Space Exploration
- To make such ambitious projects affordable, new and innovative approaches to building and controlling large, light-weight optics and structures in space are required
  - Fully integrated adaptive optics and structures may be one approach
- It will probably be a future requirement that such large telescopes, once in orbit are also deigned to be sufficiently robust that they can be serviced by future space-based assets.