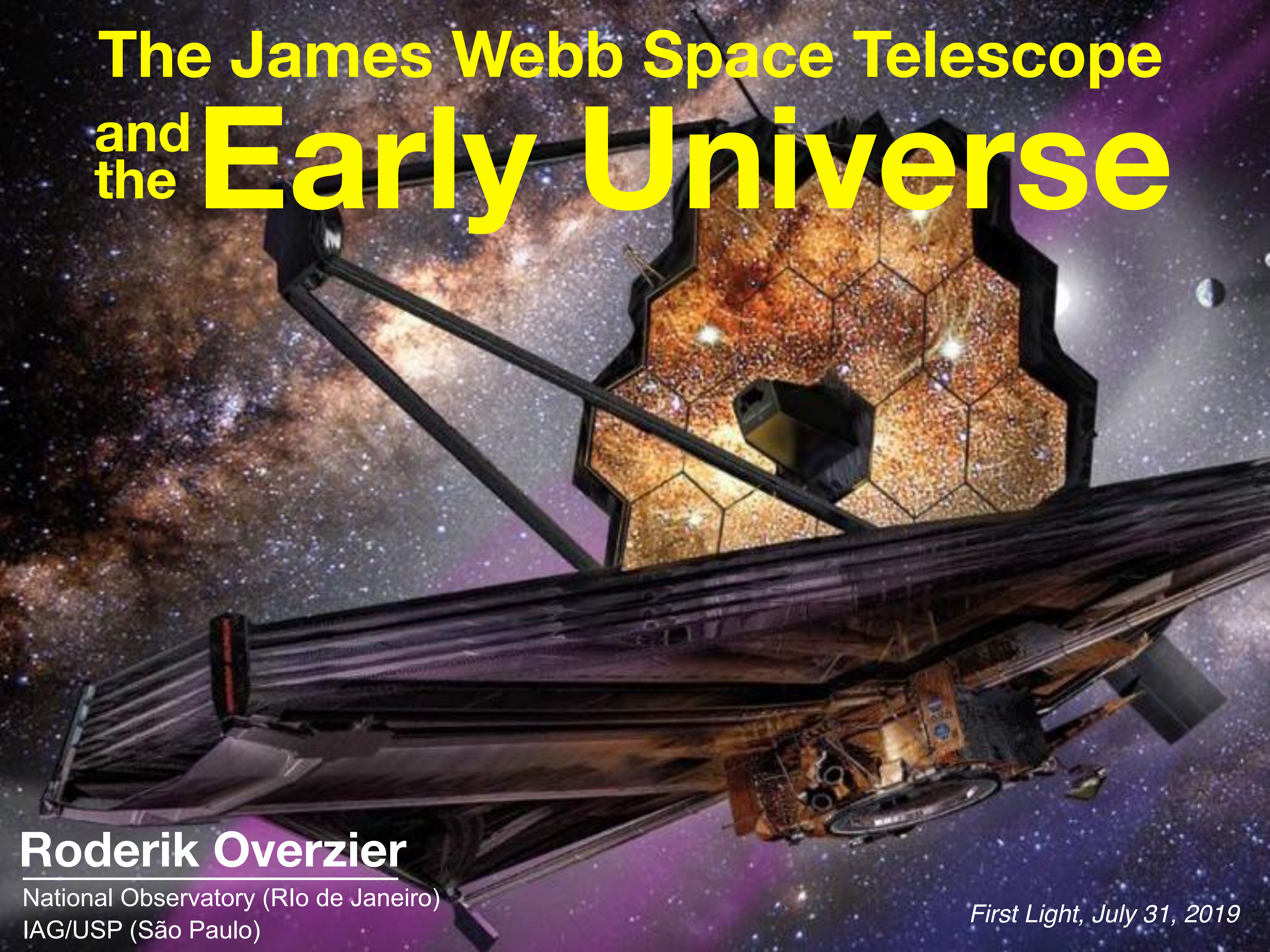
The James Webb Space Telescope and the Early Universe



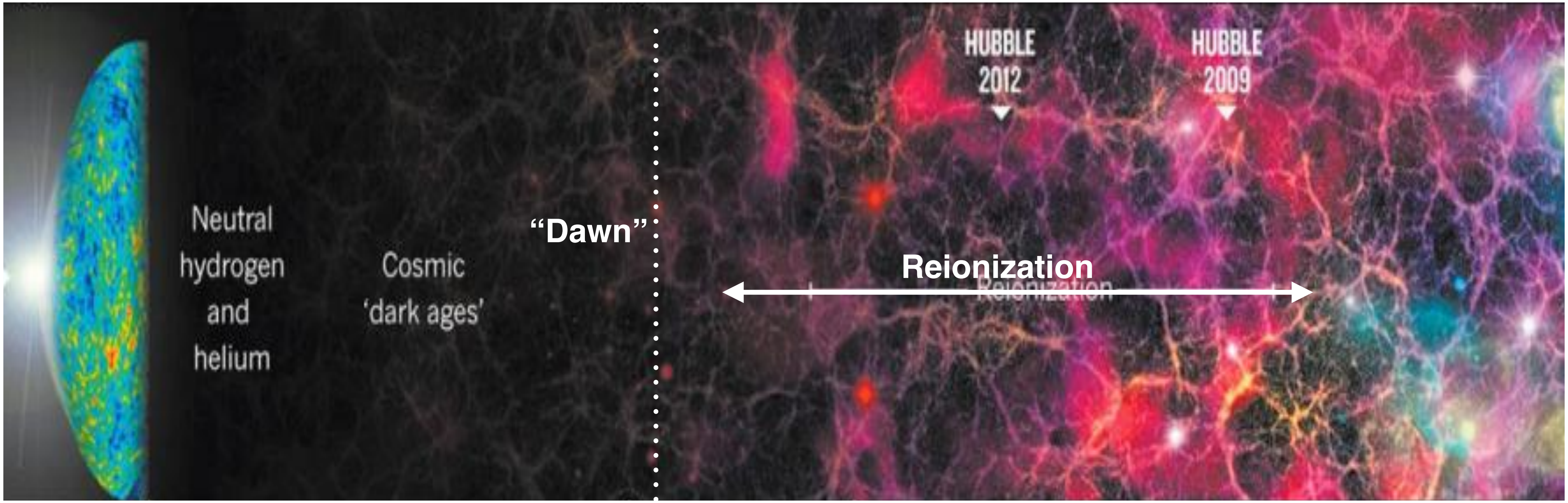
Roderik Overzier

National Observatory (RIo de Janeiro)
IAG/USP (São Paulo)

First Light, July 31, 2019

In the beginning there was… “cosmic dawn”

period during which the IGM transitioned from being completely neutral (“dark ages”) to completely ionized: **“epoch of reionization”** (z~25–5)

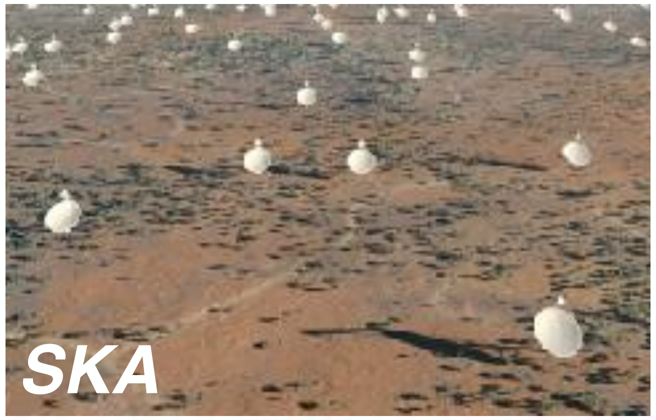


Cosmology set the **rate of growth of structure** (collapsing dark matter, gas cooling, first stars, galaxies and black holes)

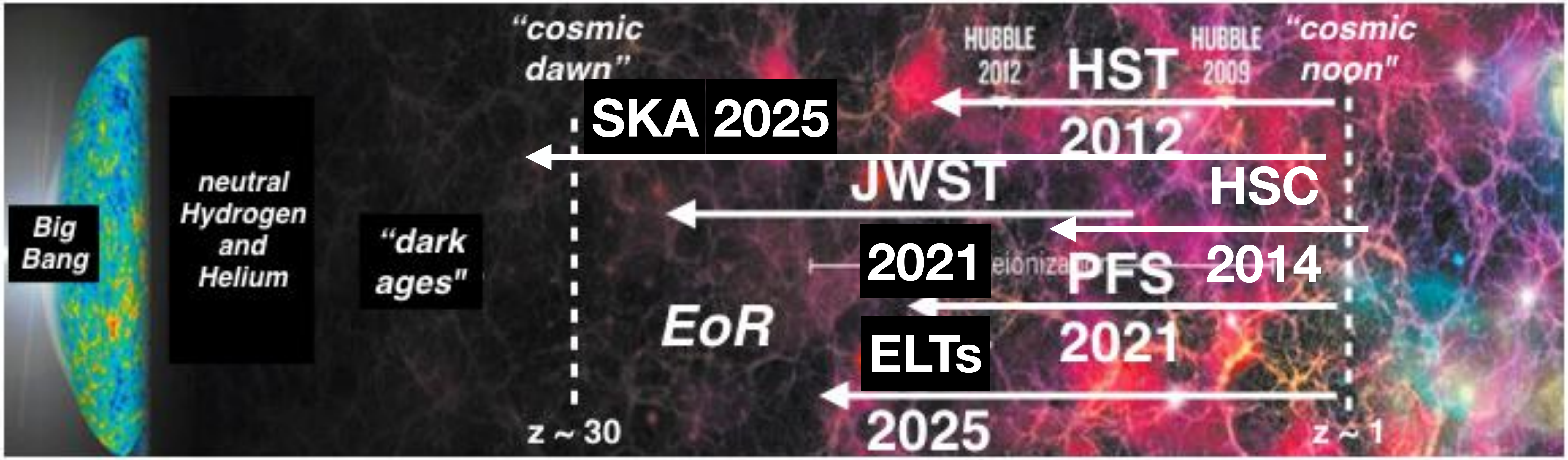
These structures led to a **cosmic burst of star-formation**

This provided a high **rate of hydrogen-ionizing photons**, which **reionized the universe within 1 billion years**

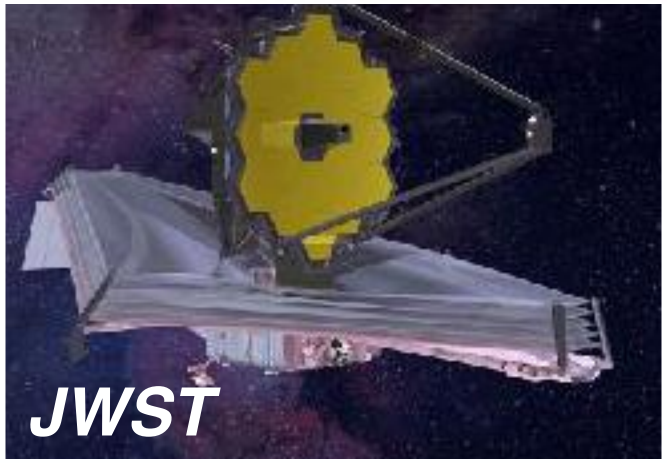
Approaching reionization from two sides



early times: radio arrays can detect **neutral hydrogen at 21 cm × (1+z)**

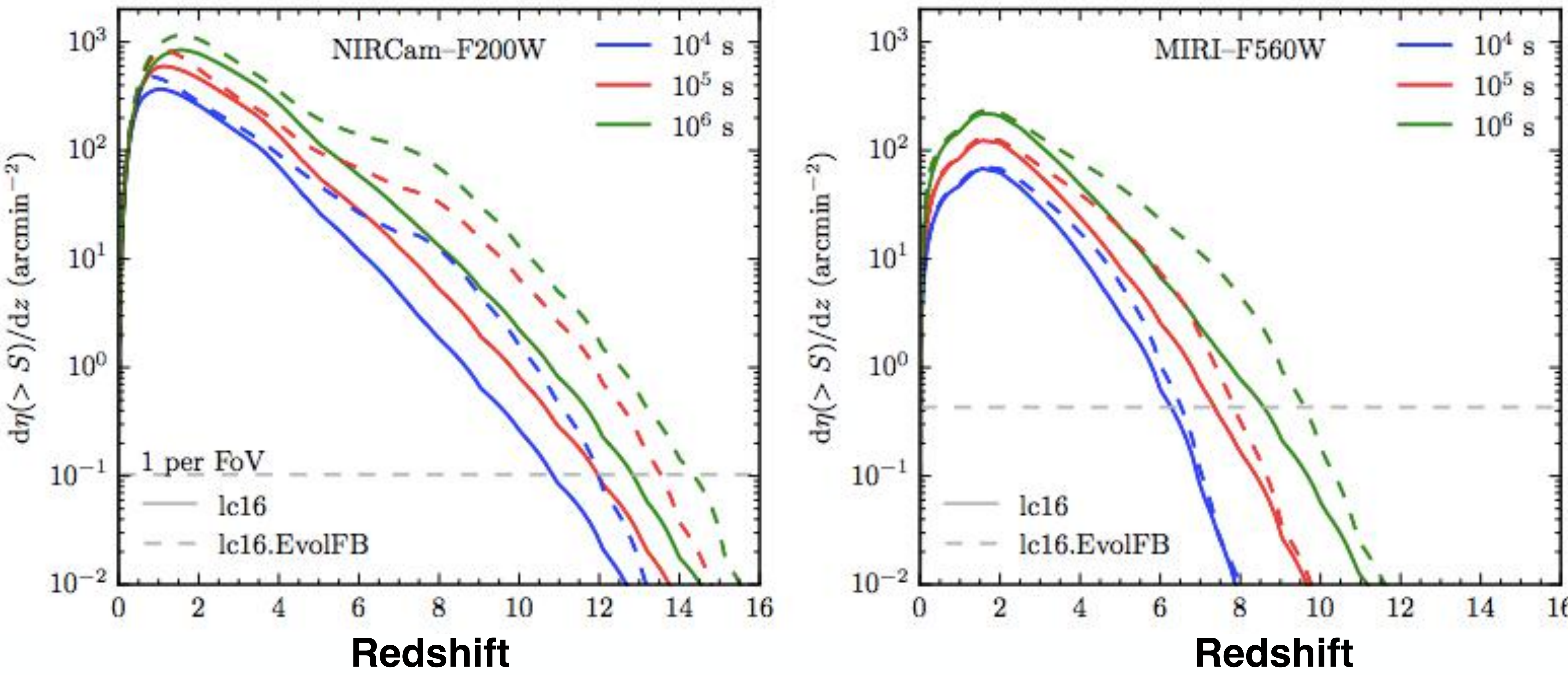


late times: optical/IR telescopes detect the light of the first stars, galaxies, black holes at **~1216 Å × (1+z)**



What will the James Webb Space Telescope see?

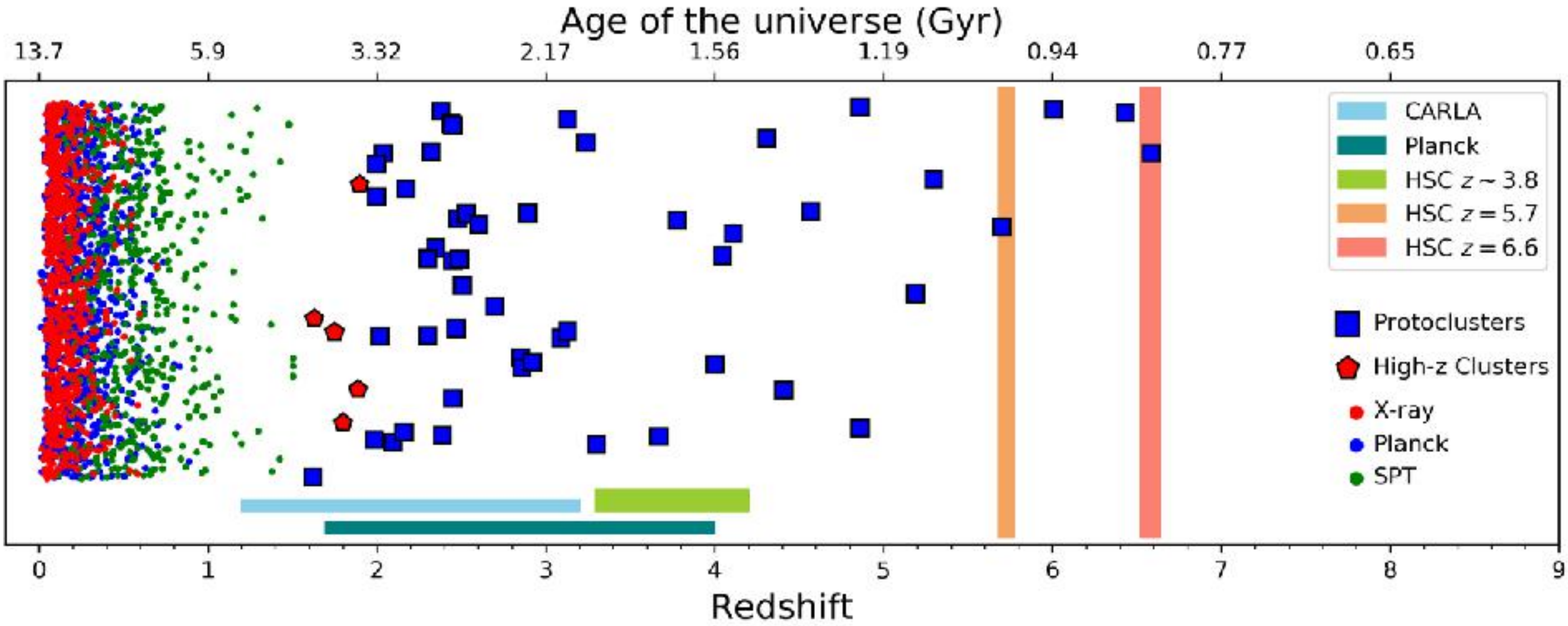
- by going to the near/mid-IR, JWST will probe the z ~ 10 - 15 range systematically
- JWST should detect about 1-100 galaxies at z > 10 per pointing
- bring high spatial resolution and rest-frame optical astrophysics to high-z universe
- the properties of all high redshift galaxies at z > 2 will be studied



Cowley et al. (2018)

Origin of today’s massive clusters of galaxies?

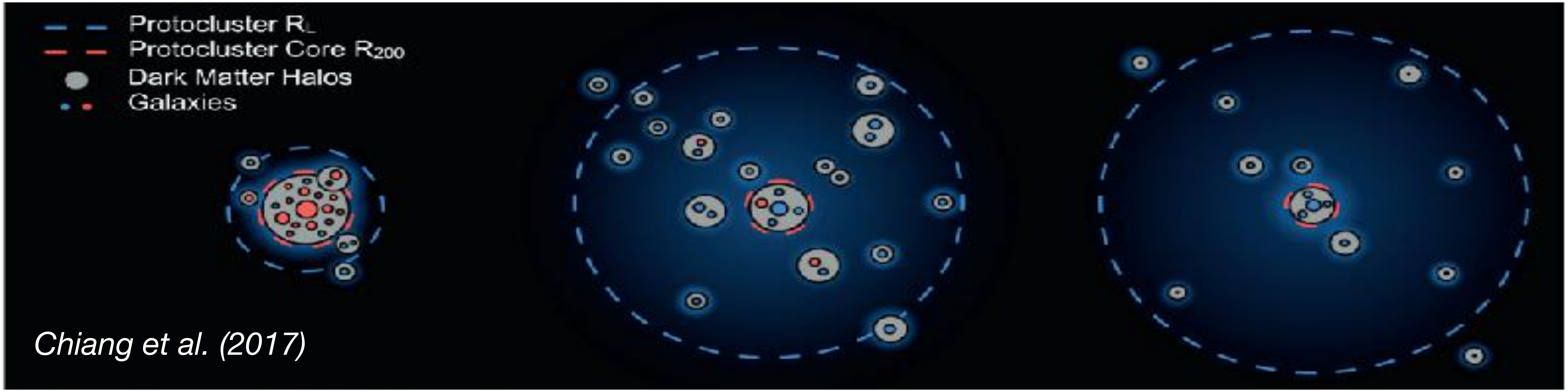
Boylan-Kolchin et al. (2012)



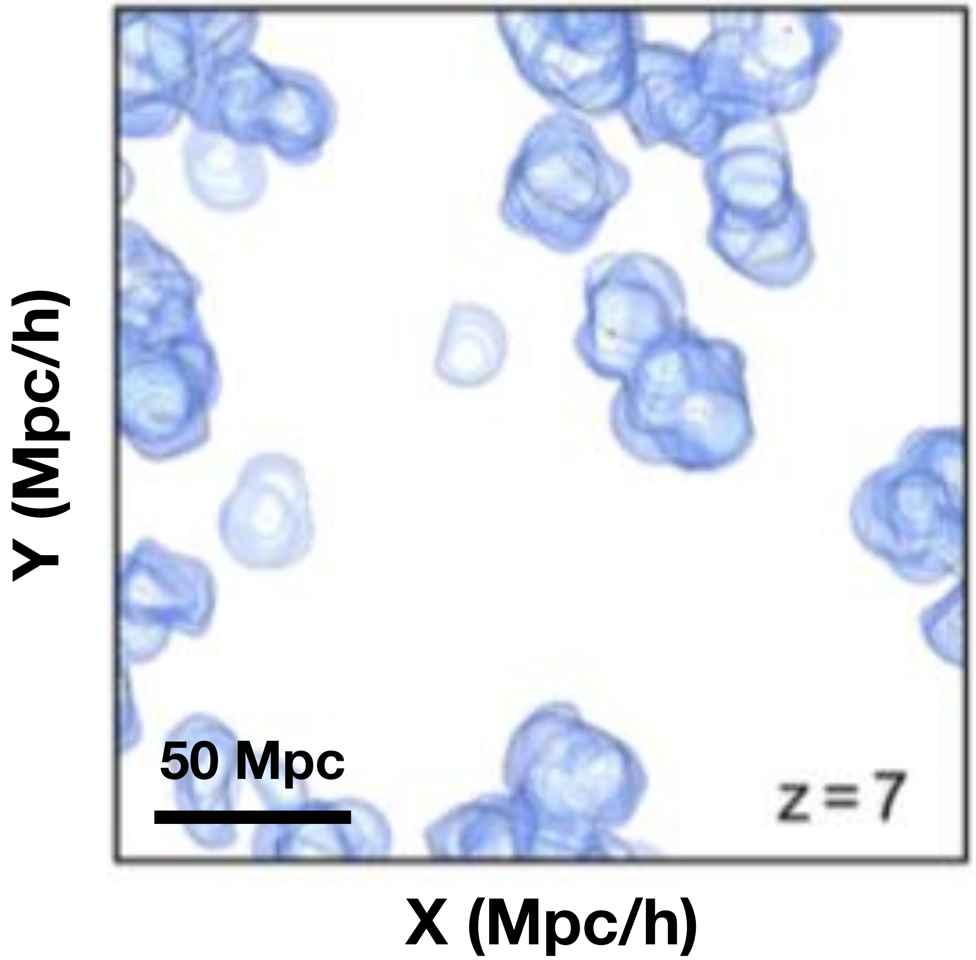
Overzier (2016); Overzier & Kashikawa (2019)

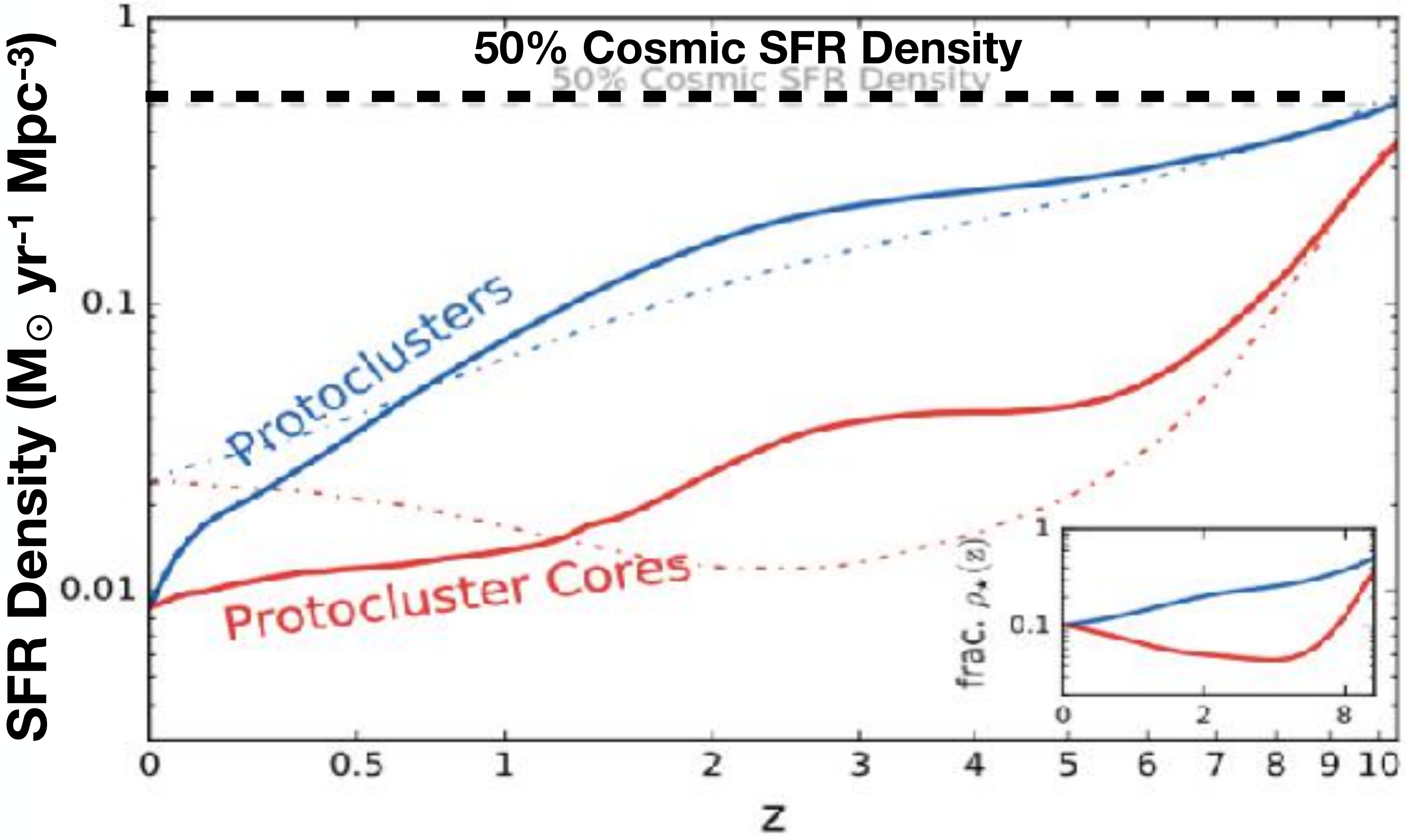
- **classical field of clusters is transitioning into that of “protoclusters”**
- **these protoclusters are important targets for JWST, ELT, GMT, …**

Origin of today’s massive clusters of galaxies?



Chiang et al. (2017)



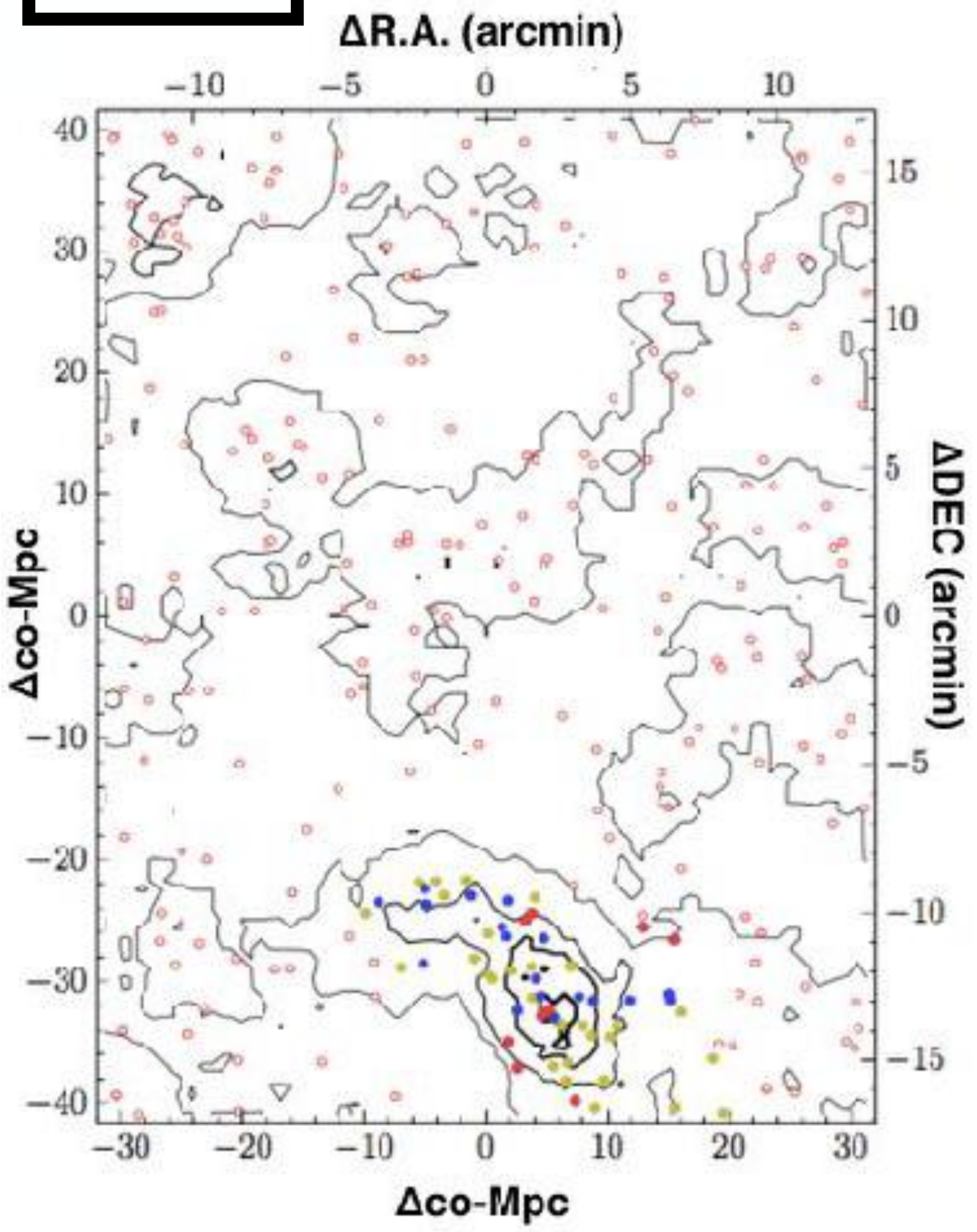


- at z ~ 6: *protoclusters* contributed >30% of all cosmic star formation

First large-scale (re-)ionized regions at z ~ 6—7

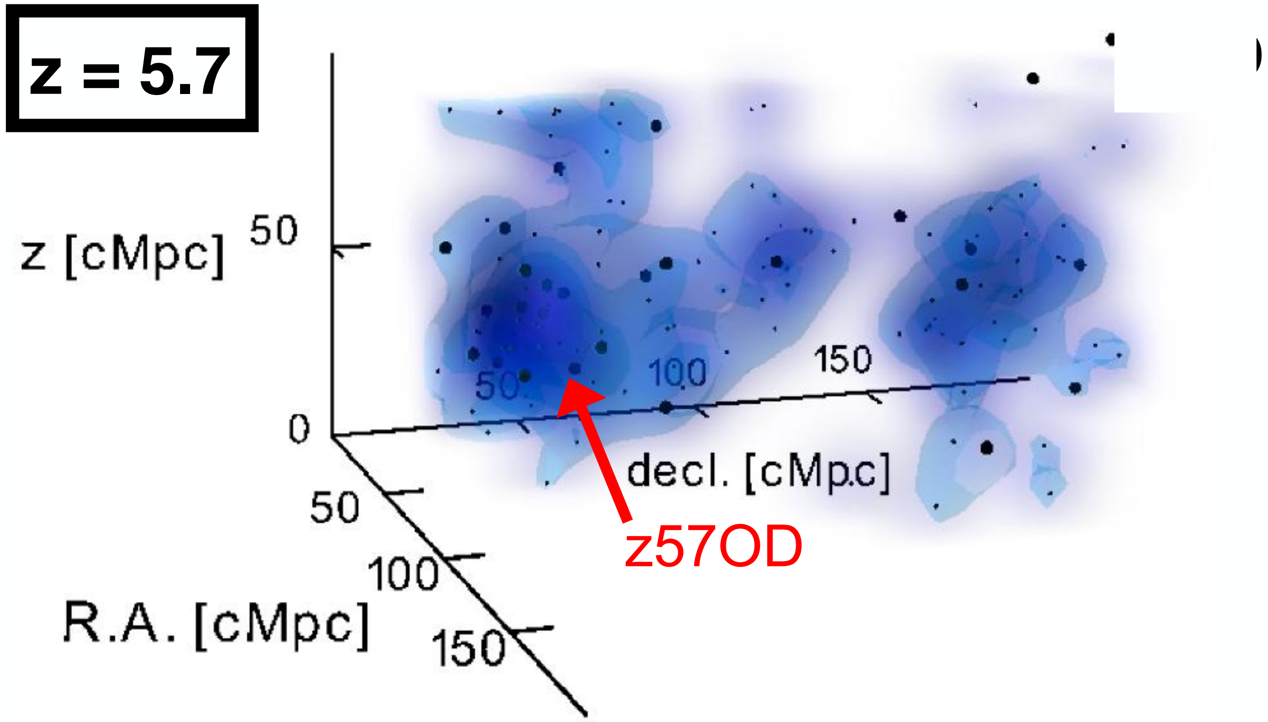
- due to high ion. photons rates, protoclusters were major sources of reionization
- we are starting to find some examples at z ~ 6—8
- very efficient regions to study with JWST and ELTs (many galaxies in small area!)

z = 6.01

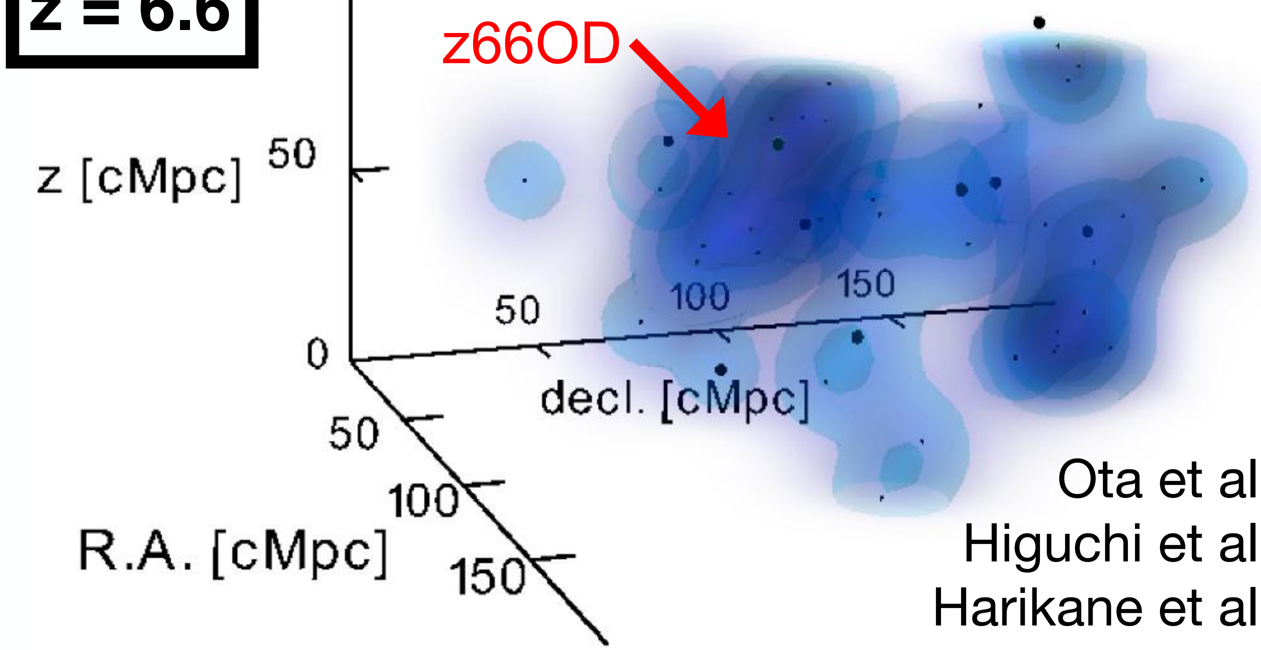


Toshikawa et al. (2014,2016)

z = 5.7

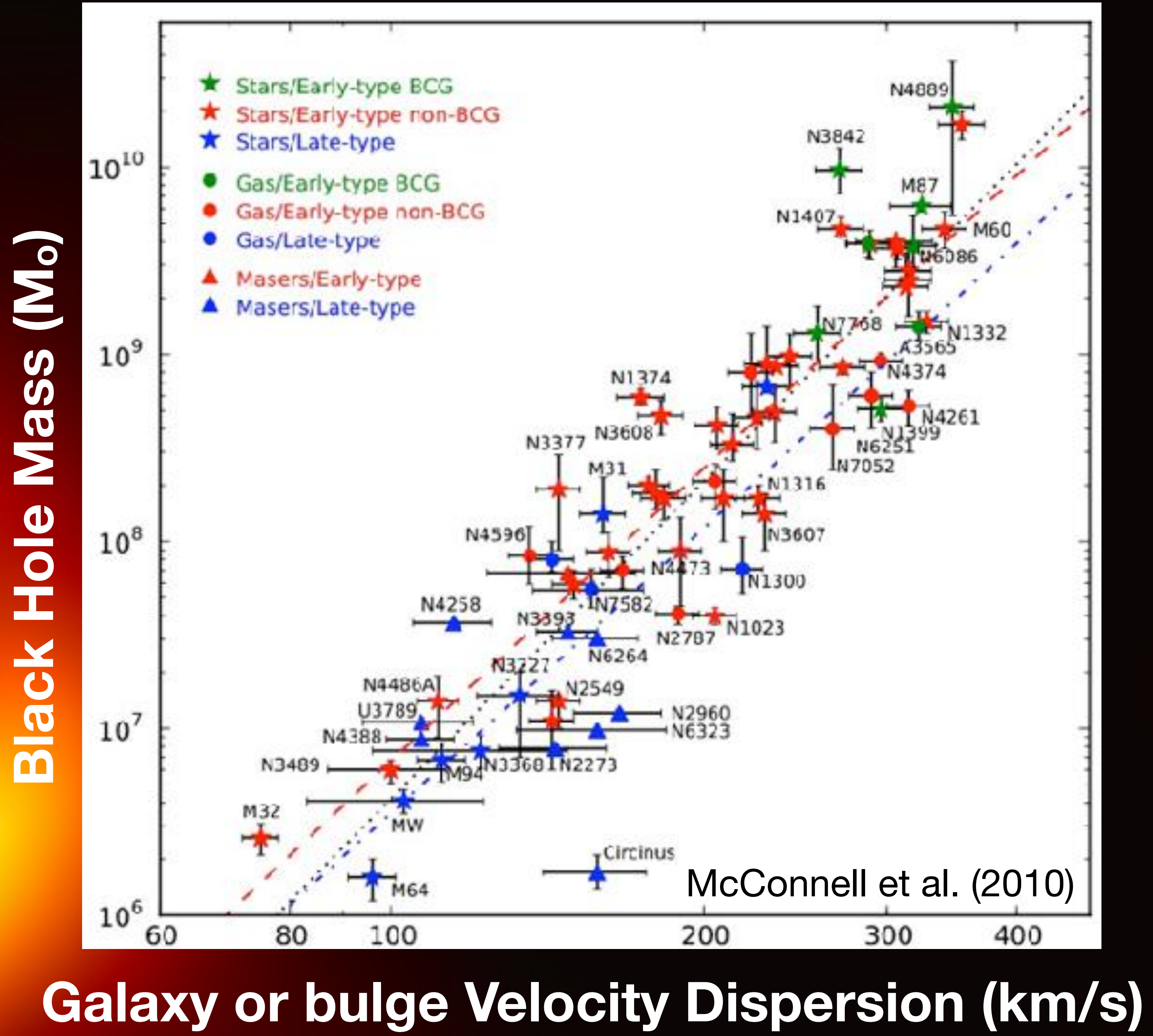


z = 6.6



Ota et al. (2018)
Higuchi et al. (2019)
Harikane et al. (2019)

Origin of today's supermassive black holes?



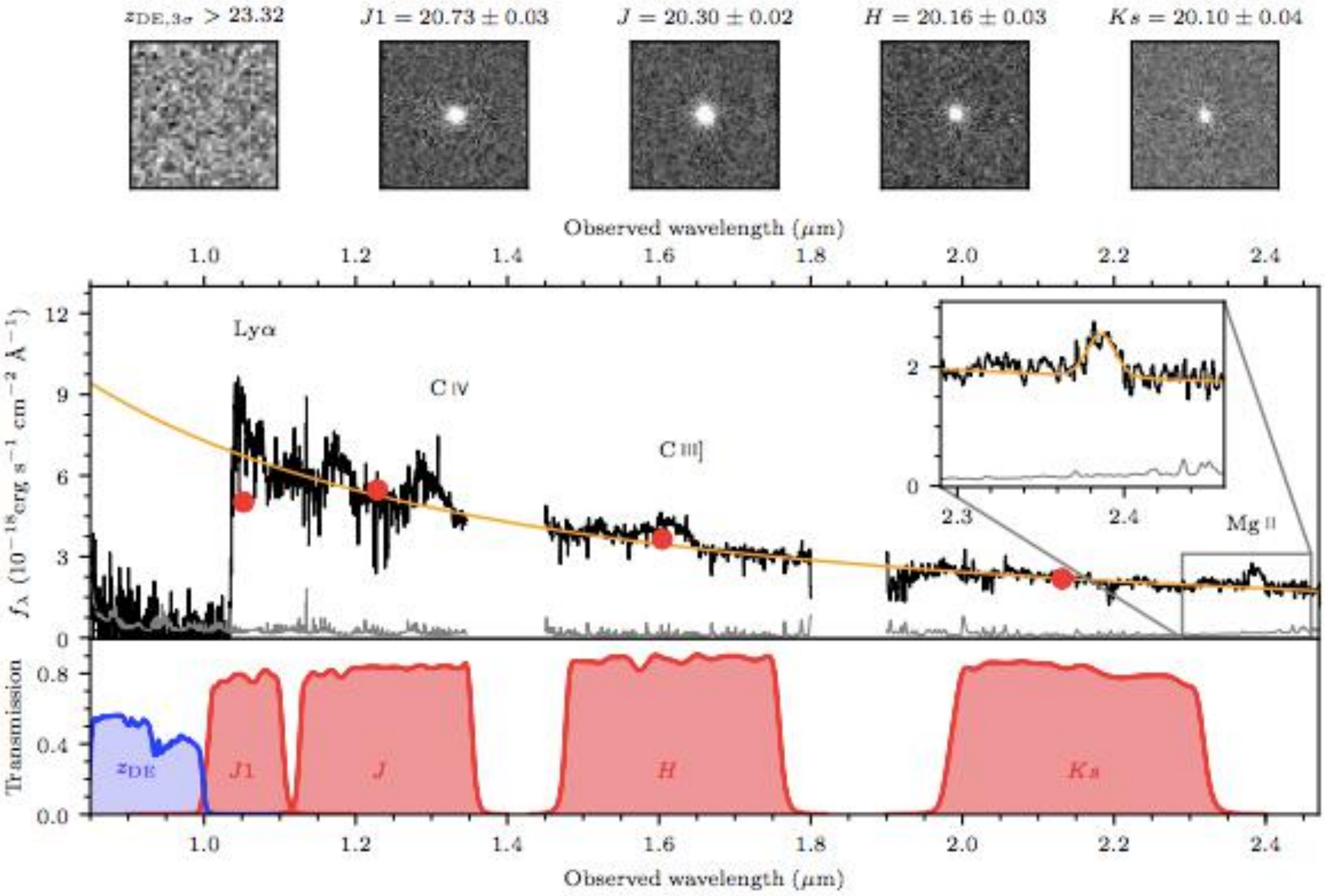
McConnell et al. (2010)

M87; Event Horizon Telescope/NSF

Origin of today's supermassive black holes?

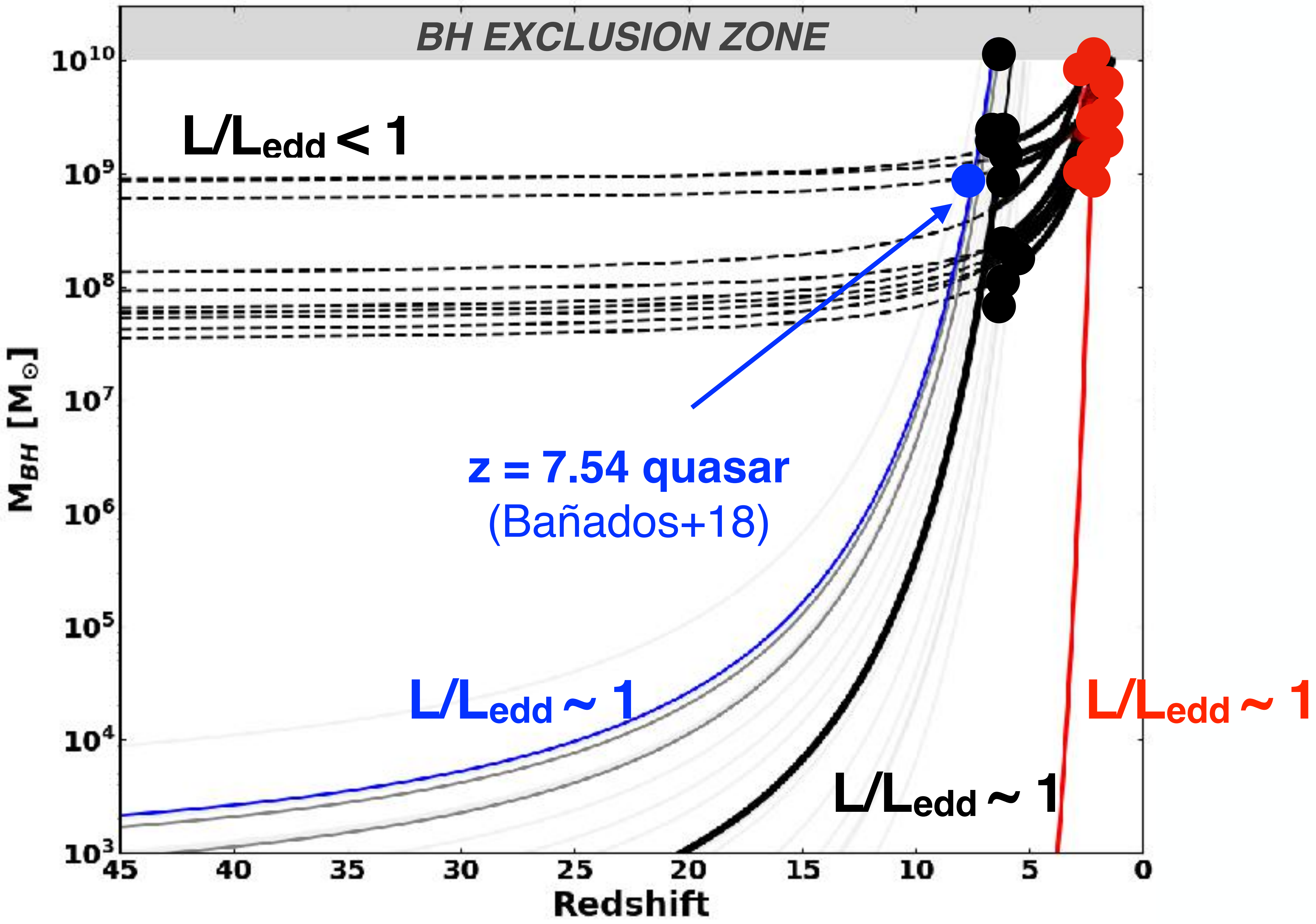
- **SMBHs with M87-like masses already existed at z > 6**

J1342+0928 at z = 7.54 (age of universe ~ 700 Myr)



Bañados et al. (2018)

Origin of today’s supermassive black holes?



$L/L_{edd} < 1$

z = 7.54 quasar
(Bañados+18)

$L/L_{edd} \sim 1$

$L/L_{edd} \sim 1$

$L/L_{edd} \sim 1$

Marinello, Overzier et al. in prep.

Perhaps the quick formation of these SMBHs at z ~ 6 could be explained if the first quasars formed in large overdense regions

but observations so far have found little evidence of this…

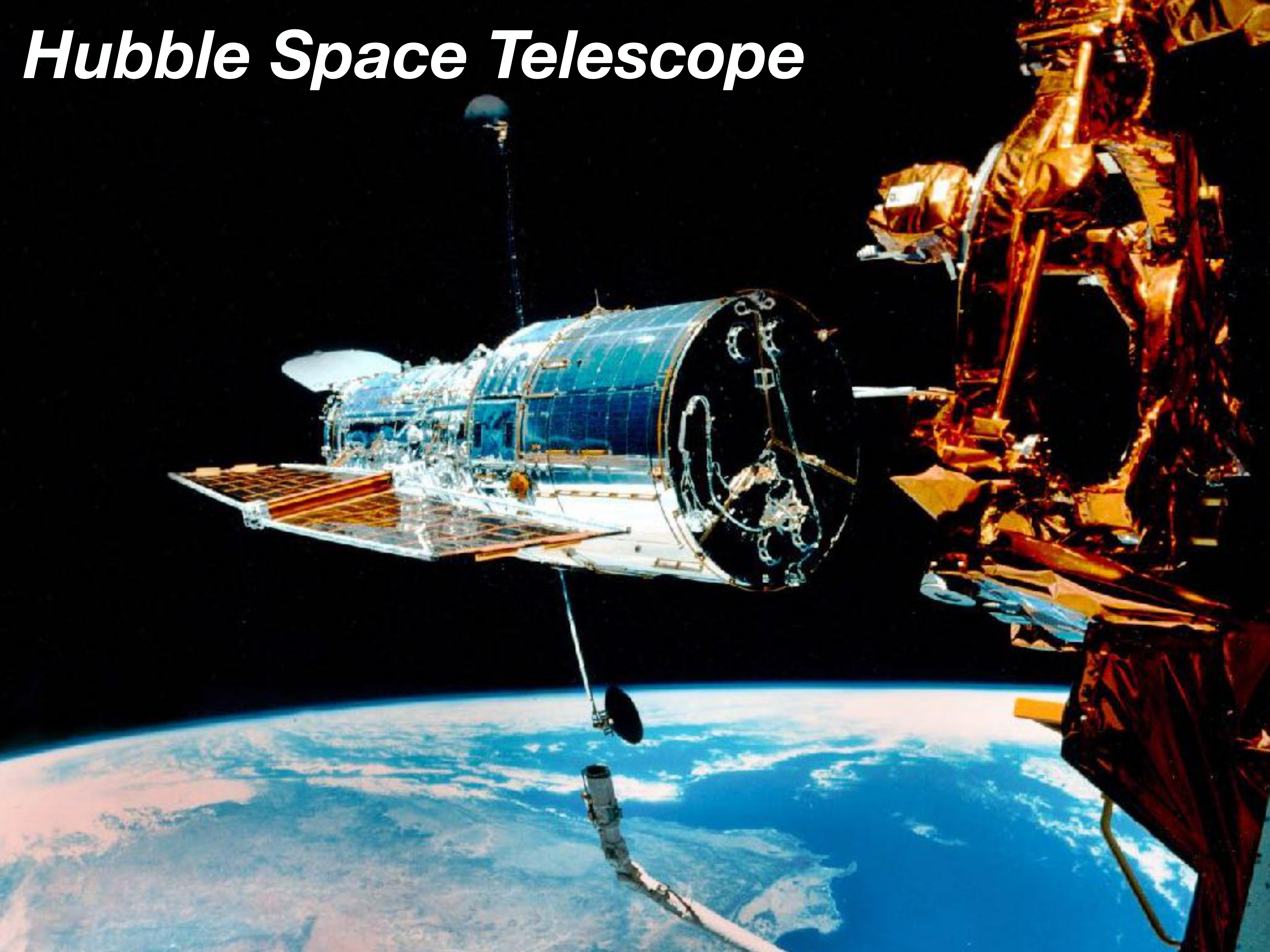
Donald J. Trump
@realDonaldTrump

Quasars at z~6 do NOT trace the densest regions of the early Universe. Sad!

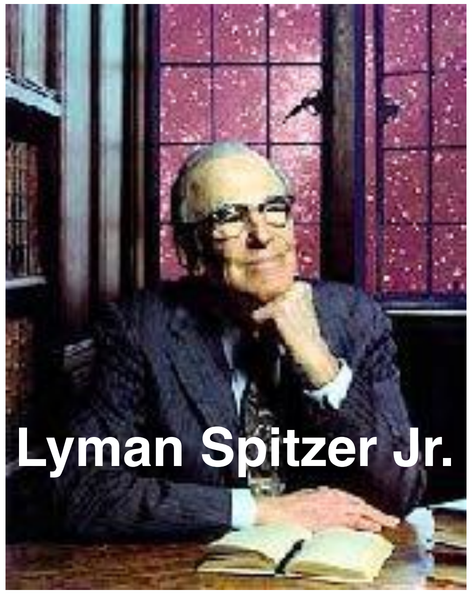
16:10 PM - 31 July 2019

2,167 6,286

Hubble Space Telescope



(Very) Brief history of the Hubble Space Telescope



1960s: US plans for a **large (3m) space telescope** (LST), launch: 1979

1974: all funding cut

1978: half of the original funding reinstated by congress, launch: 1983

1981: launch of the first Space Shuttle *Columbia*

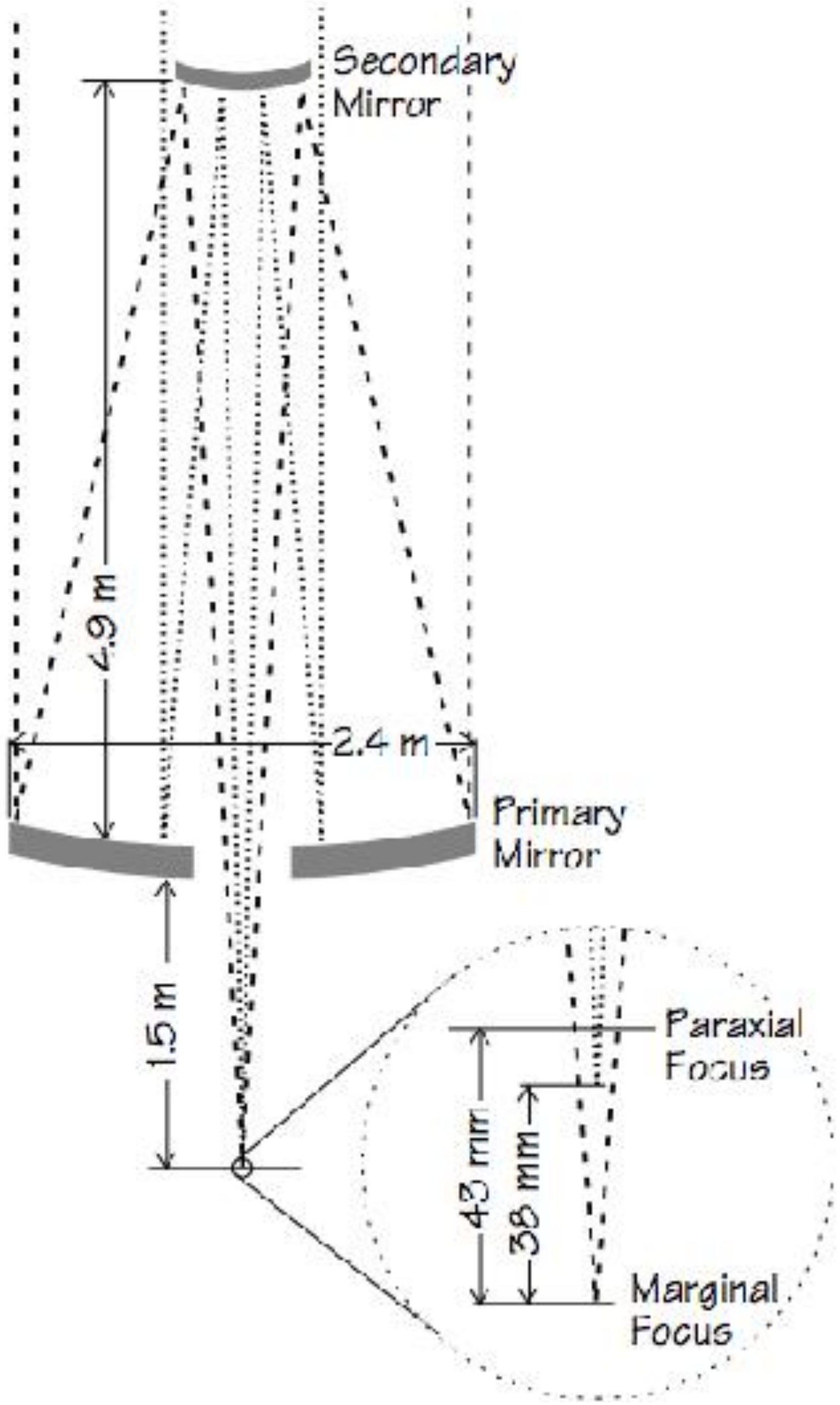
1983: LST renamed ***Hubble Space Telescope***

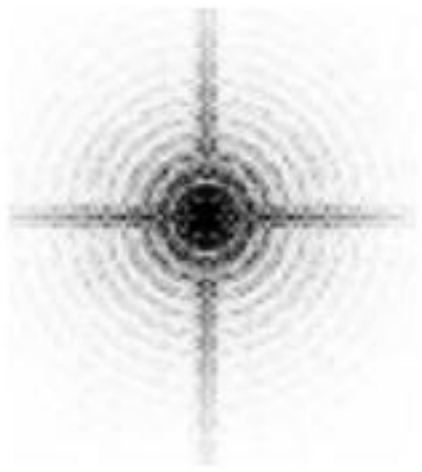
1984: delays, launch eventually scheduled for 1986

1986: Space Shuttle *Challenger* disaster

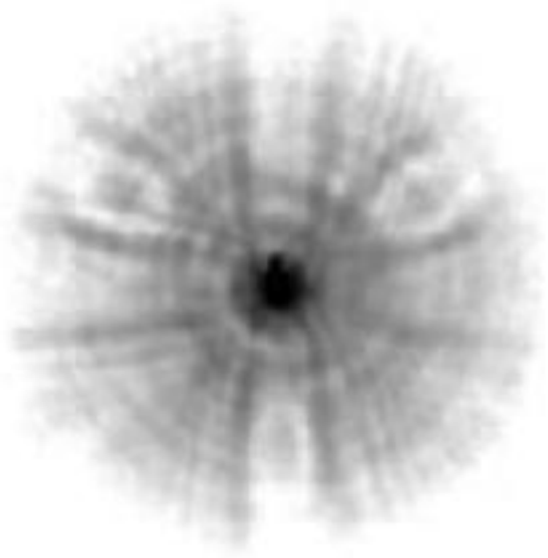
1990: Launch with Space Shuttle *Discovery*
Instruments: WFPC, FOC, FOS, HRS, HSP

1990—1993: focusing problem due to flawed mirror (2 µm too flat at mirror edge)





HST expected

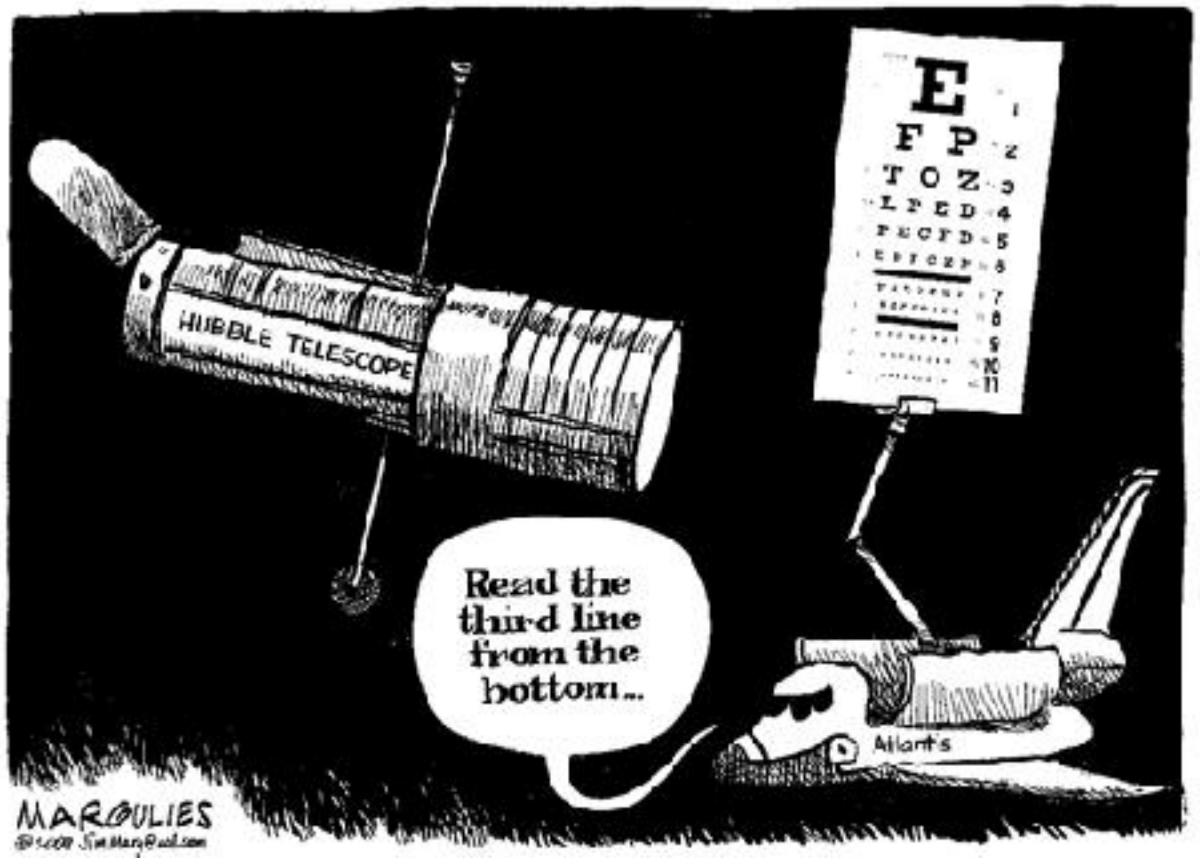


HST measured

WFPC images show the *0.1" core has only 15% instead of 70%* of encircled light

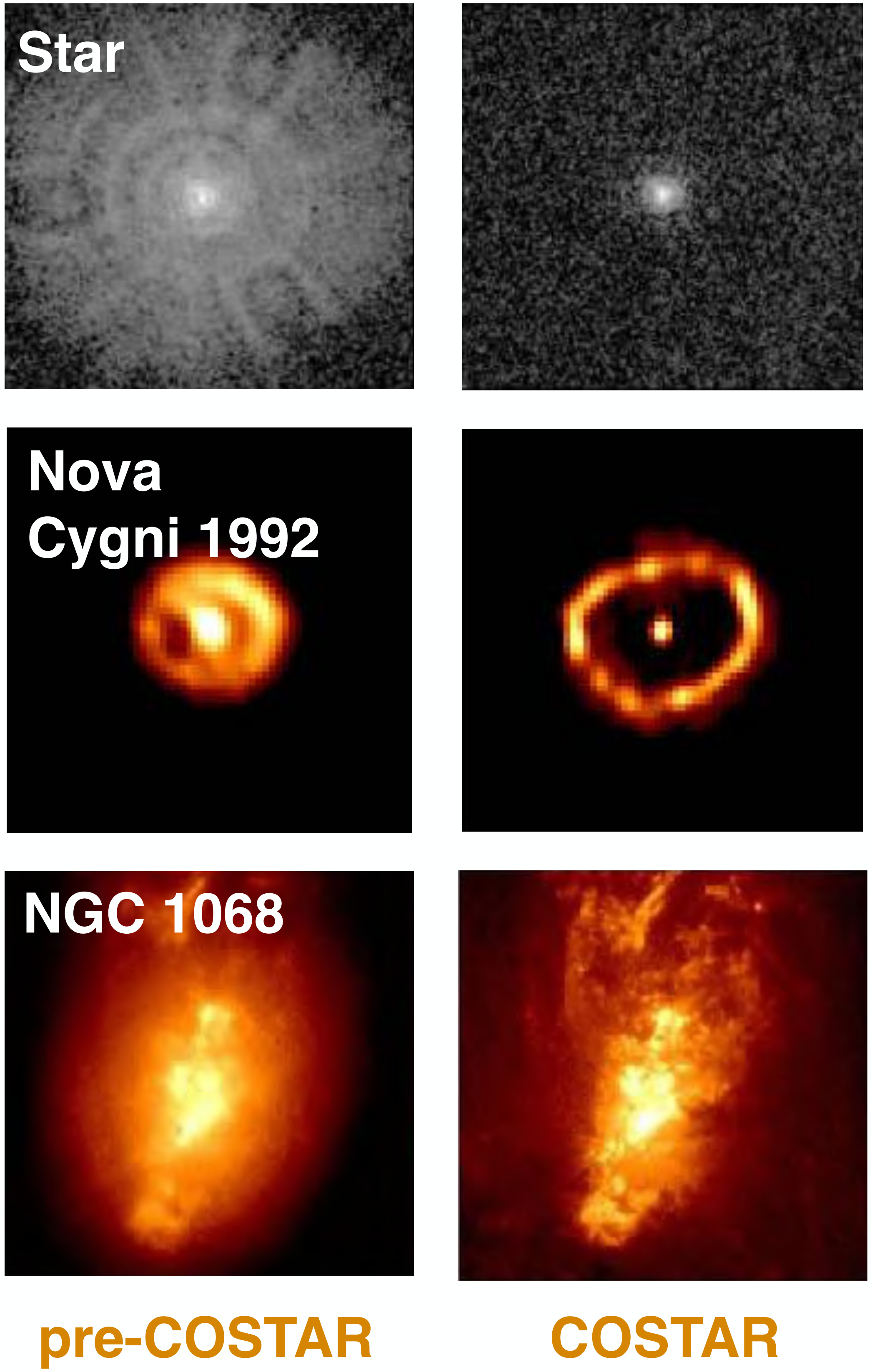
Proposed solution:

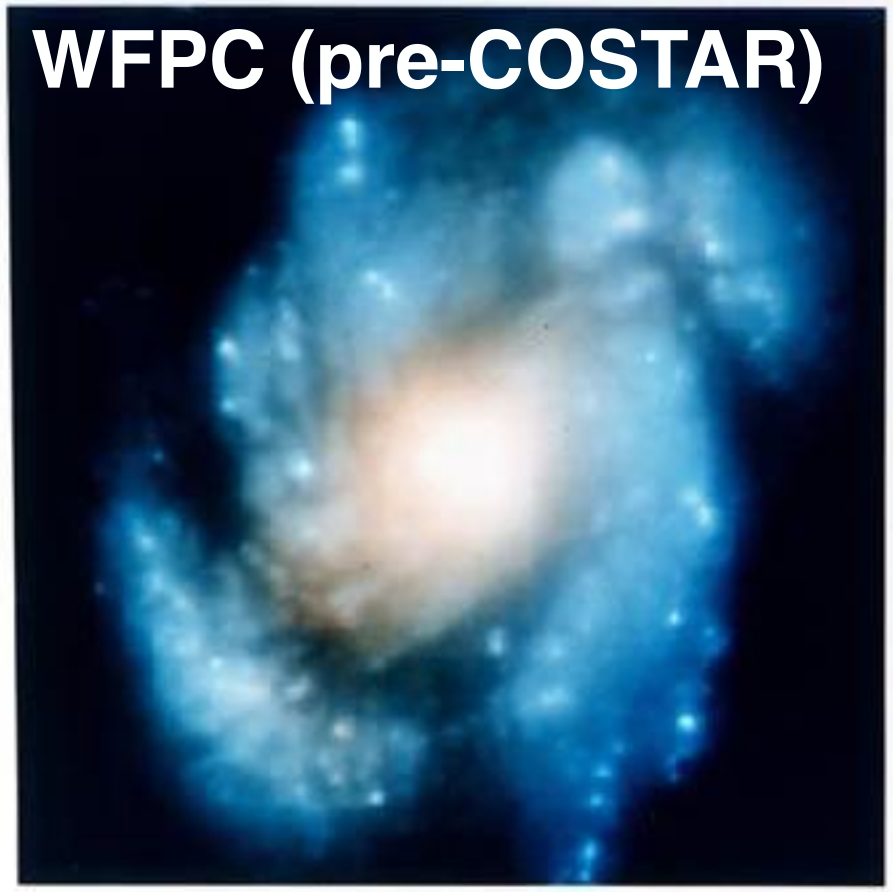
COSTAR - *Corrective Optics Space Telescope Axial Replacement (Ford & Brown, 1990)*



(Very) Brief history of the Hubble Space Telescope

Faint Object Camera images:





HST Servicing Missions

STS-61

SM #1 (1993) - remove HSP, WFPC, **install COSTAR and WFPC2**, new solar panels, gyros

STS-82

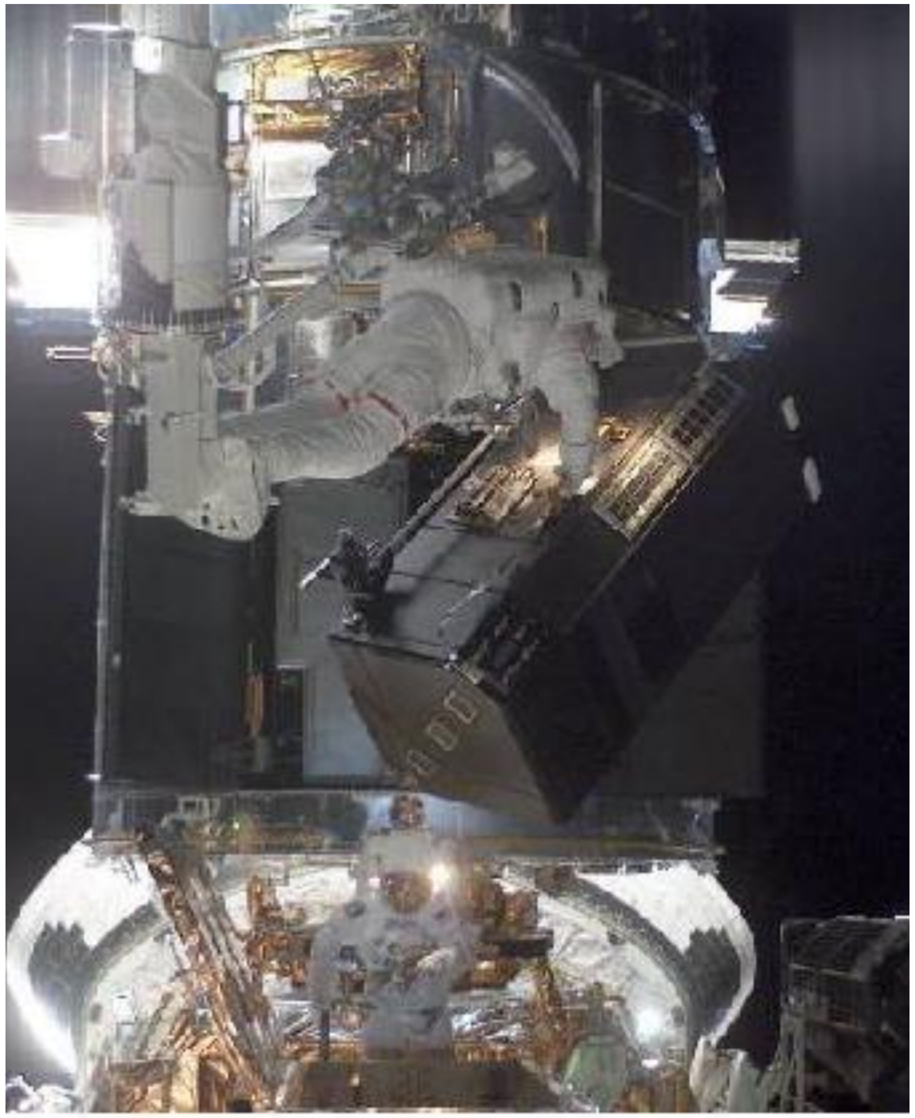
SM #2 (1997) - remove FOS, HRS, **install NICMOS, STIS**, Fine Guidance Sensor, Data Recorder, and Reaction Wheels

STS-103

SM #3A (1999) - replace all gyroscopes and a fine guidance sensor, new central computer, battery improvements and thermal blankets

STS-109

SM #3B (2002) - remove FOC, **install ACS**, replace solar panels, **repair of NICMOS** and reaction wheel



2004: Space Shuttle Columbia disaster

STS-125

SM #4 (2009) - remove WFPC2, COSTAR, **repair ACS, STIS**, **install WFC3, COS**, replace batteries, gyroscopes, Fine Guidance Sensor and insulation blankets, added a backup instrument data handling unit, **soft capture device for future de-orbiting**

- 2011: retirement of the Space Shuttle Program
- today: HST still in reasonable shape, and producing lots of science

The legacy of HST

The *pre*-HST universe was VERY different:

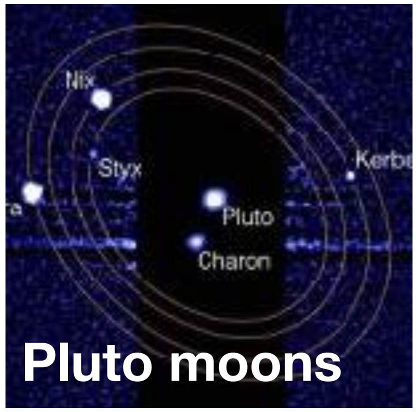
- value of matter density and Hubble-Lemaître constant were not known precisely
- galaxies were not known to evolve strongly
- central black holes were suspected in galaxies but demographics unknown
- many details of solar system objects not known
- no exoplanet had ever been “seen”

Community impact:

- today **>15,000 refereed publications**, with on average 40 citations
- **10% of best-cited papers** each year are based on HST data
- only **2% of HST papers have no citations** (~30% considering all papers)
- HST papers receive **15x more citations** compared to 4-m telescope papers
- but: **HST cost >100x more** than a 4-m telescope observatory!
- **public’s appreciation** for this flagship project is very important for astrophysics

DISCLAIMER:

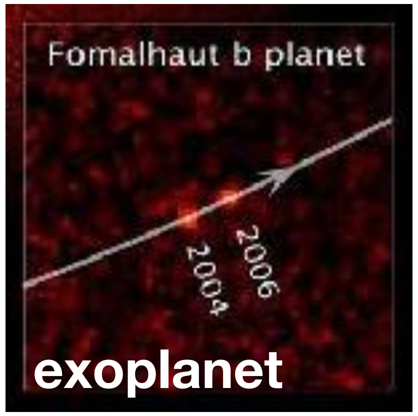
Many of HST’s breakthrough discoveries were not planned:



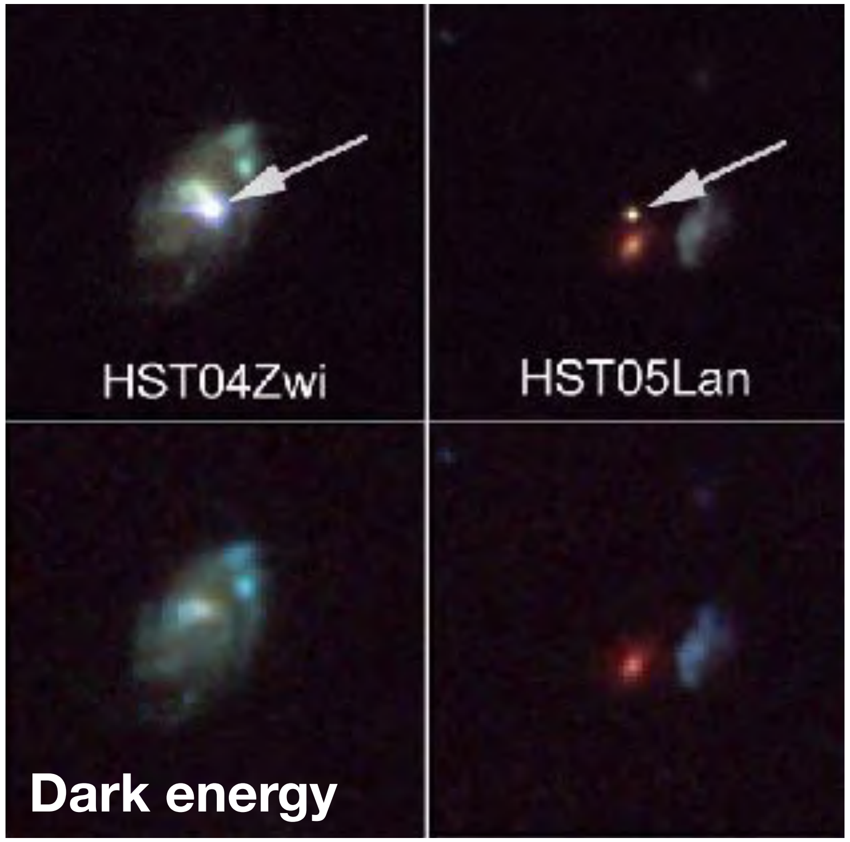
Pluto moons

protoplanetary disk

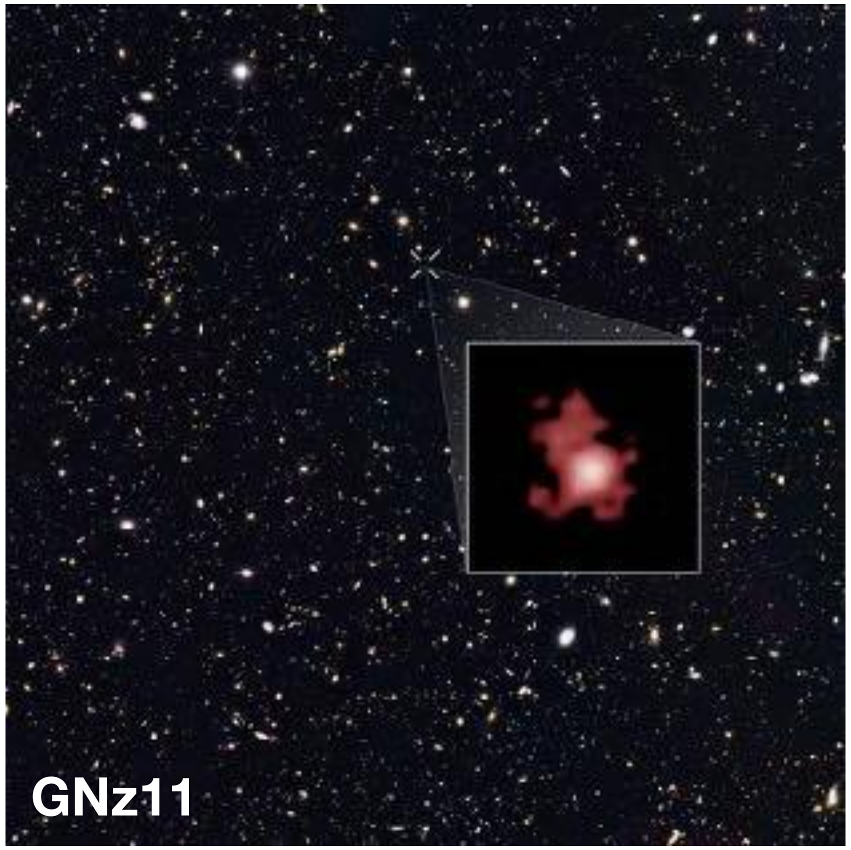
Schoemaker-Levy



exoplanet



Dark energy



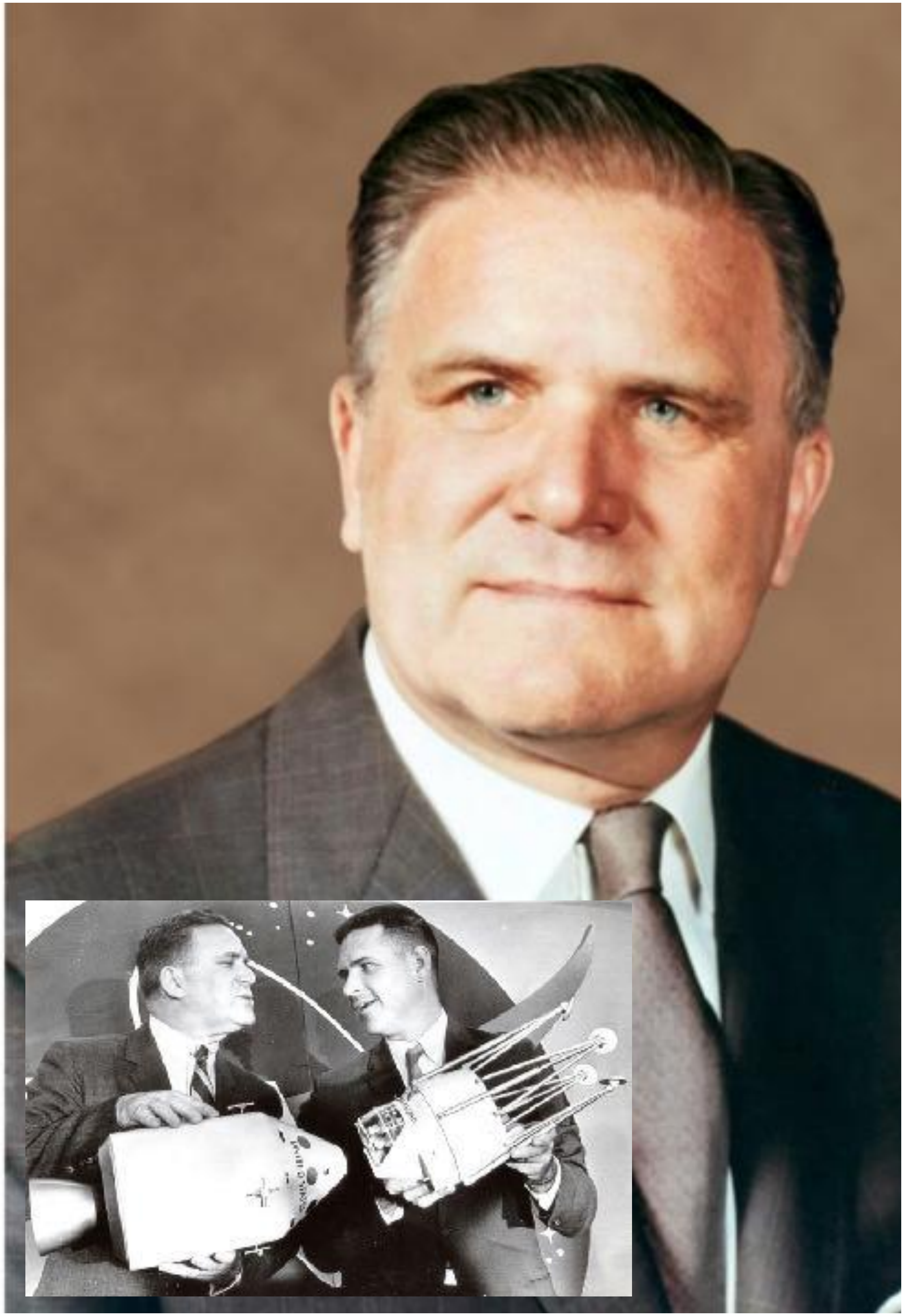
GNz11

Likewise,

None of the most novel discoveries made by the Keck telescopes between 1992 and 2007 were in the 1985 ***Keck Science Book***:

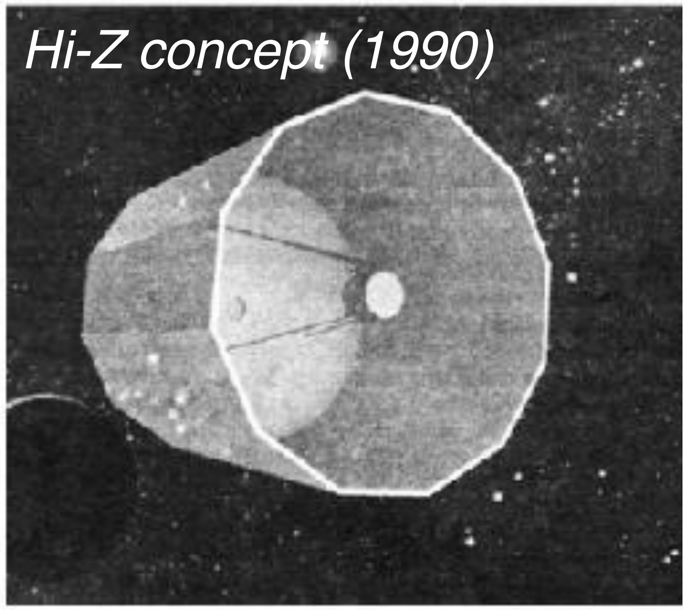
- **Galaxies at z = 3** (Steidel+96)
- **Gamma Ray Bursts** (Kulkarni+98)
- **Type 1A SNe hosts** (Perlmutter+97)
- **Exoplanets** (Marcy+97)

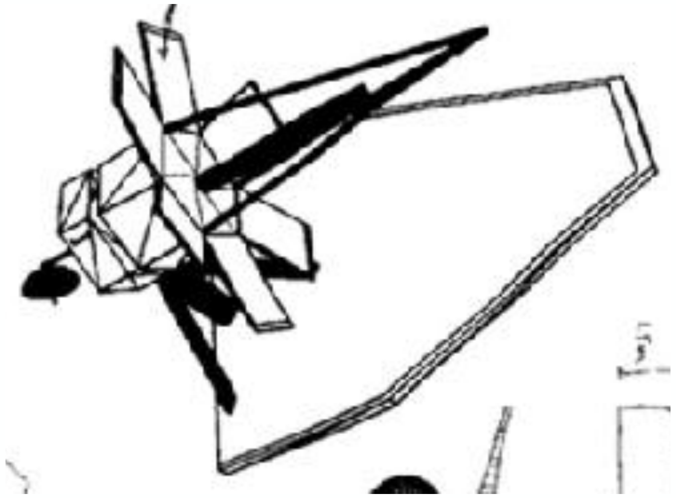
James Webb Space Telescope

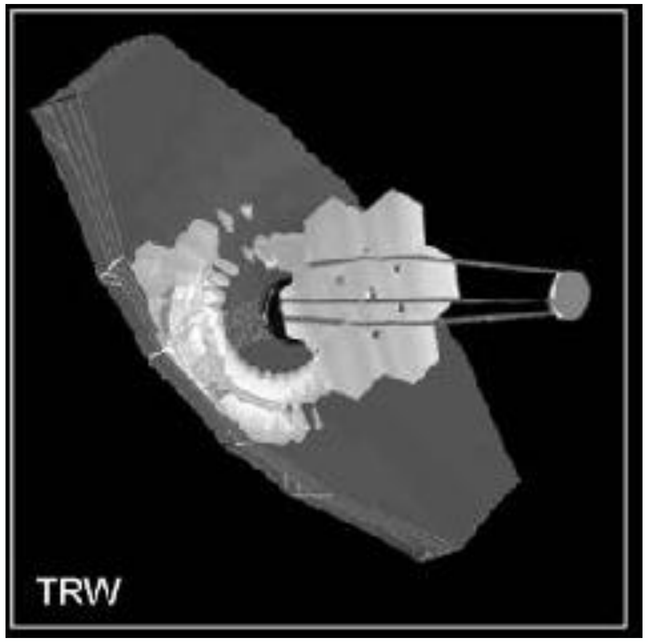


Development started more than 30 years ago, even before Hubble was launched

- 1989 workshop “The Next Generation: A 10 m Class UV/Opt/IR Successor to HST”
- 1990-1993 Community pushed the concept along by recommending a 6-8m cooled Next Generation Space Telescope (NGST) as a successor to Hubble
- 1995: STScI panel recommended 4-m optical/IR, restored by NASA director Goldin to an 8-m NGST concept located at L2, estimated to cost 0.5 B$ and **launch in 2007**


Hi-Z concept (1990)


Bély/GSFC (1995)



- 2002: NASA awarded the 1 B$ prime contract to TRW, now descoped to a 6.1-meter primary mirror and **launch in 2010**
- 2002: NGST renamed the ***James Webb Space Telescope***
- **2005: Launch with Ariane 5 rocket contributed by ESA; FGS by Canada**

Year	Launch	Delay (years)	Budget (Billion US$)	Overbudget (Billion US$)	
1997	2007	+0	0.5	+0	
1998	2007	+0	1.0	+0.5	
1999	2007/2008	+0/1	1.0	+0.5	
2000	2009	+2	1.8	+1.3	
2002	2010	+3	2.5	+2.0	
2003	2011	+4	2.5	+2.0	
2005	2013	+6	3.0	+2.5	replanning and cost-jump
2006	2014	+7	4.5	+4.0	independent review
2007	2014	+7	4.5	+4.0	critical technology review
2008	2014	+7	5.1	+4.6	
2010	2015/2016	+8/9	6.5	+6.0	mission critical design review
2011	2018	+11	8.7	+8.2	independent review
2011	**cost overrun dominating NASA's total astrophysics budget.** US Congress almost cancels the project (3 B$ spent and 75% of hardware in production). JWST is placed outside NASA's astrophysics division and given 8 B$ max. budget.				
2013	2018	+11	8.8	+8.3	
2017	2019	+12	8.8	+8.3	
2018	2020	+13	>8.8	>+8.3	failure of sunshield tests
2018	2021	+14	9.7	+9.2	independent review

June, 2011:

Threat of James Webb Space Telescope Cancellation Rattles Astronomy Community

Congress puts NASA and JWST on the chopping block

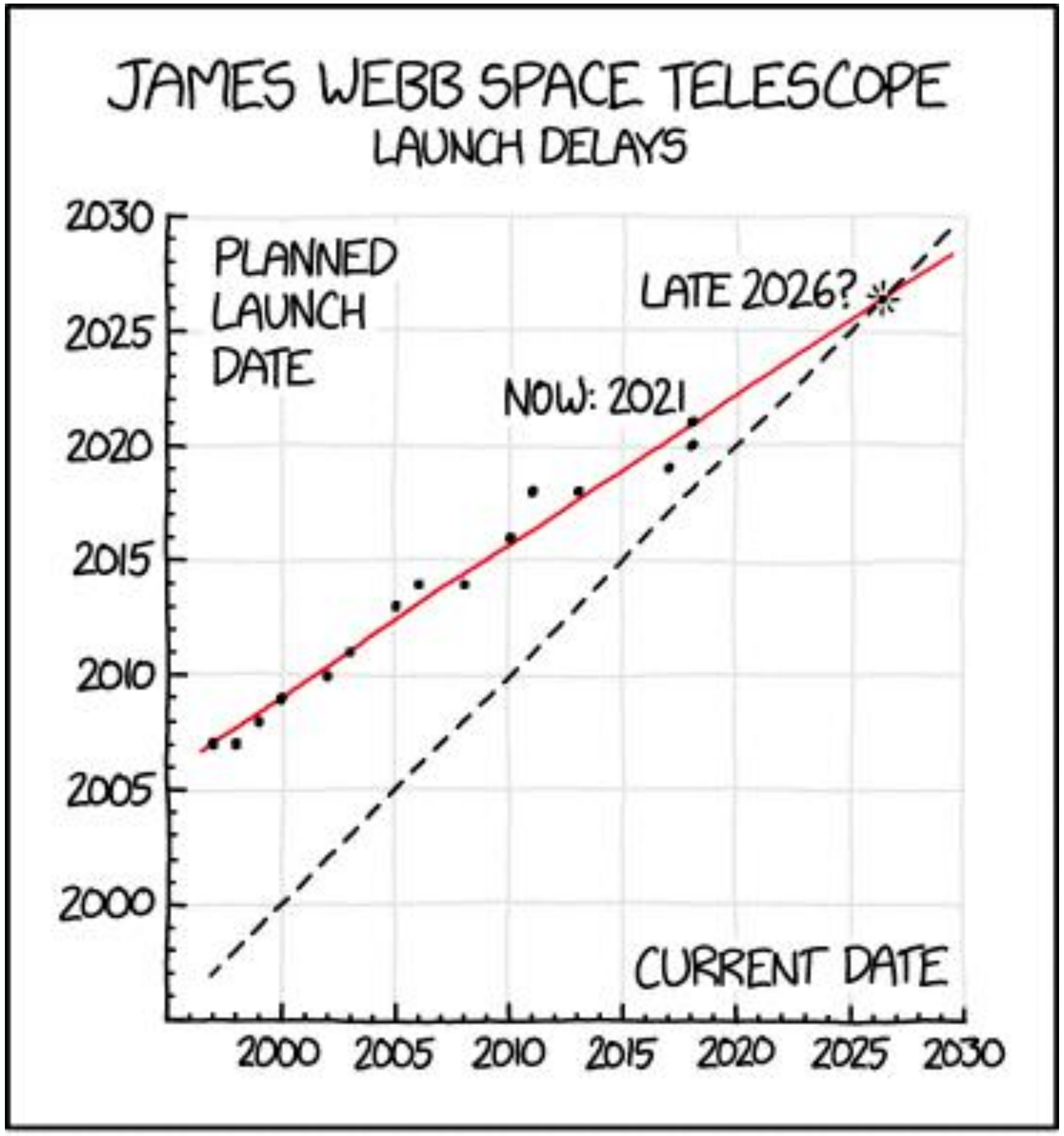
By Phil Plait | July 7, 2011 6:00 am

September, 2011:

Senate Panel Restores James Webb Space Telescope Funding

By Dan Leone, Space News Writer | September 16, 2011 10:32am ET

Will it really launch in 2021, or more like 2026?



LOOK, AT LEAST THE SLOPE IS LESS THAN ONE.

*“Since delays should get less likely closer to the launch, **most astronomers in 2018 believed the expansion of the schedule was slowing, but by early 2020 new measurements indicated that it was actually accelerating.**”*

https://xkcd.com/2014/

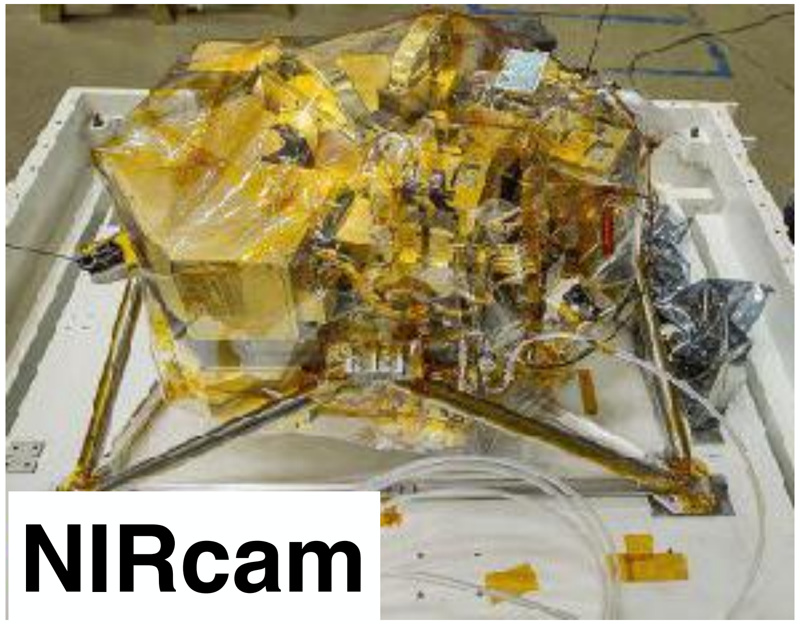
The James Webb Space Telescope

1:1 model

mirrors folded

mirrors open

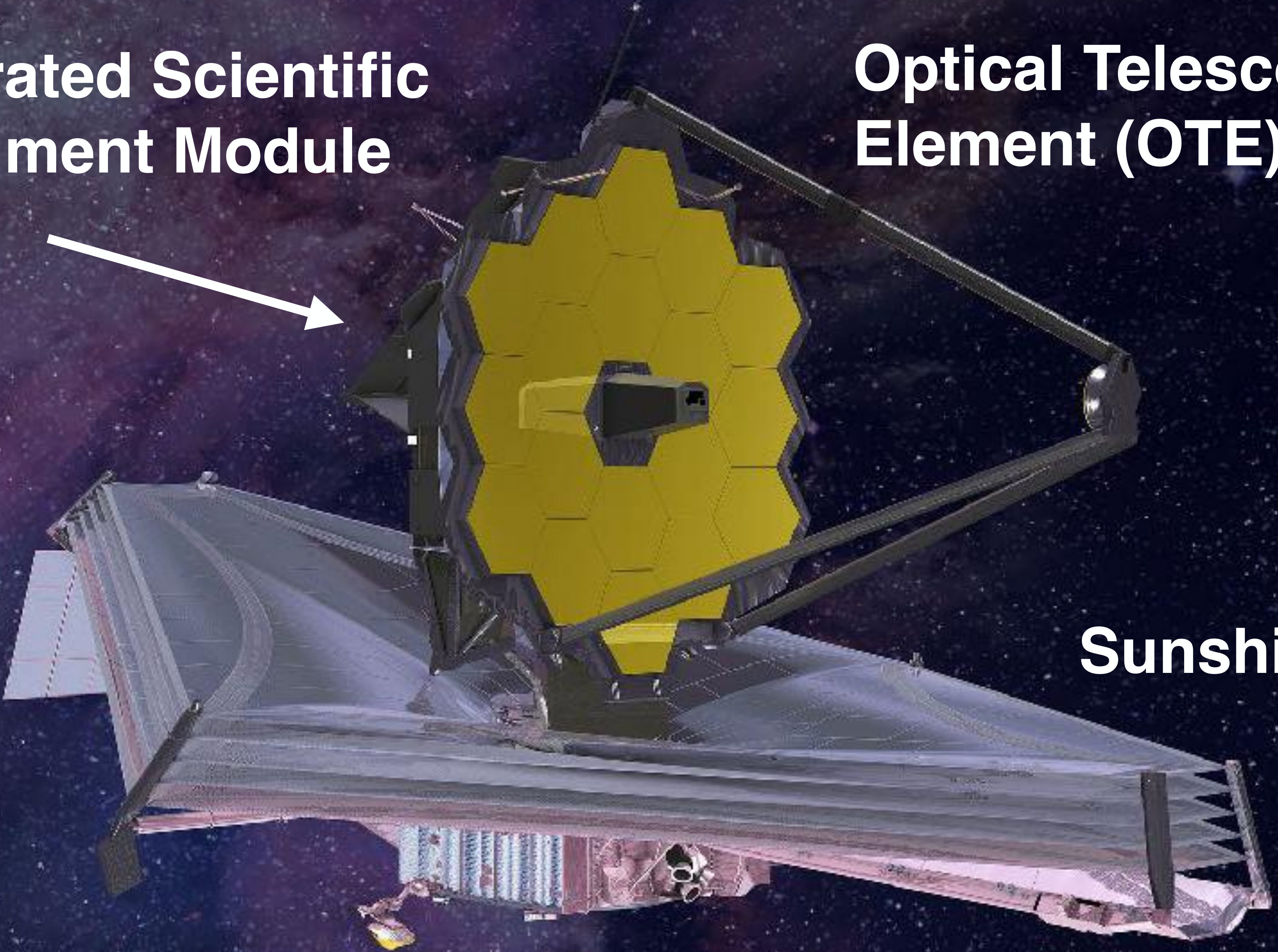
sunshield



NIRcam

NIRspec

4 Main components: spacecraft bus, sunshield, OTE, ISIM

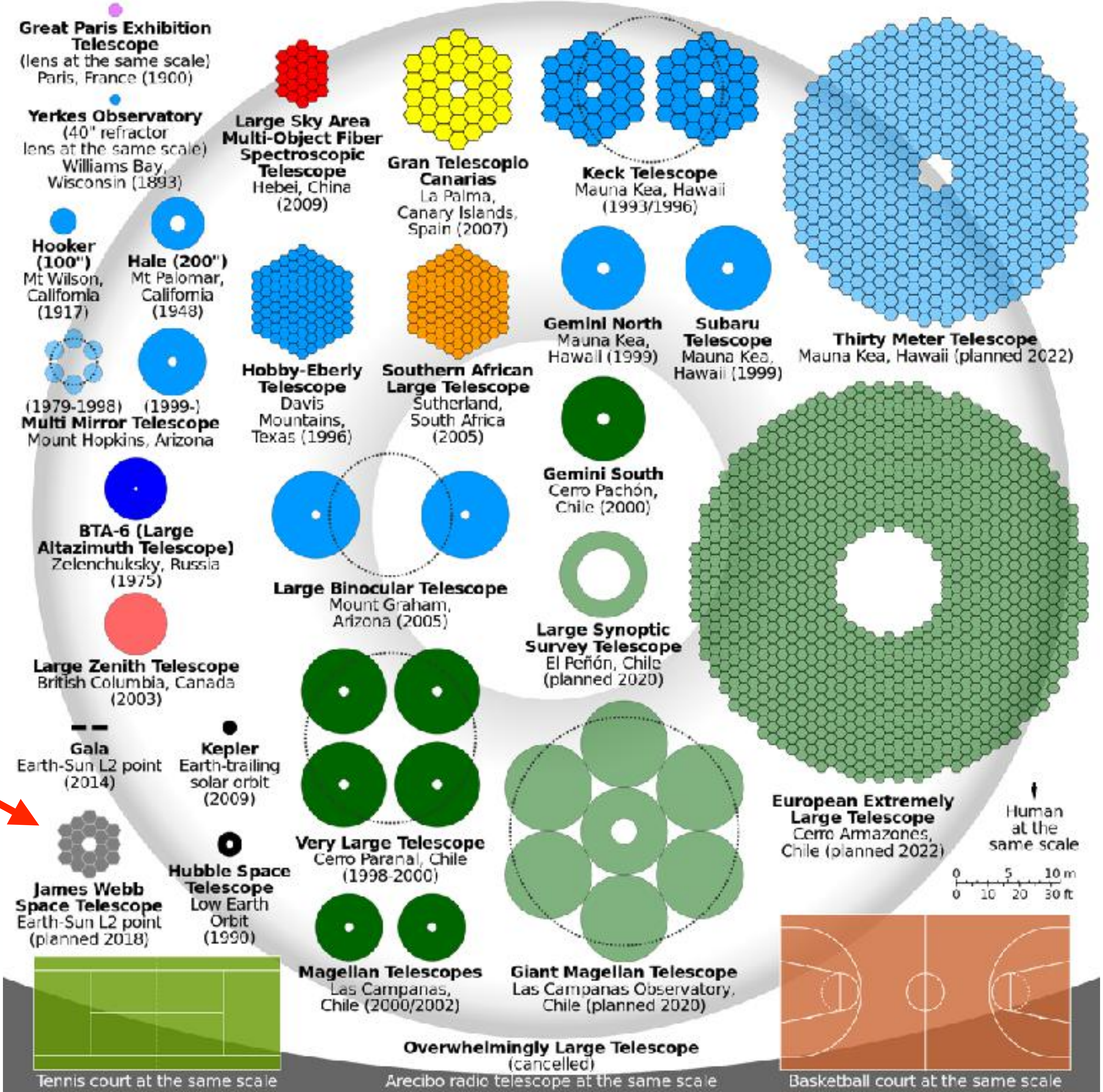


Integrated Scientific Instrument Module (ISIM)

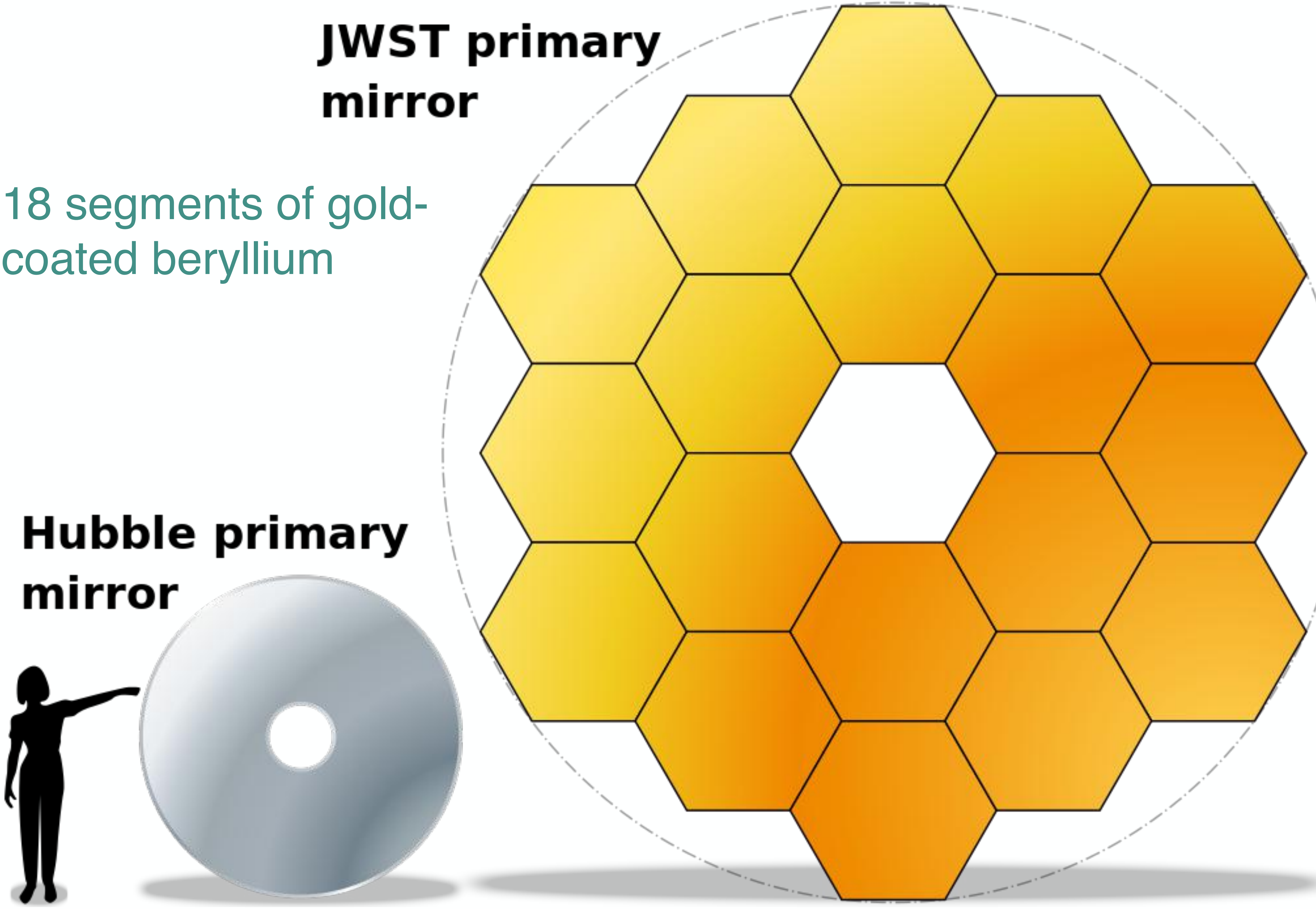
Optical Telescope Element (OTE)

Sunshield

Spacecraft Bus

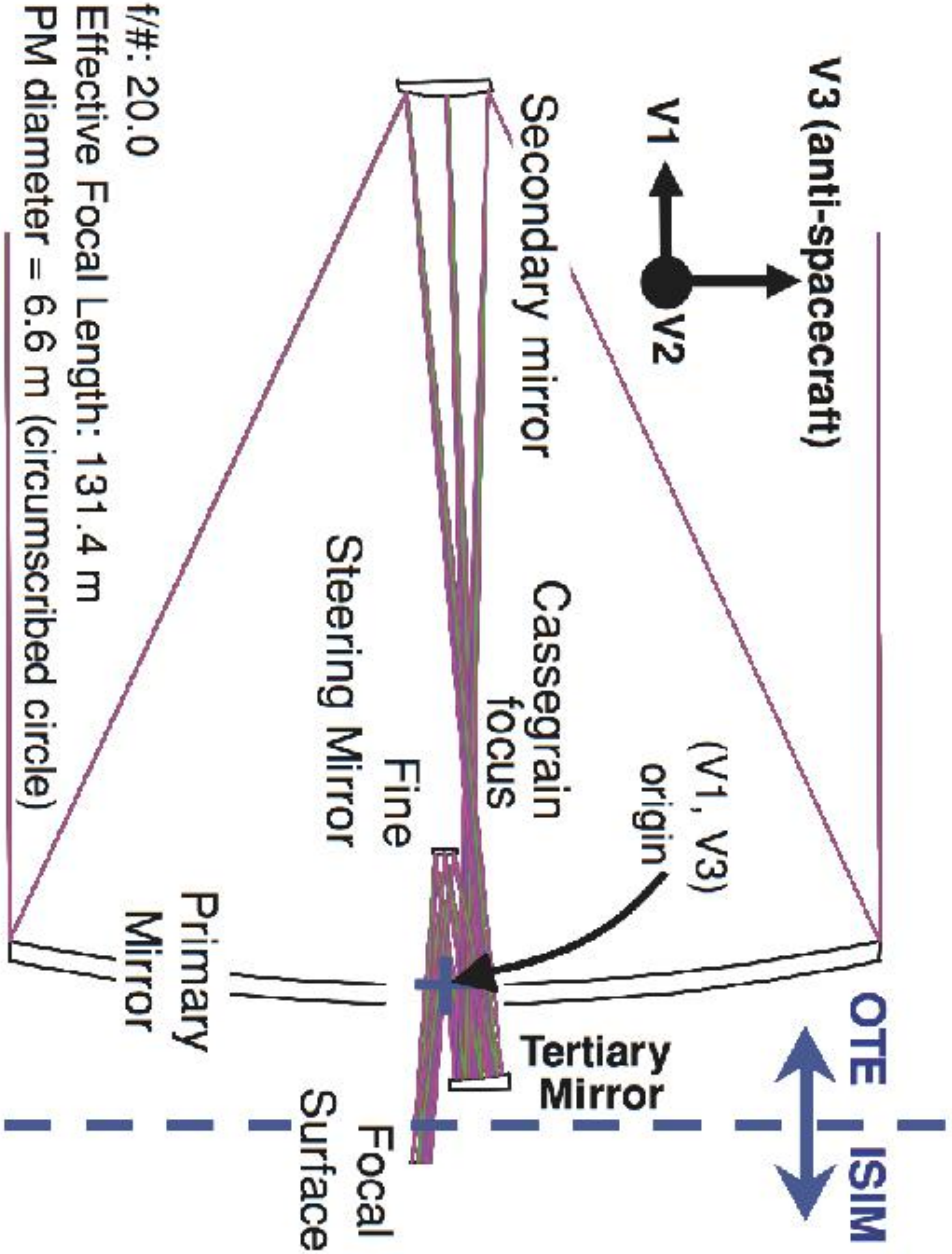

Great Paris Exhibition Telescope
(lens at the same scale)
Paris, France (1900)
Yerkes Observatory
(40" refractor
lens at the same scale)
Williams Bay,
Wisconsin (1893)
Large Sky Area Multi-Object Fiber Spectroscopic Telescope
Hebei, China
(2009)
Gran Telescopio Canarias
La Palma,
Canary Islands,
Spain (2007)
Keck Telescope
Mauna Kea, Hawaii
(1993/1996)
Thirty Meter Telescope
Mauna Kea, Hawaii (planned 2022)
Hooker (100")
Mt Wilson,
California
(1917)
Hale (200")
Mt Palomar,
California
(1948)
Hobby-Eberly Telescope
Davis
Mountains,
Texas (1996)
Southern African Large Telescope
Sutherland,
South Africa
(2005)
Gemini North
Mauna Kea,
Hawaii (1999)
Subaru Telescope
Mauna Kea,
Hawaii (1999)
(1979-1998)
(1999-)
Multi Mirror Telescope
Mount Hopkins, Arizona
Gemini South
Cerro Pachón,
Chile (2000)
BTA-6 (Large Altazimuth Telescope)
Zelenchuksky, Russia
(1975)
Large Binocular Telescope
Mount Graham,
Arizona (2005)
Large Synoptic Survey Telescope
El Peñón, Chile
(planned 2020)
Large Zenith Telescope
British Columbia, Canada
(2003)
Gaia
Earth-Sun L2 point
(2014)
Kepler
Earth-trailing
solar orbit
(2009)
Very Large Telescope
Cerro Paranal, Chile
(1998-2000)
European Extremely Large Telescope
Cerro Armazones,
Chile (planned 2022)
Human
at the
same scale
0 5 10 m
0 10 20 30 ft
James Webb Space Telescope
Earth-Sun L2 point
(planned 2018)
Hubble Space Telescope
Low Earth
Orbit
(1990)
Magellan Telescopes
Las Campanas,
Chile (2000/2002)
Giant Magellan Telescope
Las Campanas Observatory,
Chile (planned 2020)
Overwhelmingly Large Telescope
(cancelled)
Tennis court at the same scale
Arecibo radio telescope at the same scale
Basketball court at the same scale

CG: Space-E.com | Pockn



18 segments of gold-coated beryllium

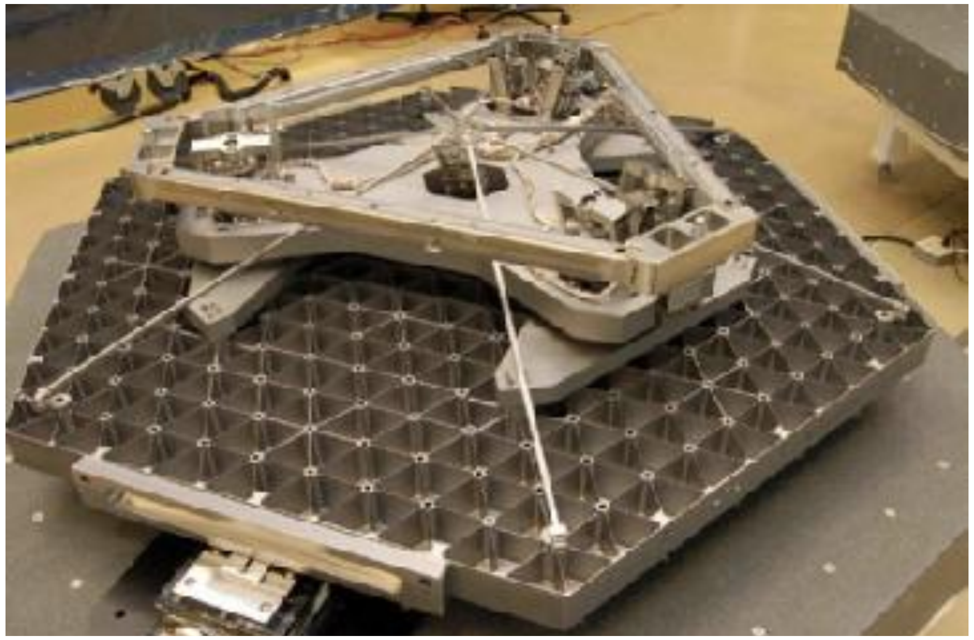
Three mirror anastigmatic design

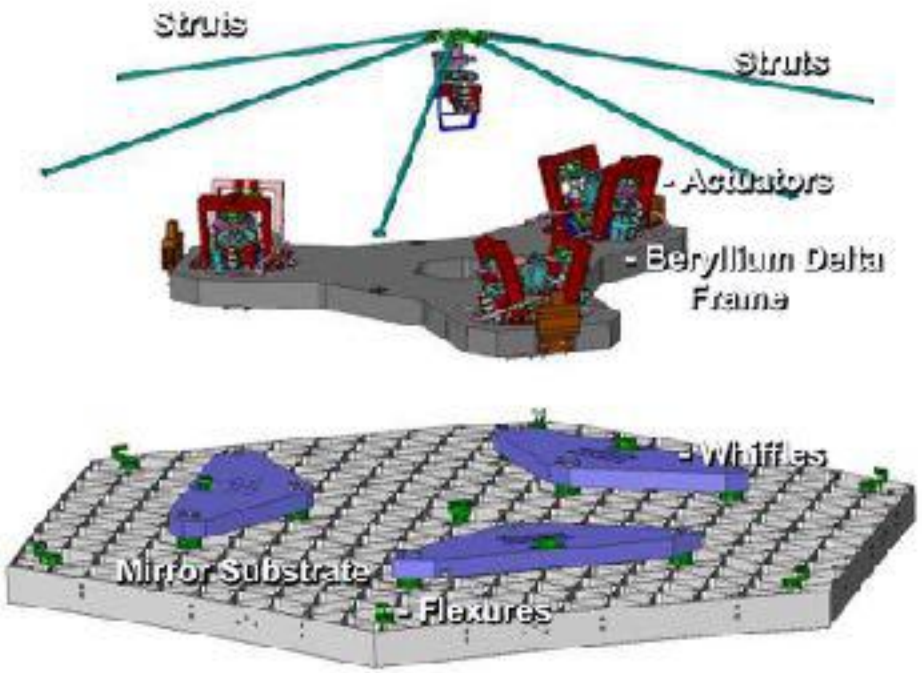


f/#: 20.0
Effective Focal Length: 131.4 m
PM diameter = 6.6 m (circumscribed circle)

Primary mirror

- segmented to fit in the Ariane 5 nose-cone
- 18 segments **gold-coated beryllium** (1.3m flat-to-flat)
- 6.5 m flat-to-flat, 25 m^2 collecting area
- each segment has 6 DoF + curvature radius control



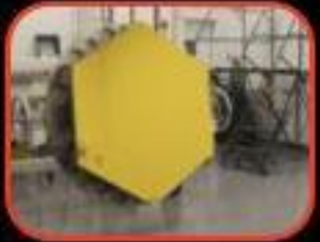


A3

C1

B2

B7

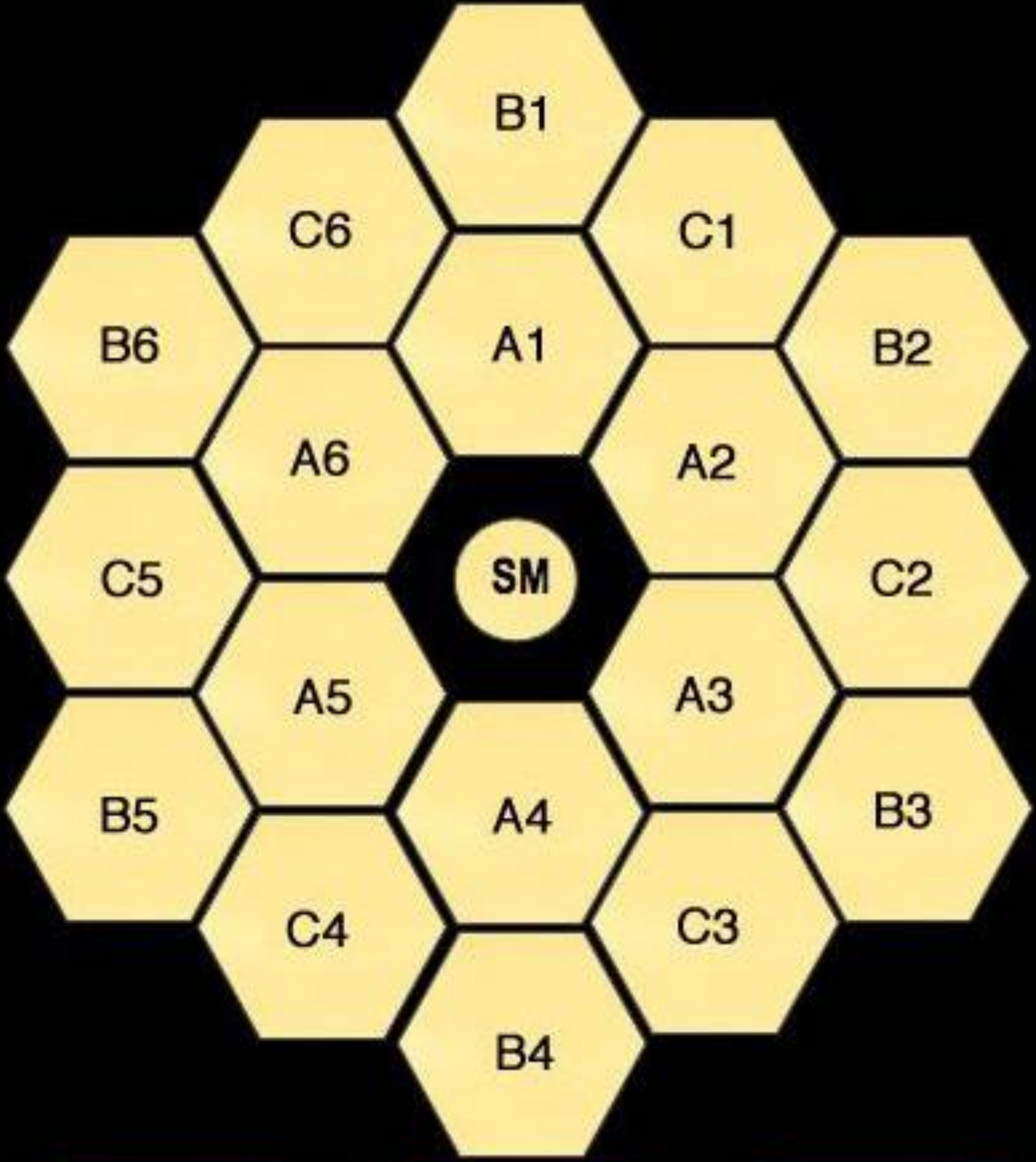


C2

A6

B8

C6



A5

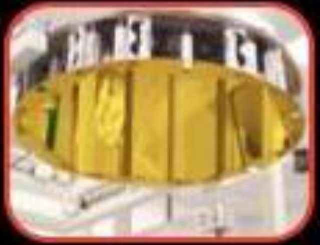
Secondary

A2

C4

Tertiary

B5



B3

Fine Steering

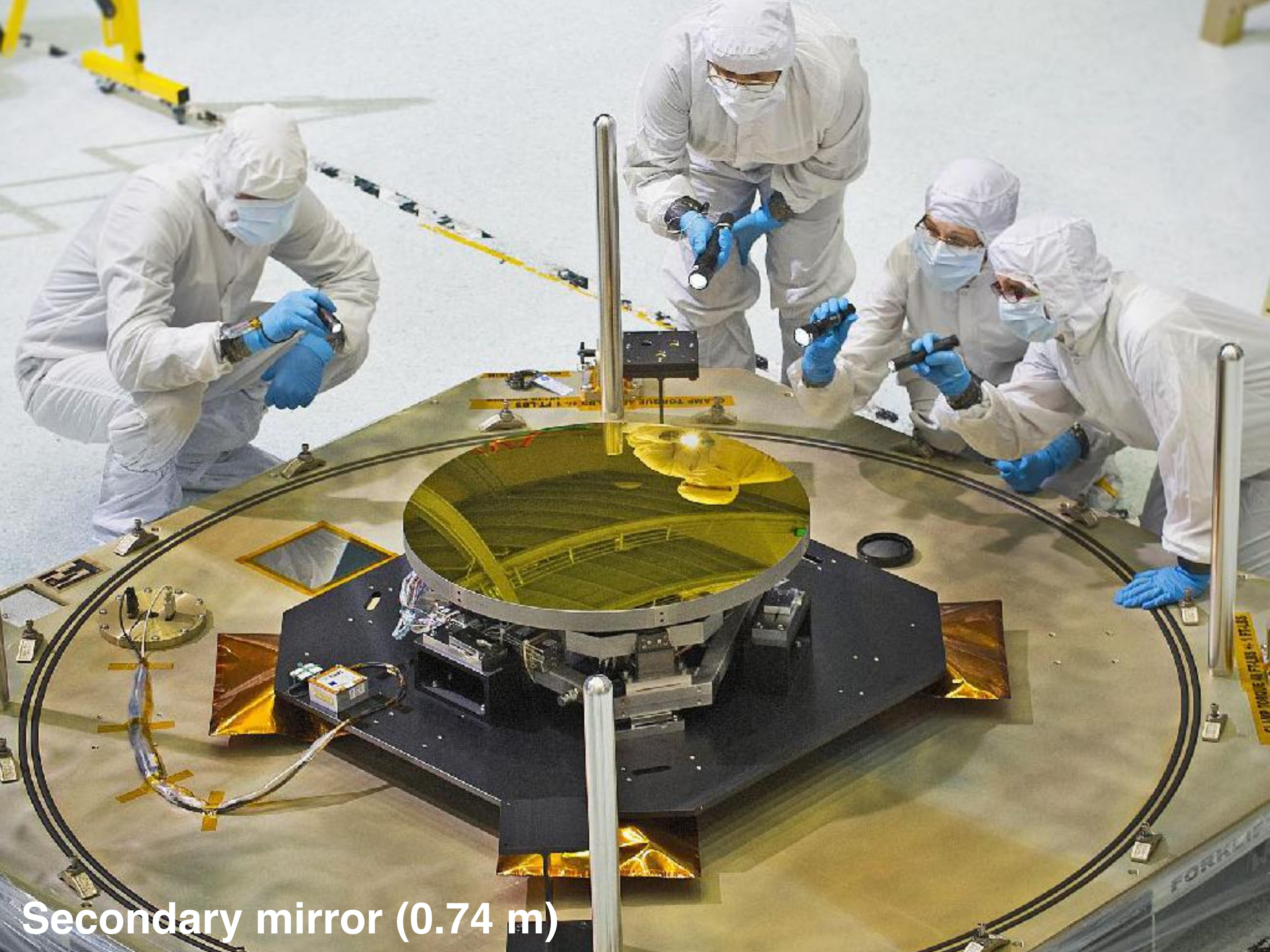
C5

B6

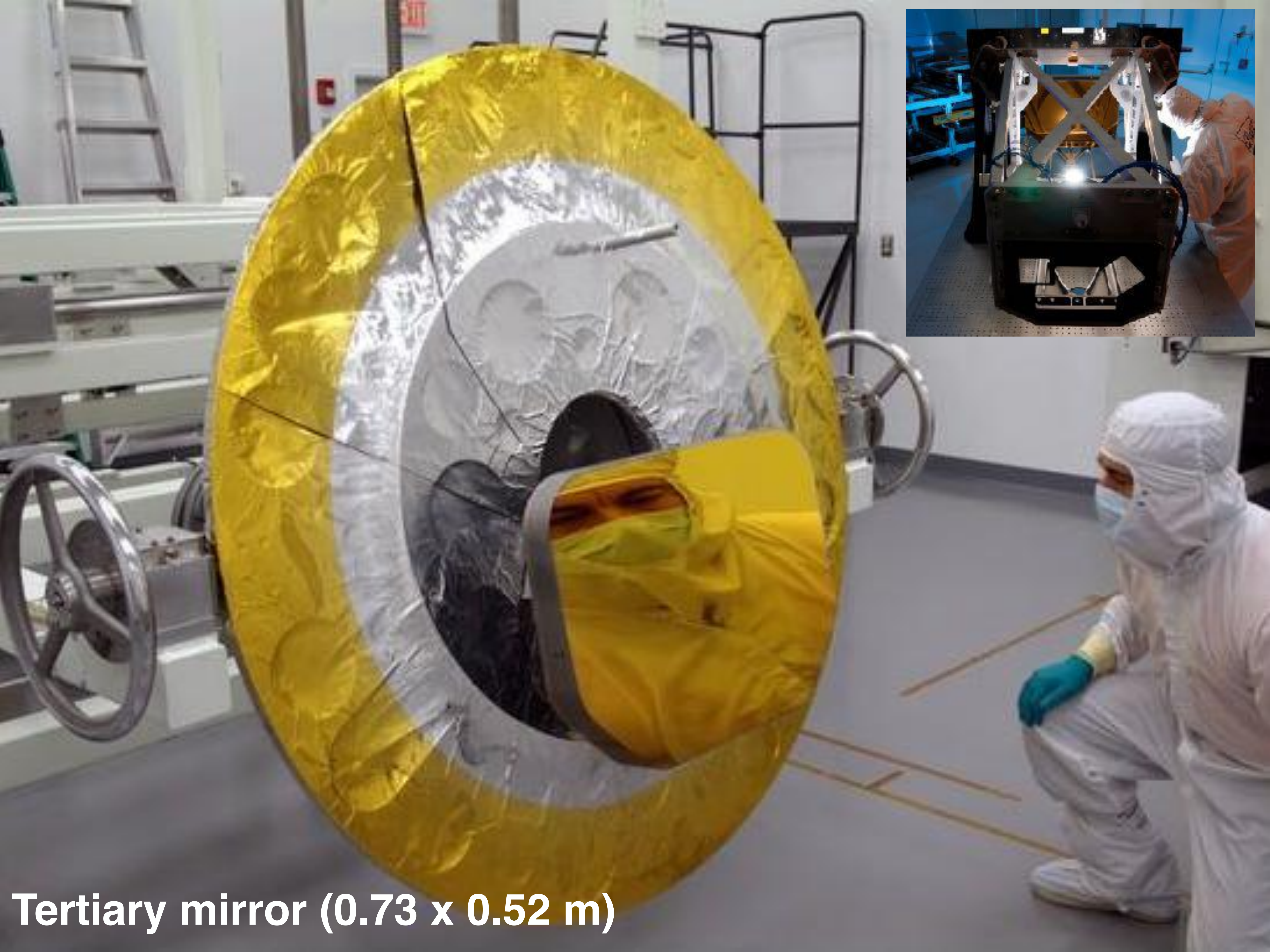
A1

C3

A4

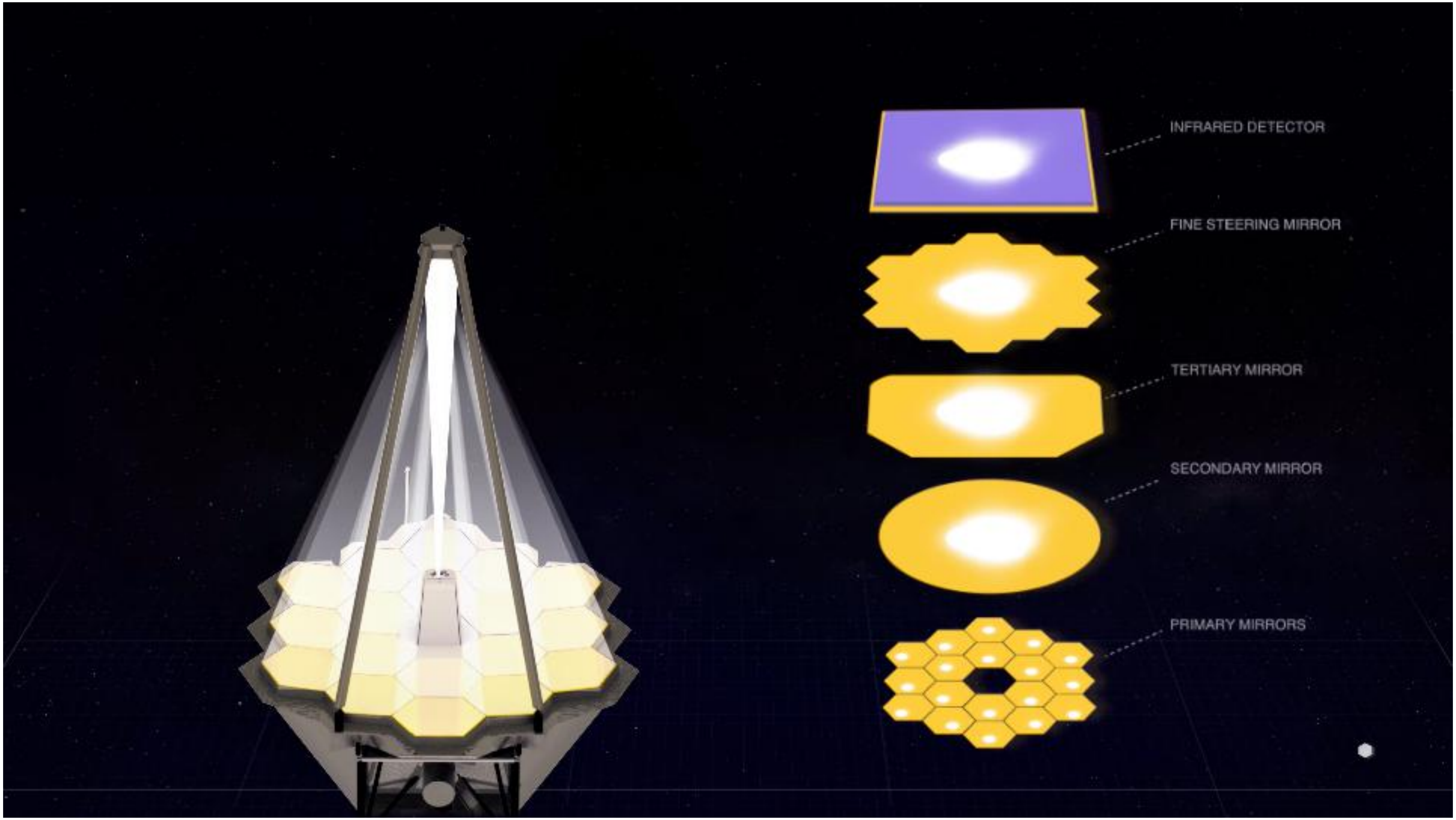


Secondary mirror (0.74 m)



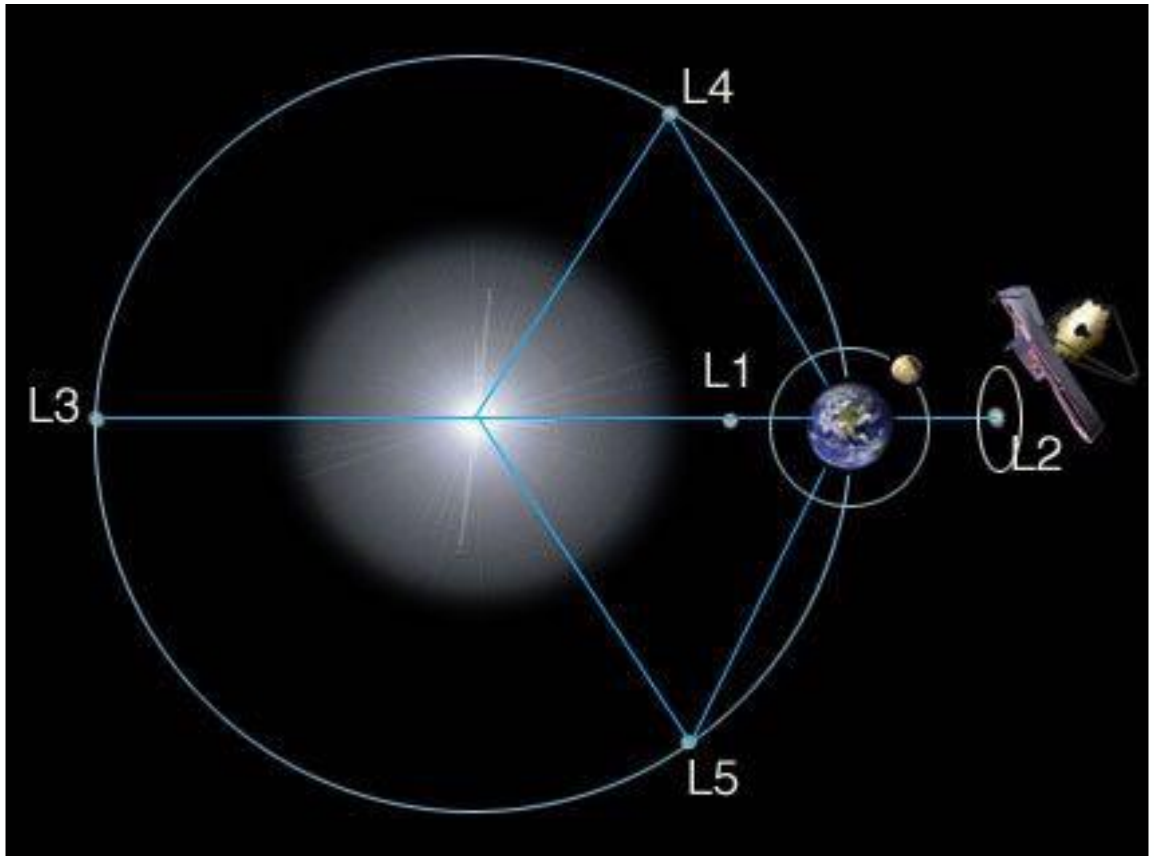
Tertiary mirror (0.73 x 0.52 m)

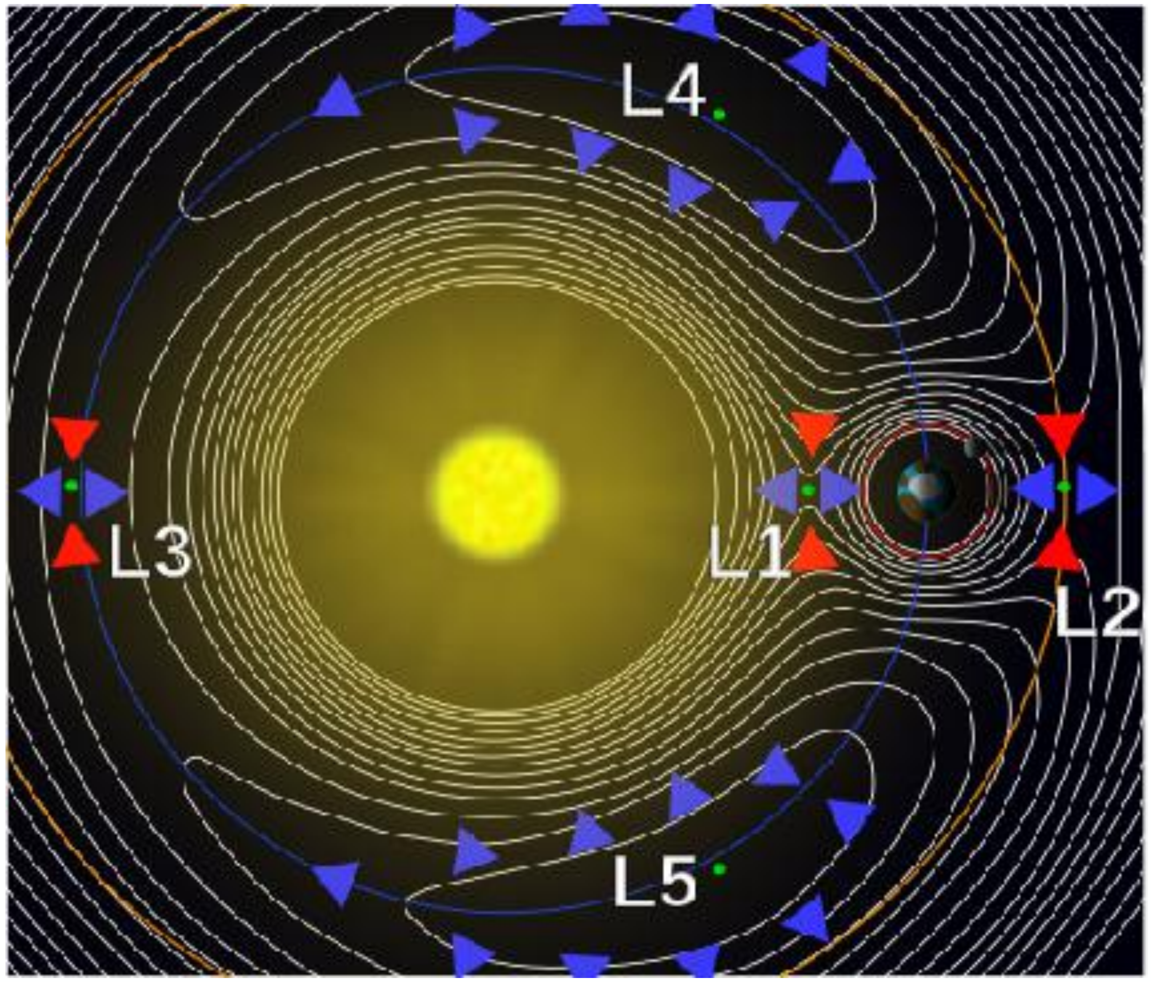
Phasing of the primary mirror segments



each mirror will be aligned to 1/10000th the thickness of a human hair!

JWST will go to L2

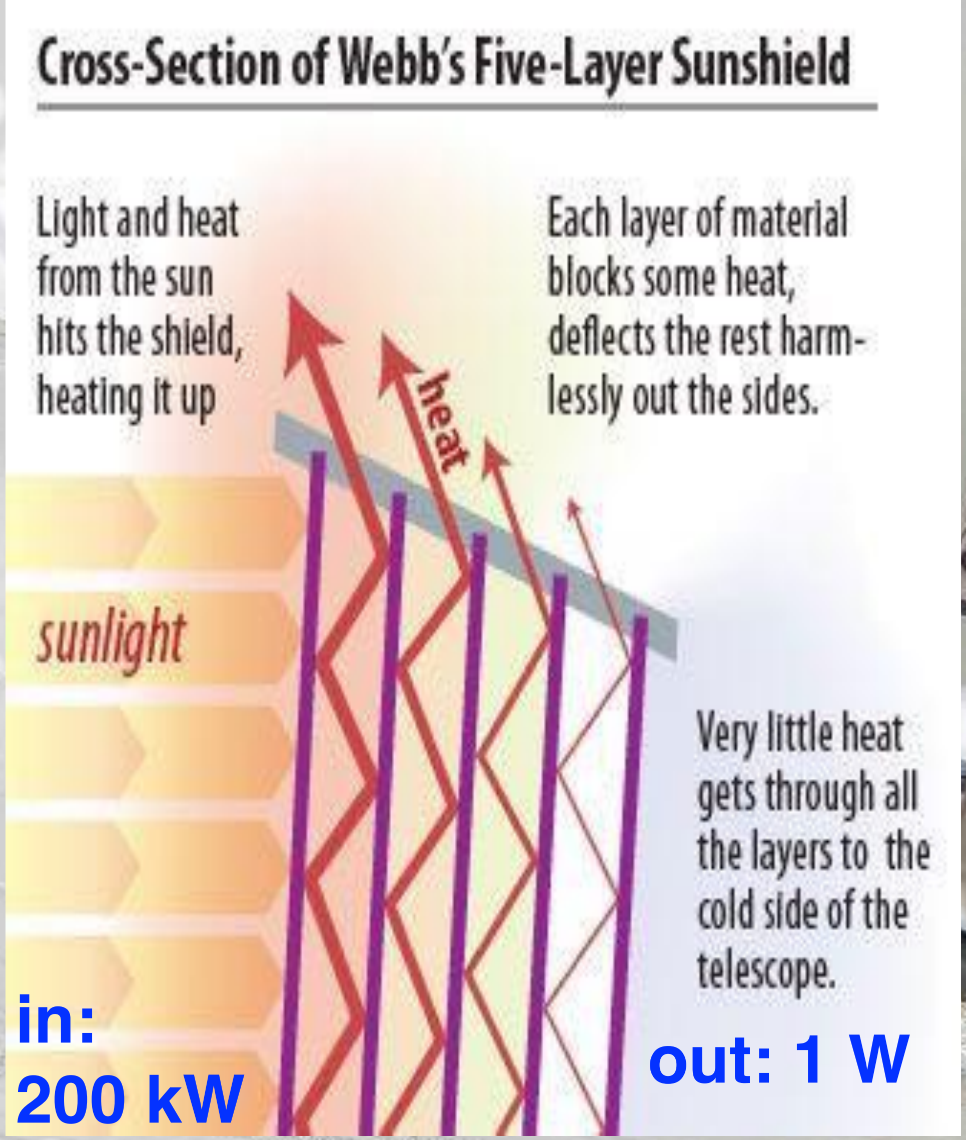




the magic of the Sun-Earth system Lagrange points:

JWST will be “passively cooled” to near cryogenic

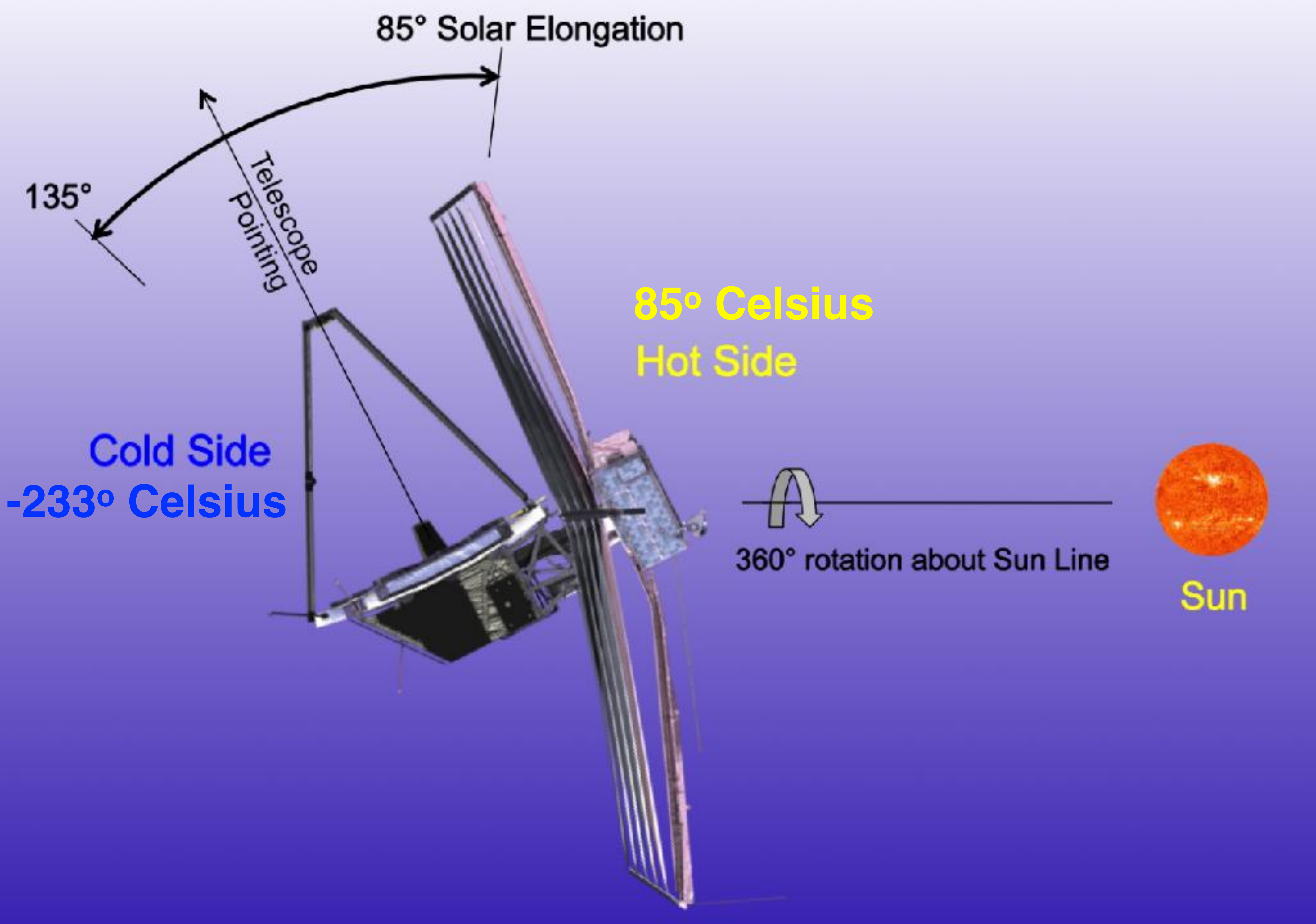
21 x 14 m (5x)



in: 200 kW

out: 1 W

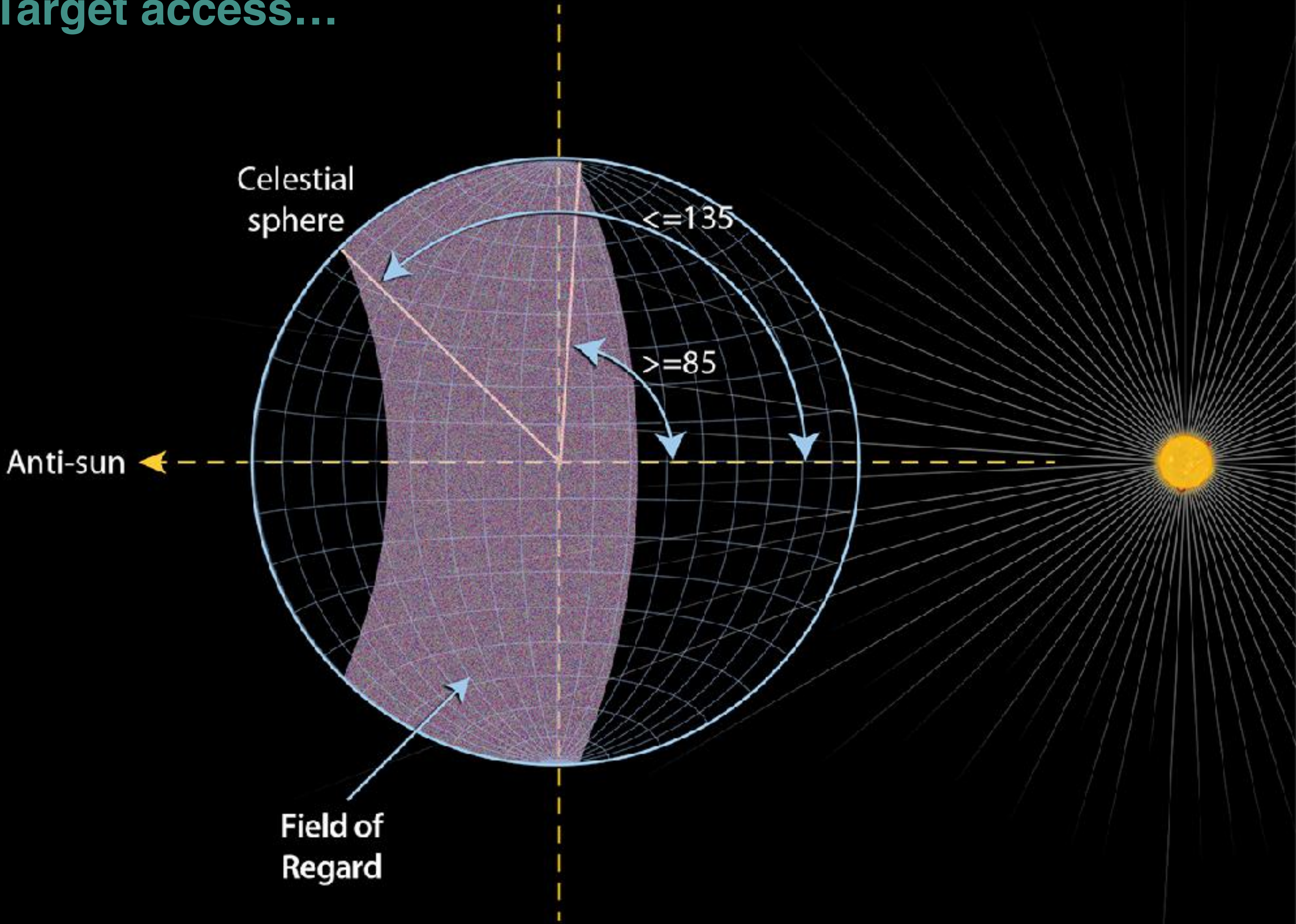
Keepin' it cool…



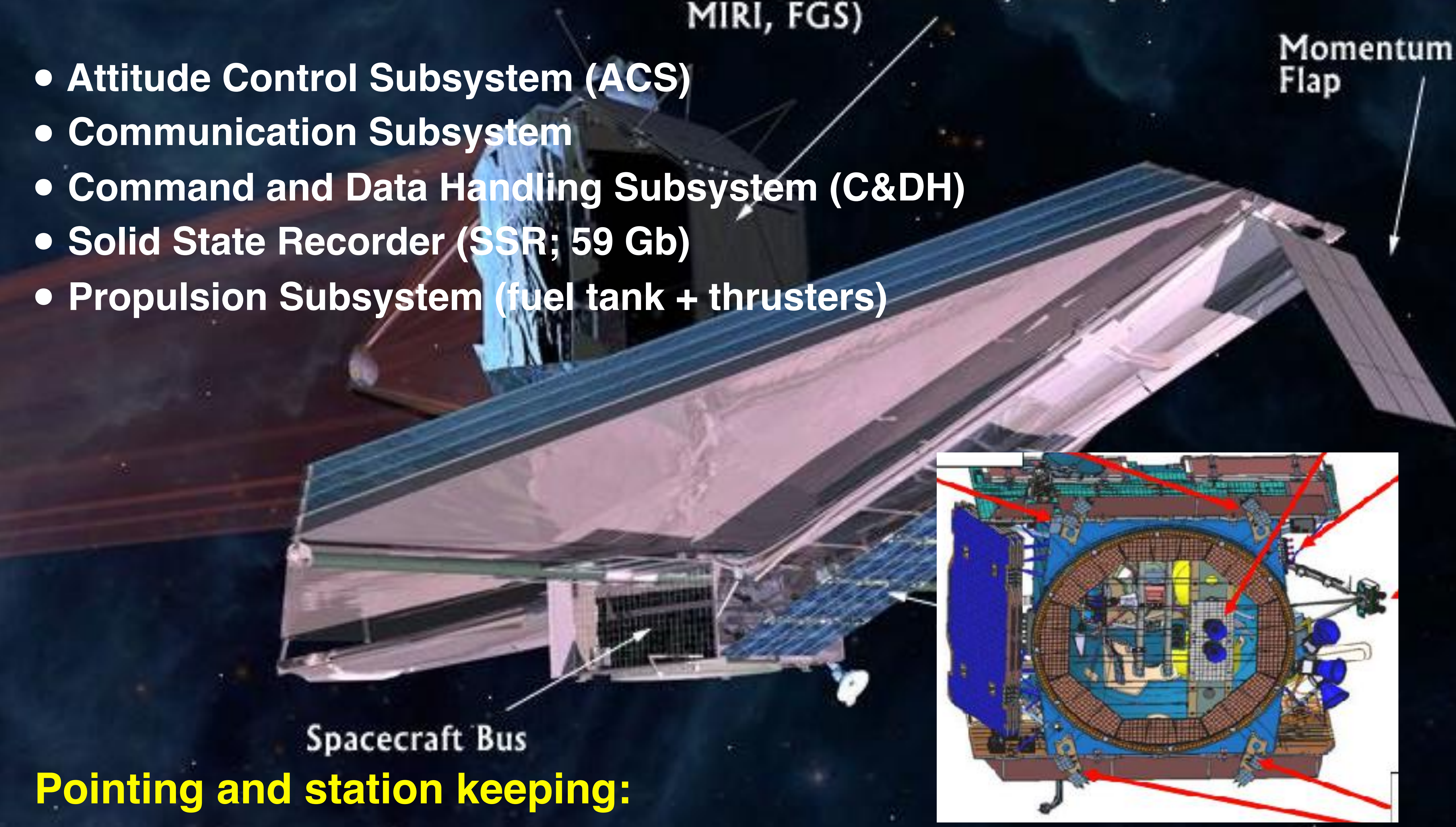
85° Celsius

-233° Celsius

Target access…



Spacecraft bus

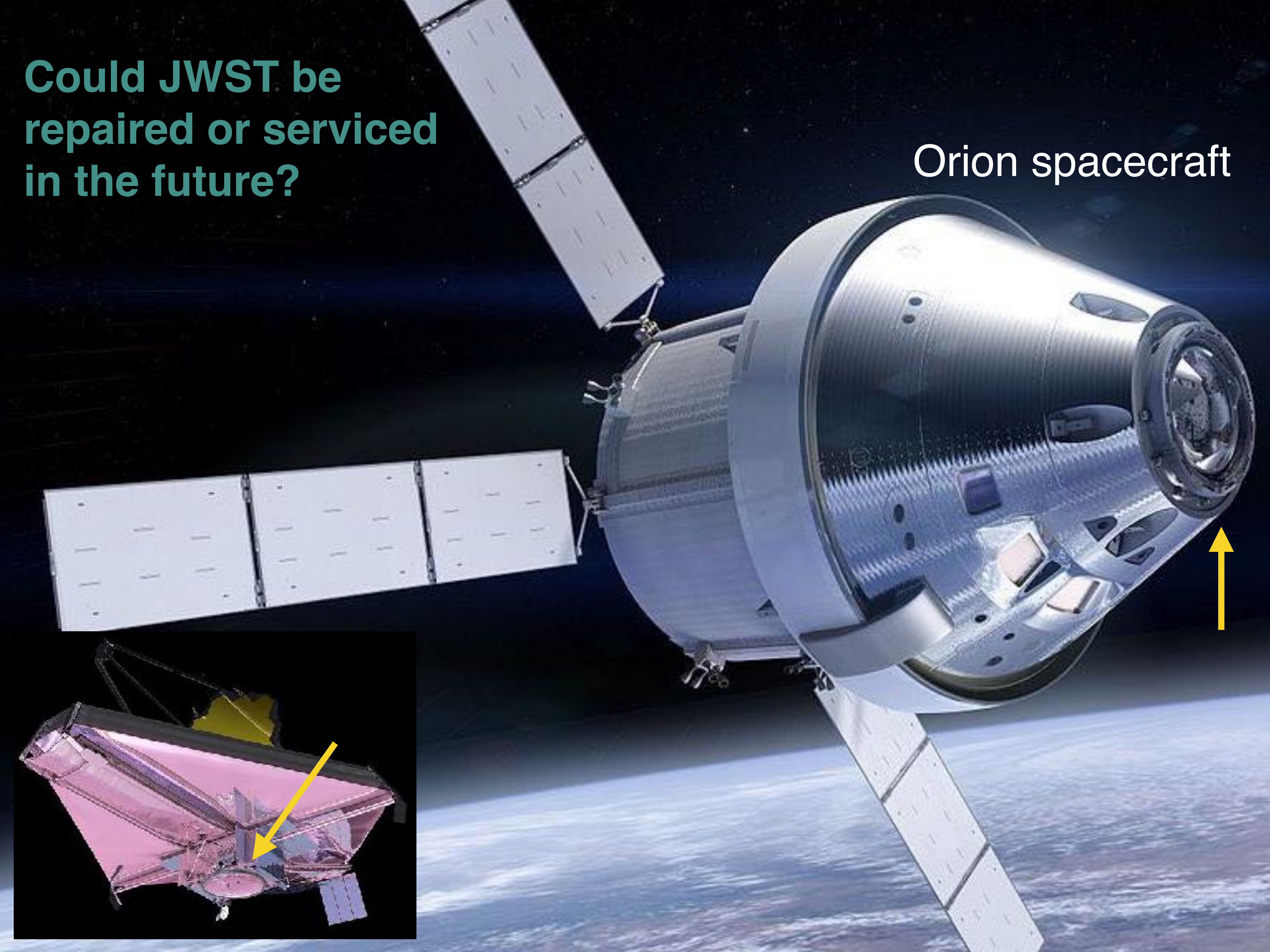


- Attitude Control Subsystem (ACS)
- Communication Subsystem
- Command and Data Handling Subsystem (C&DH)
- Solid State Recorder (SSR; 59 Gb)
- Propulsion Subsystem (fuel tank + thrusters)

Pointing and station keeping:

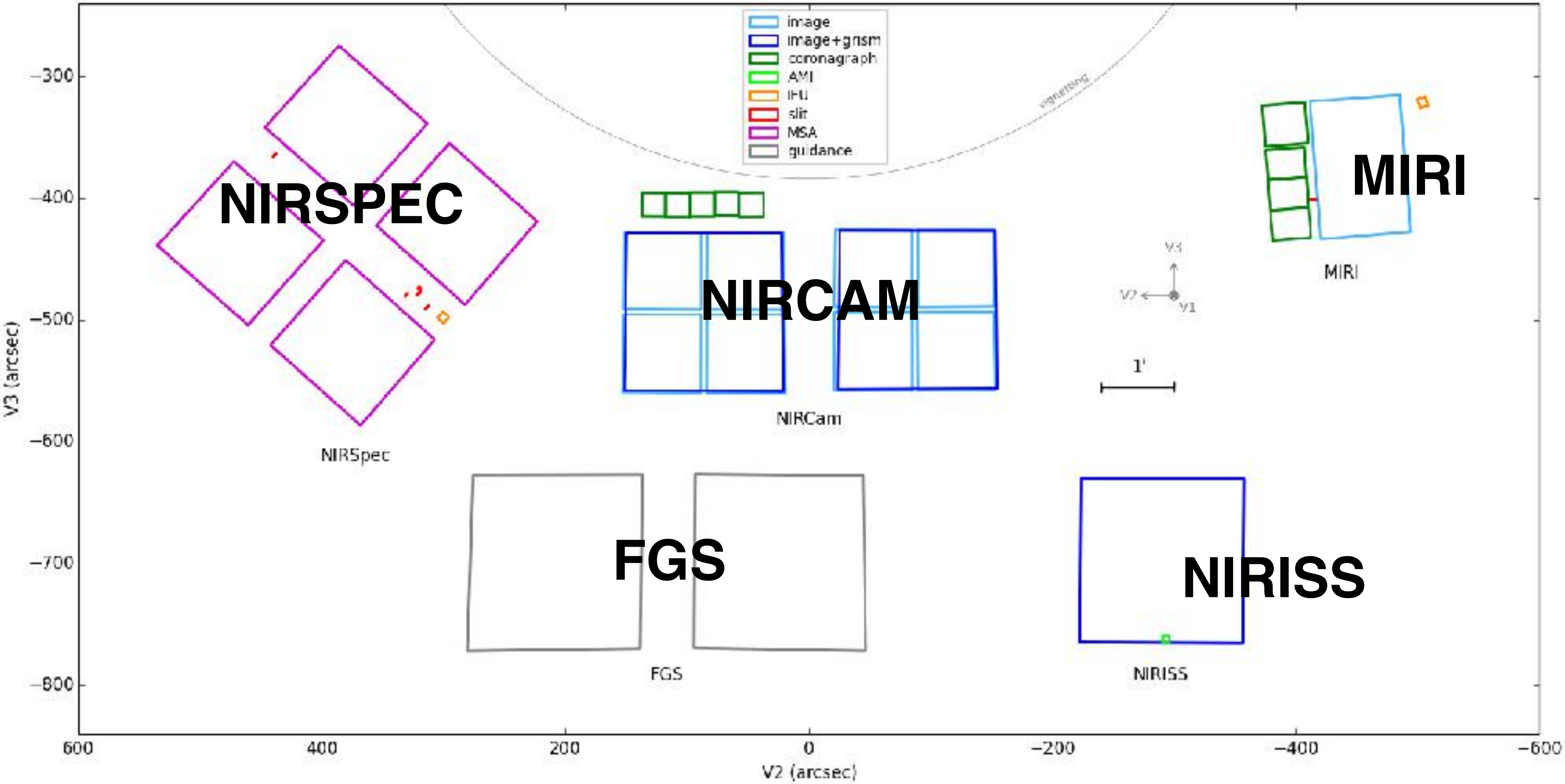
ACS: 3 star trackers, 6 gyroscopes, 6 reaction wheels change the orientation of the telescope without having to use thrusters

Could JWST be repaired or serviced in the future?



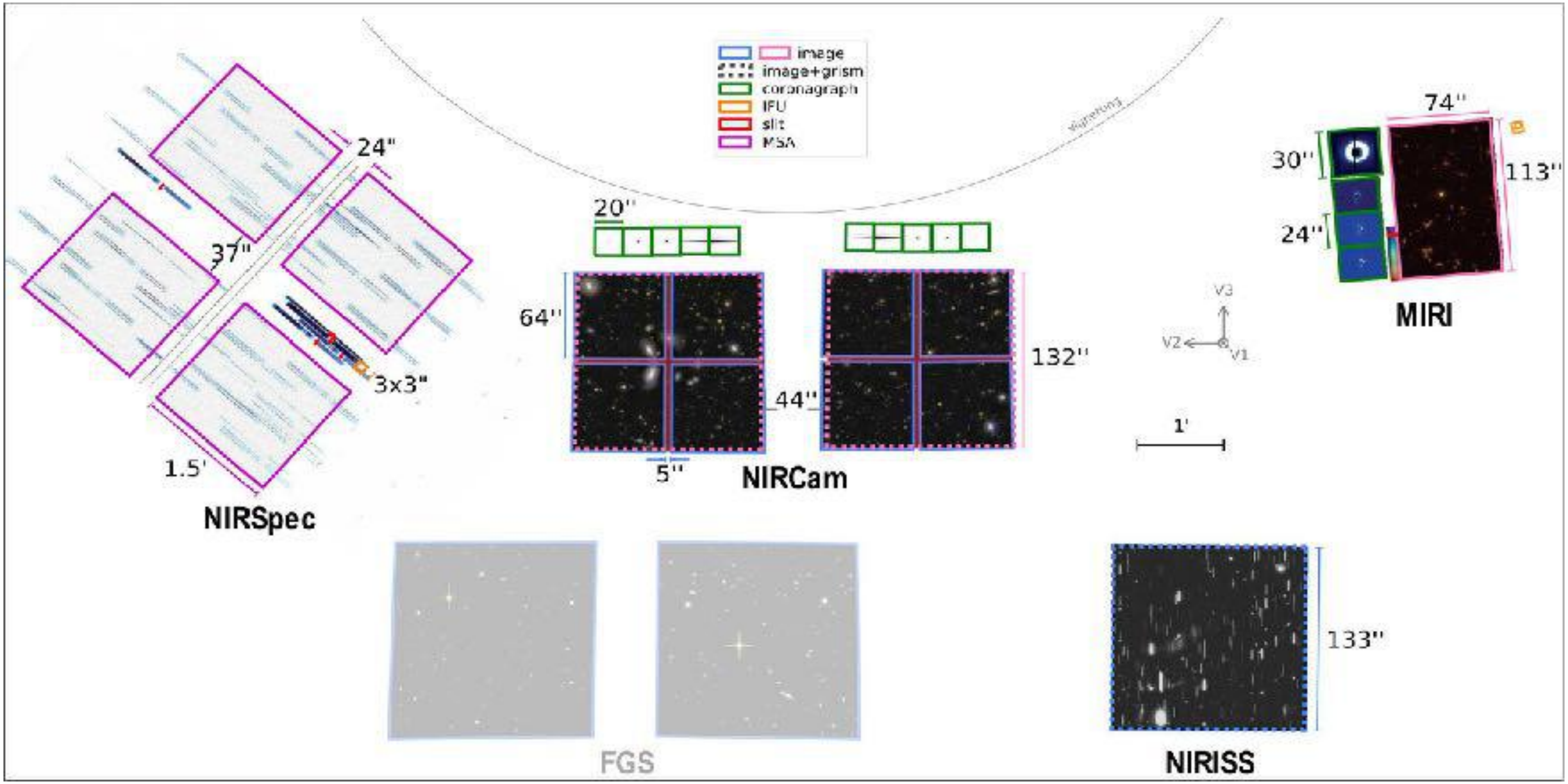
Integrated Science Instruments Module (ISIM)

Integrated Science Instruments Module (ISIM)



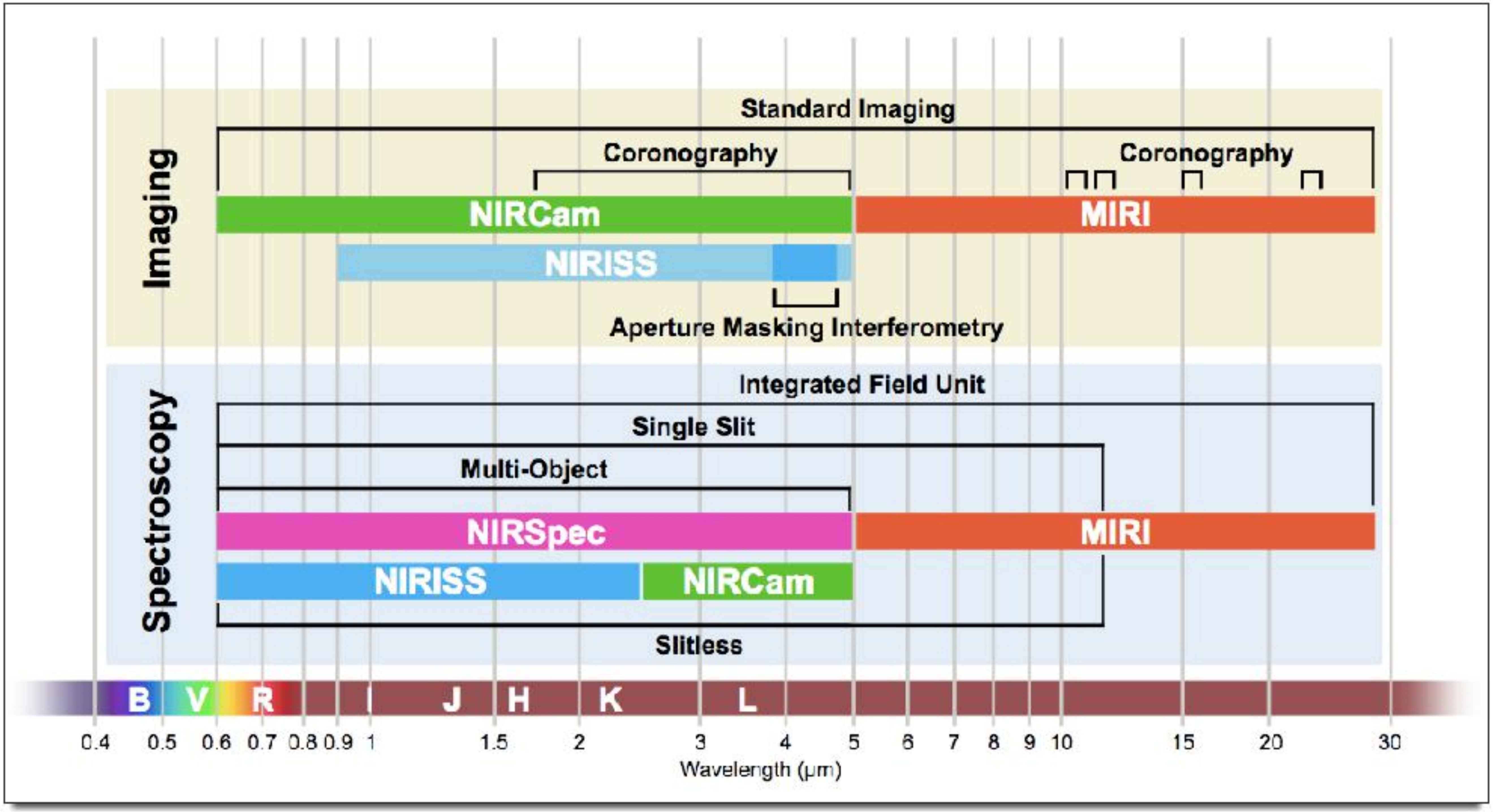
https://jwst-docs.stsci.edu/display/JTI/JWST+Field+of+View

Overview of JWST instruments’ fields of view



parallel observations allowed (with some caveats)

JWST Interactive Instrument Finding Chart…

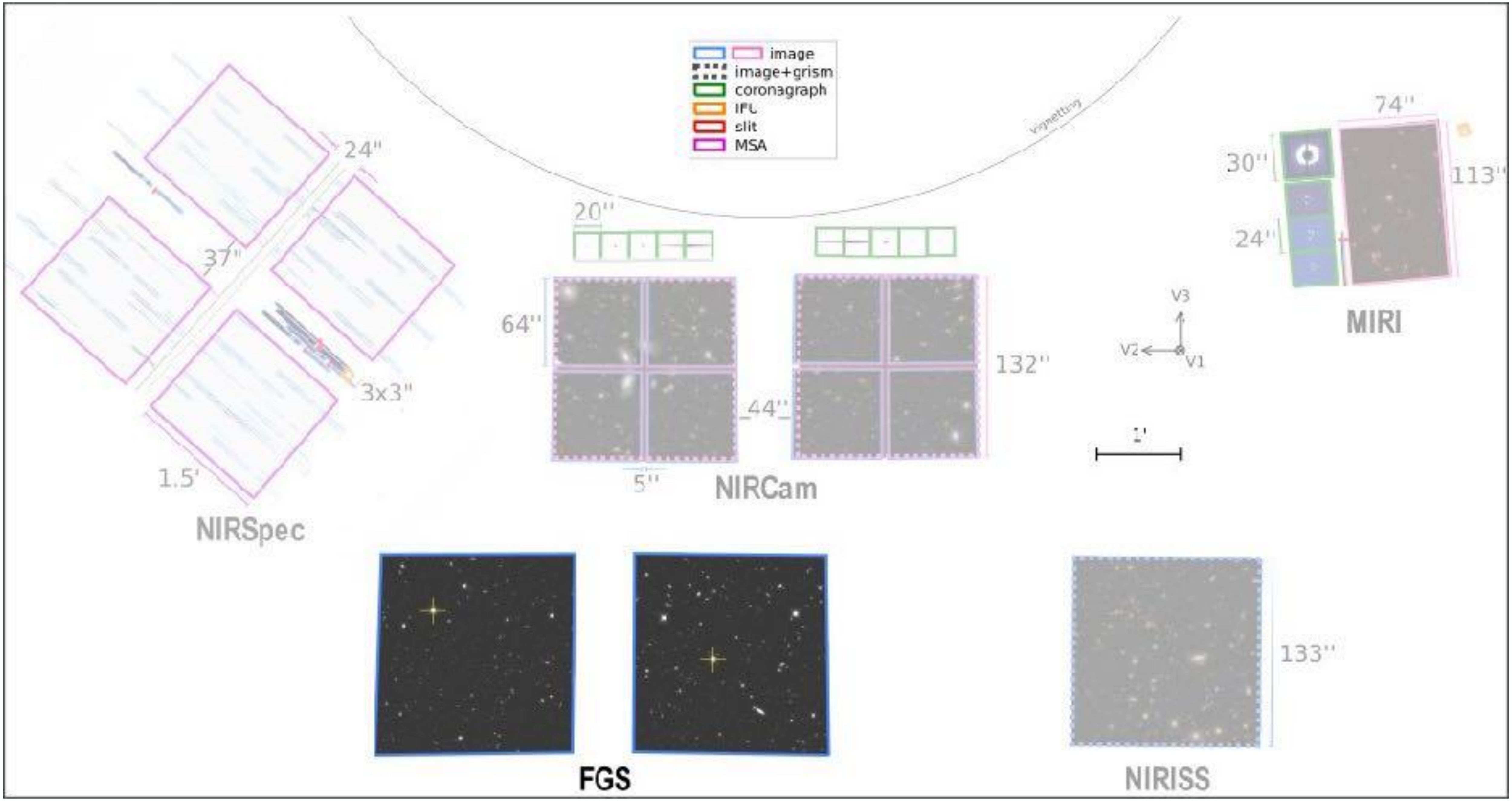


Fine Guidance Sensor (FGS)

1. Identify and acquire a guide star from the GSC 2.4 catalog

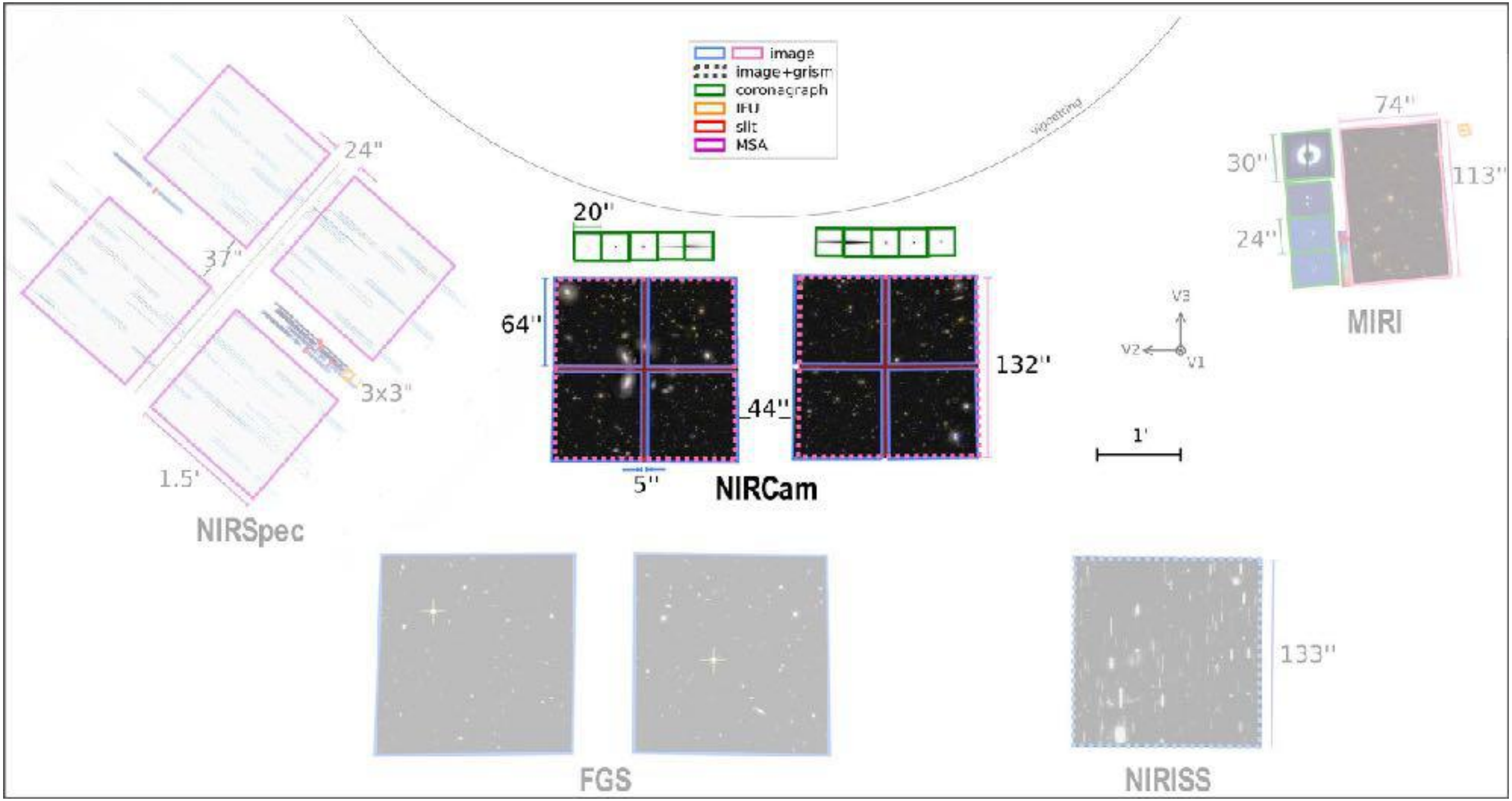
2. Track a moving target or fine-guiding of fixed target

- 0.6–5 μm imaging of two 2.3’ × 2.3' fields

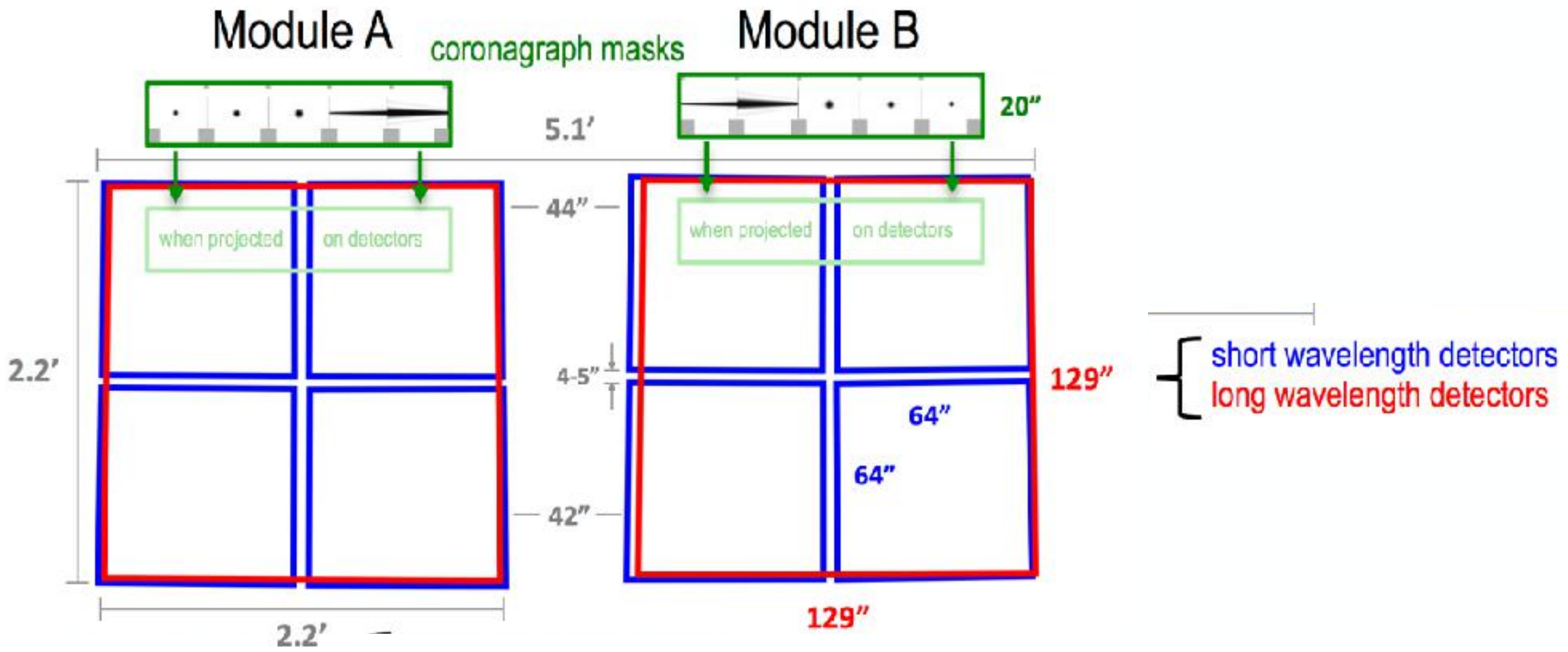


NIRCam Overview

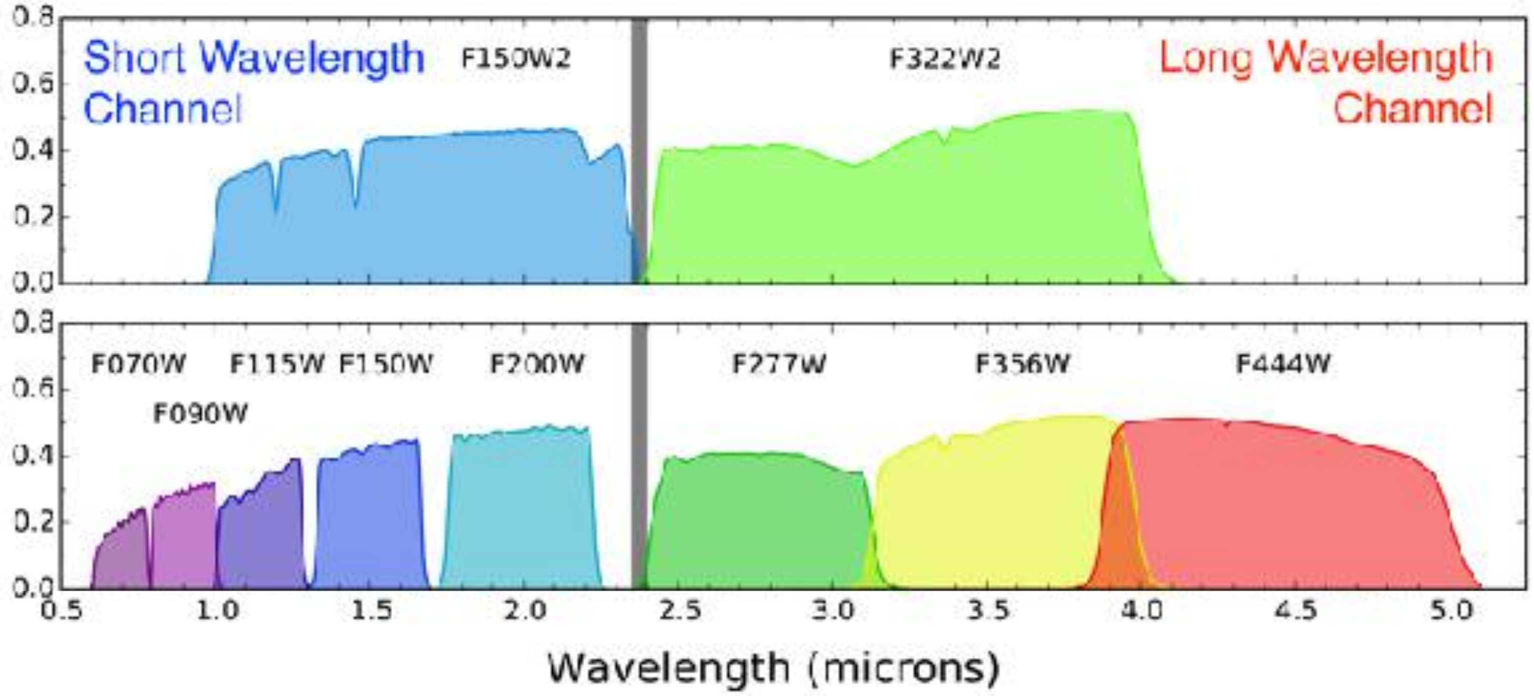
- 0.6–5 μm imaging of two 2.2'×2.2' fields in 2 channels simultaneously (0.06”–0.13” PSF)
- coronagraphic imaging with occulting masks (spot and bar)
- wide field slitless spectroscopy (2.4–5.0 μm) using R = λ/Δλ ~ 1,600 grisms



NIRCam imaging in two channels

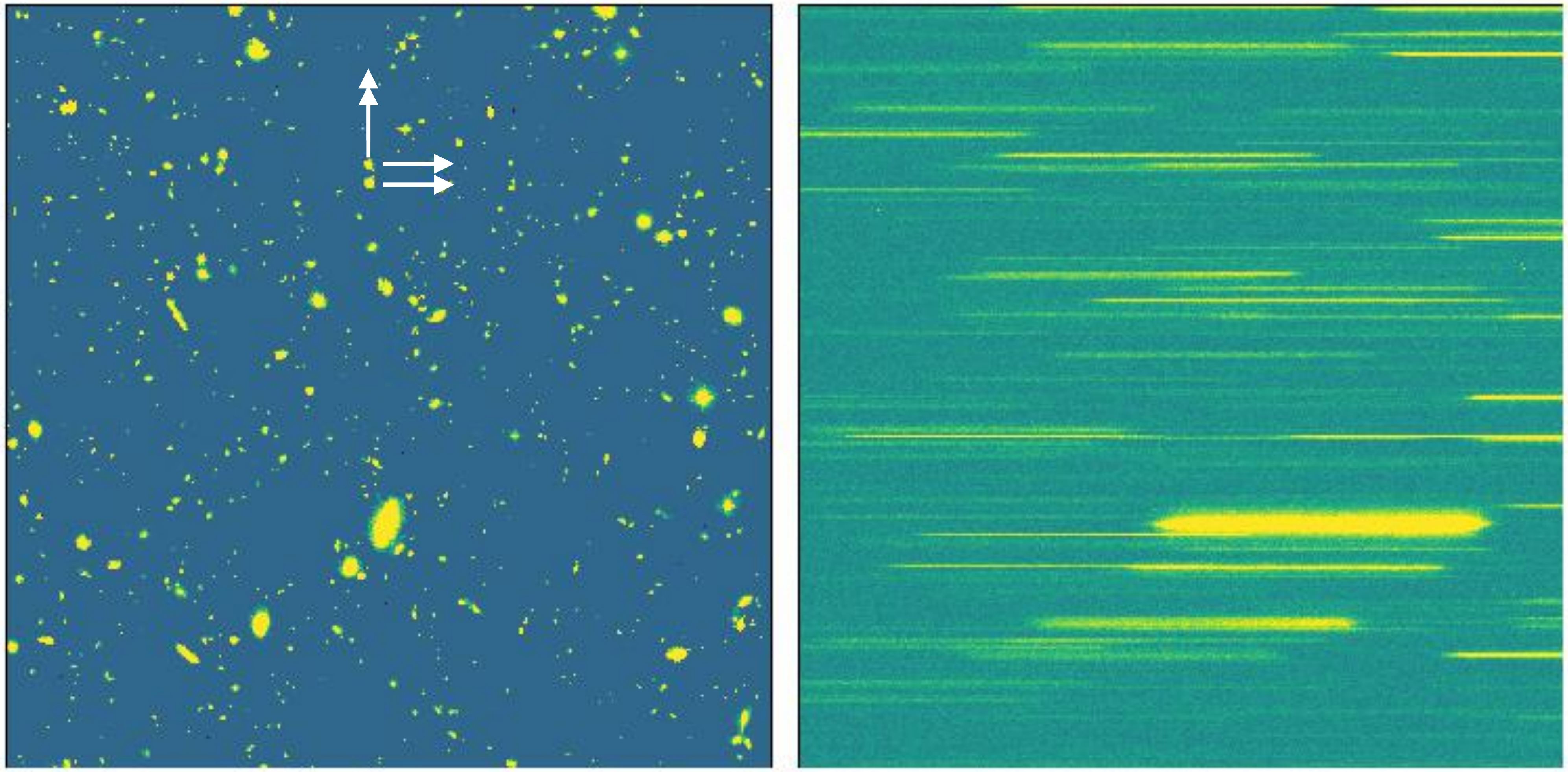


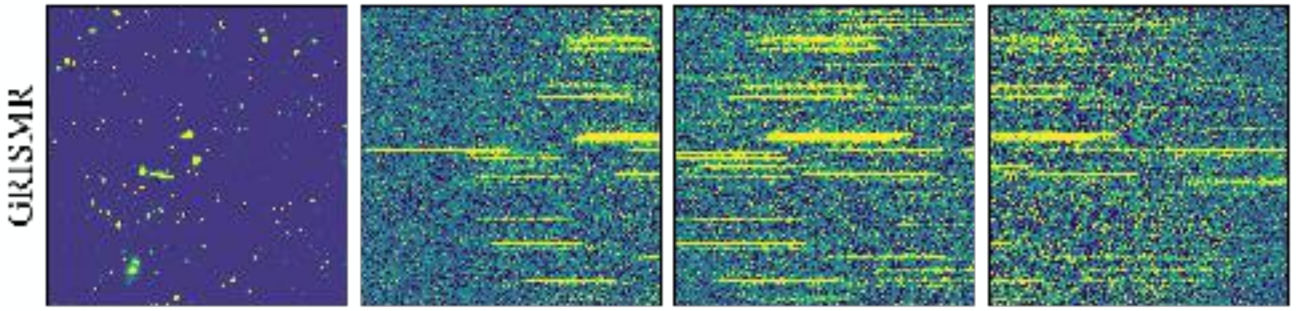
imaging filters:

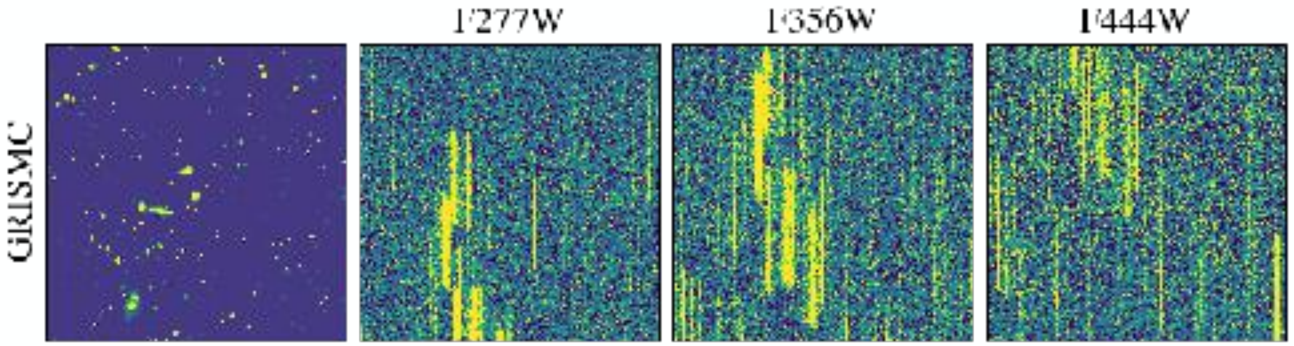


NIRCam slitless spectroscopy

- wide field slitless spectroscopy (2.4–5.0 μm) using R = λ/Δλ ~ 1,600 grisms
- simultaneously you get a short wavelength channel image
- spectra can be dispersed along columns or rows (use both to better separate sources)

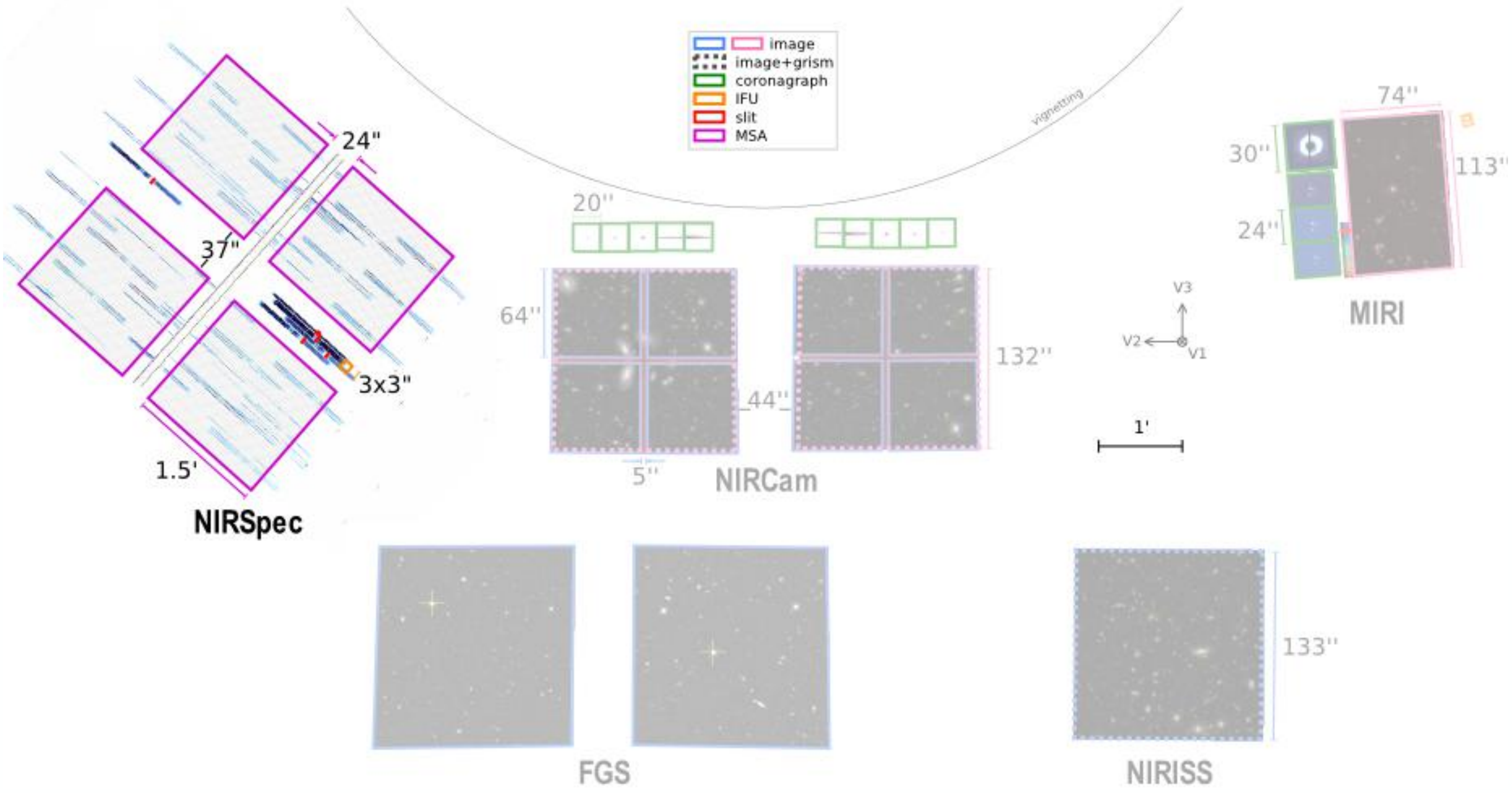






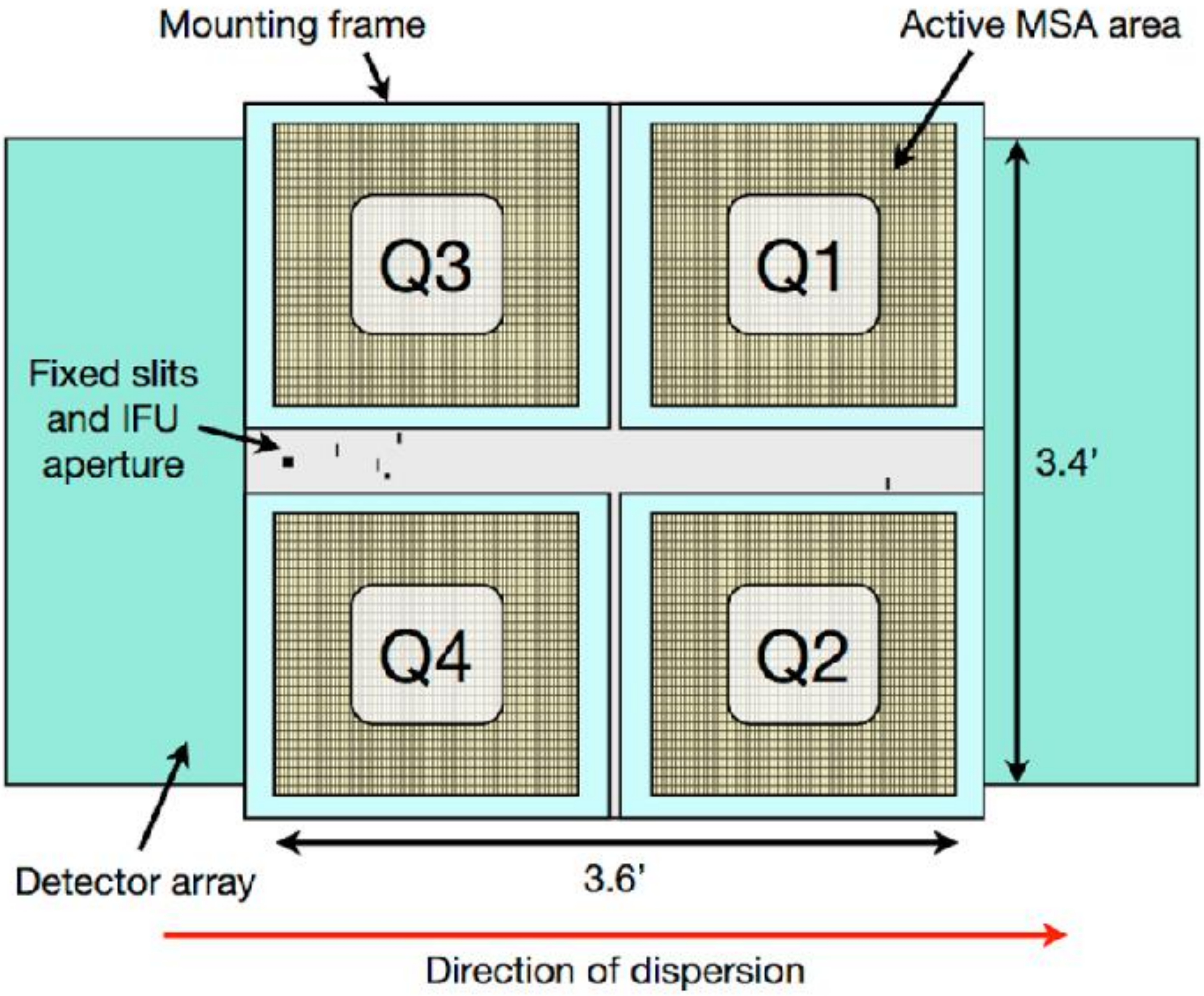
NIRSpec Overview

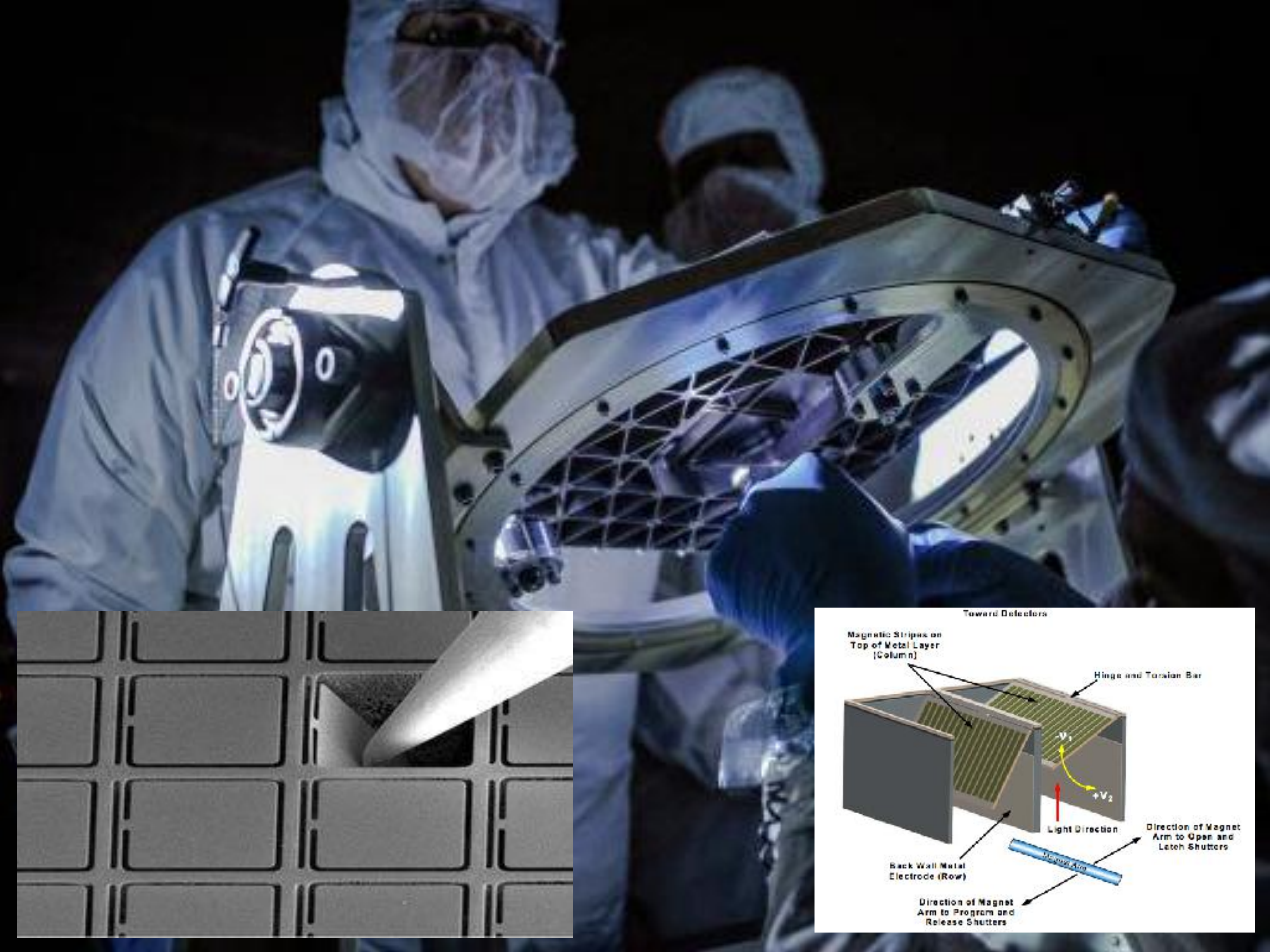
- 0.6–5.3 μm spectroscopy in a 3.4'×3.6' field (4 separate quadrants)
- MSA: multi-object spectroscopy, fixed slits, and 1 integral-field spectrograph (3”x3”)
- medium (R~1000) and high (R~2700) resolution)



NIRSpec Micro Shutter Array (MSA)

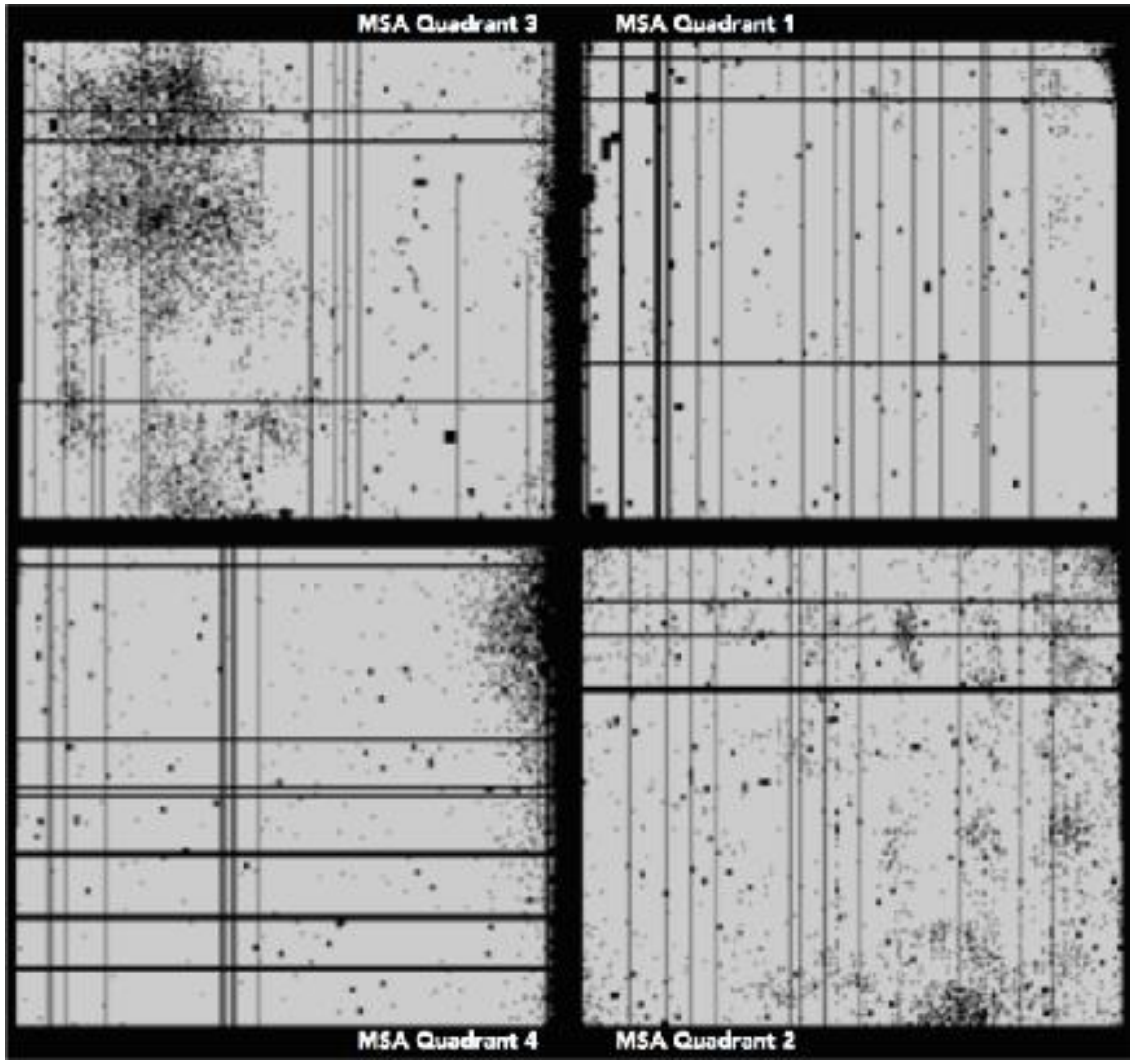
- 250,000 microshutters of 0.2”x0.46” in 4 quadrants
- opened and closed in any desired configuration by a magnetic “arm”

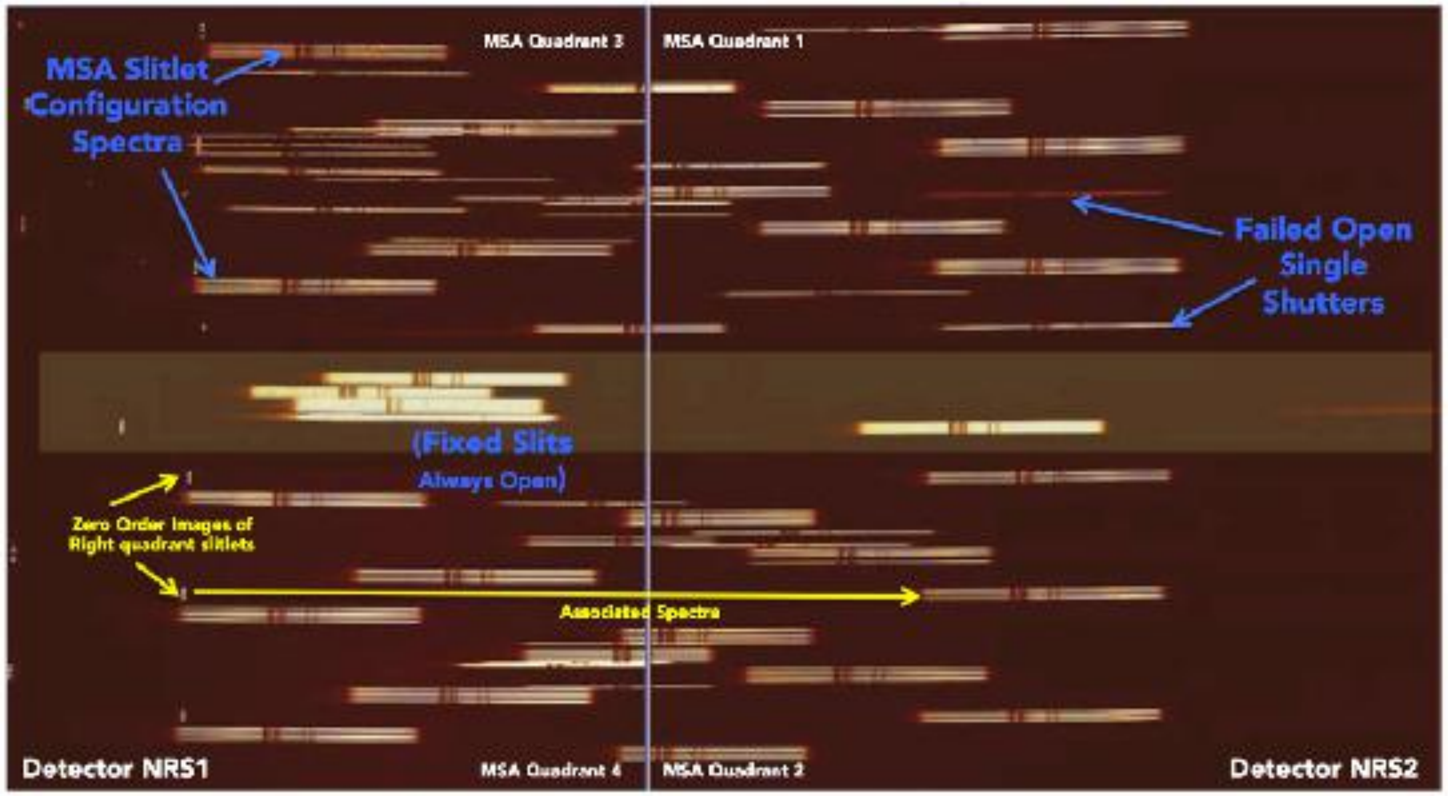



Toward Detectors
Magnetic Stripes on Top of Metal Layer (Column)
Hinge and Torsion Bar
$-V_1$
$+V_2$
Light Direction
Direction of Magnet Arm to Open and Latch Shutters
Magnet Arm
Back Wall Metal Electrode (Row)
Direction of Magnet Arm to Program and Release Shutters

NIRSpec microshutter array

- ~14% of all shutters (~35,000) permanently broken (closed) and not useful for science
- about 24 microshutters permanently open (can create unwanted spectra)
- all these open and broken shutters make the planning difficult (APT will help you)

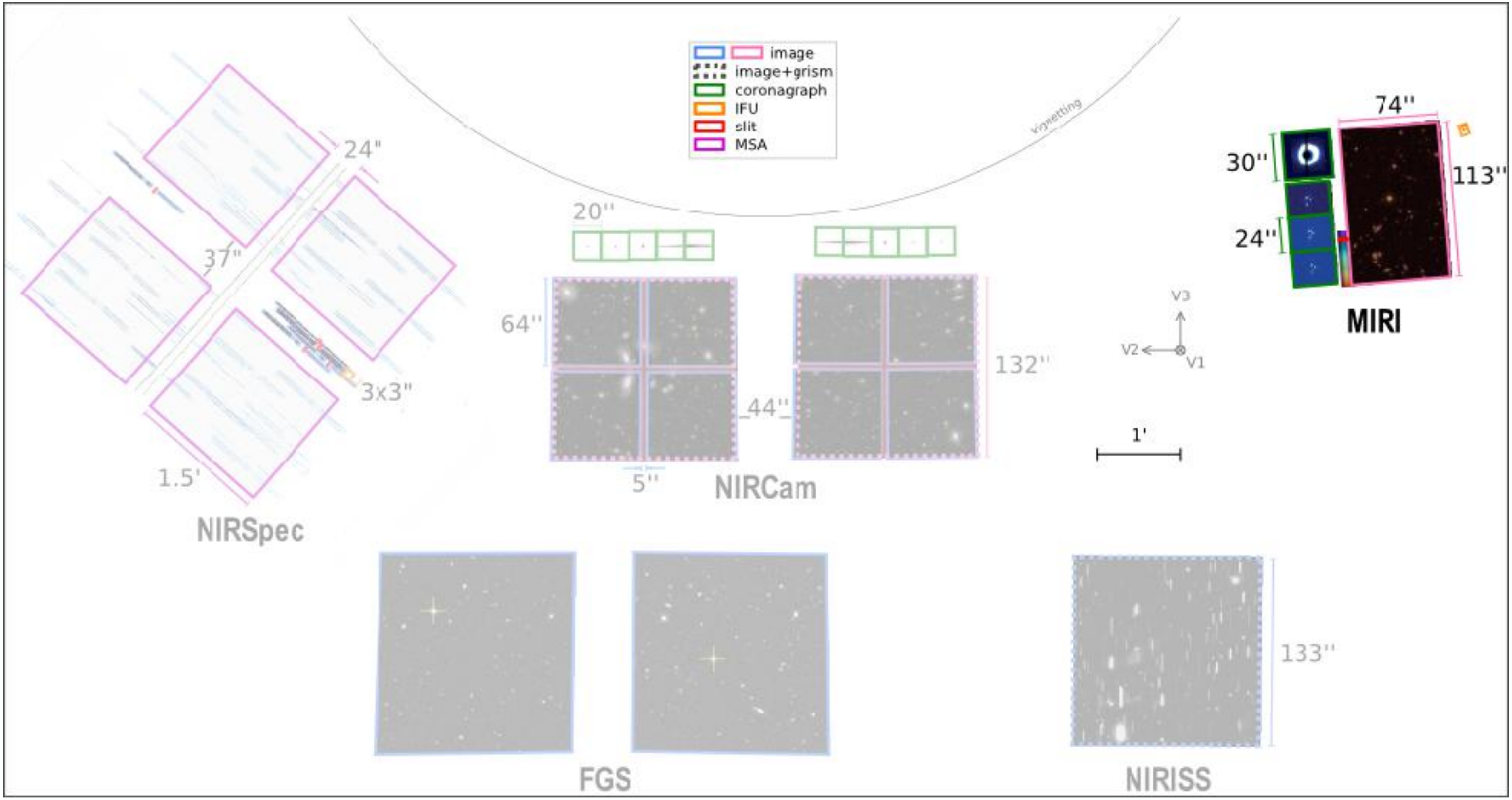




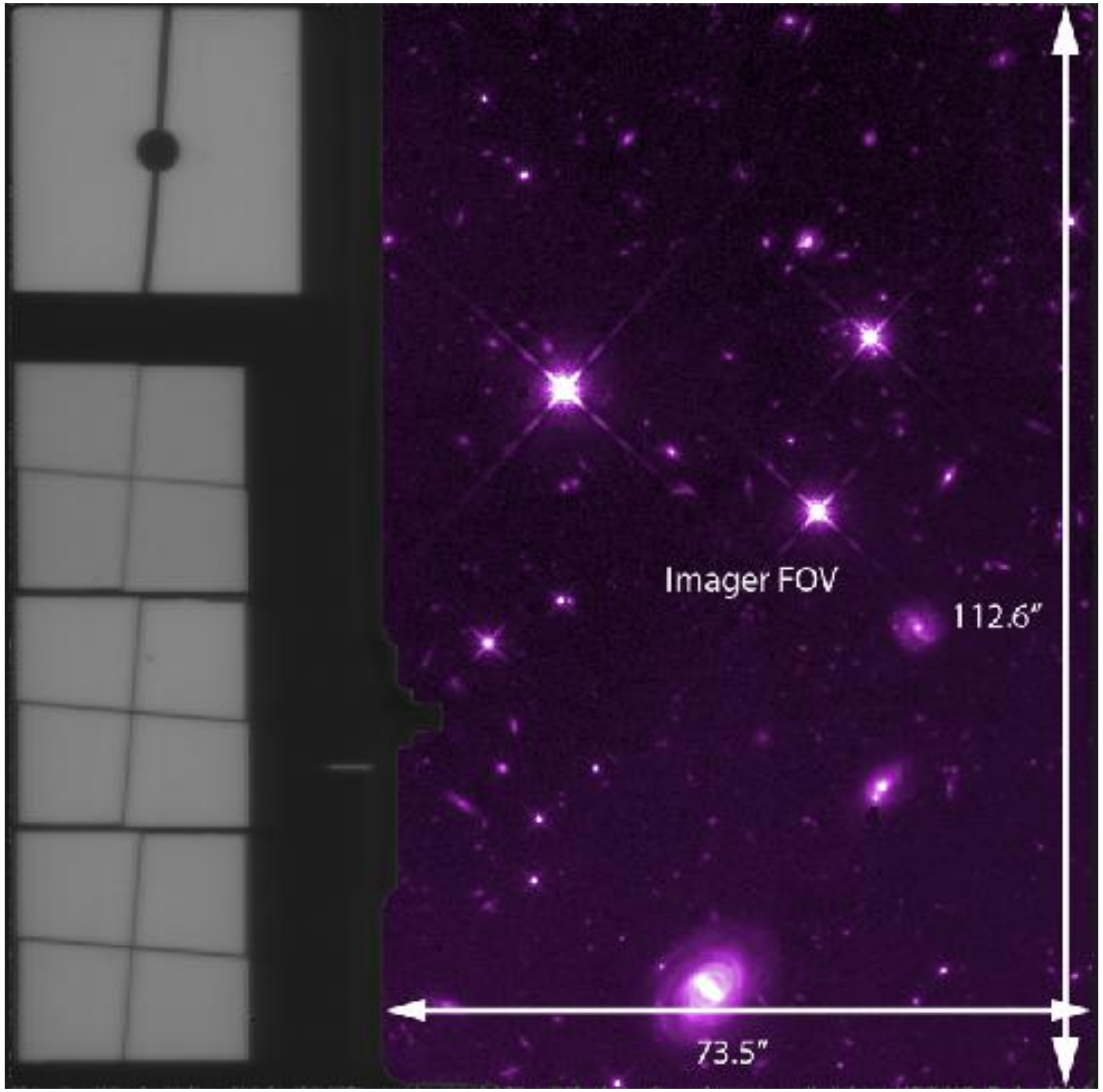
- you need to know your targets location **within ~50 mas (groundbased is no good)**
- in most cases: **pre-imaging with NIRCAM (or HST/WFC3)**

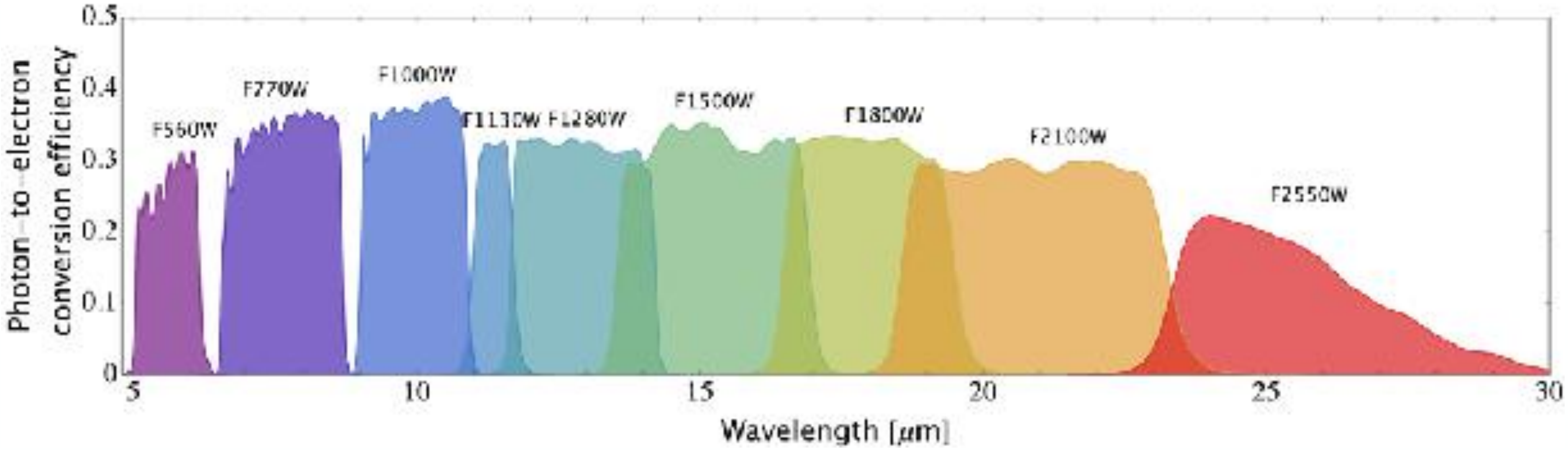
Mid-Infrared Instrument (MIRI) Overview

- 5.6 – 25.5 μm imaging over 74”×113” field (0.11”/pixel and 0.2”–1.0” PSF)
- coronagraphic imaging with occulting masks
- slit spectroscopy and medium resolution IFU of 7.2”x7.9” covering 5—28 μm



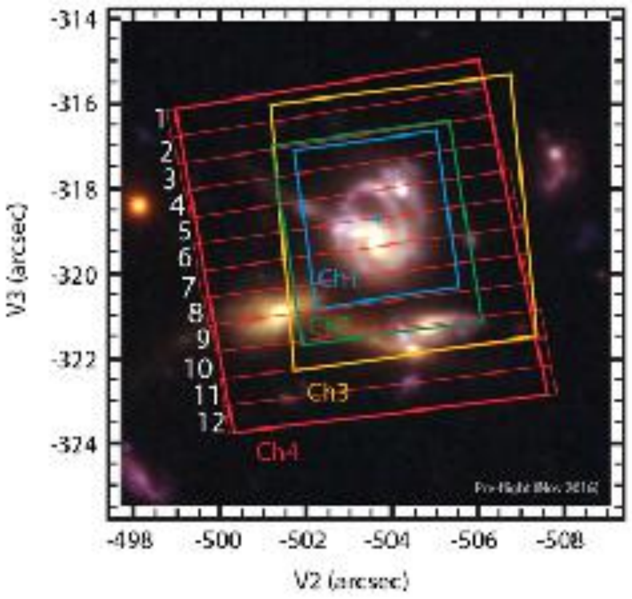
MIRI focal plane example



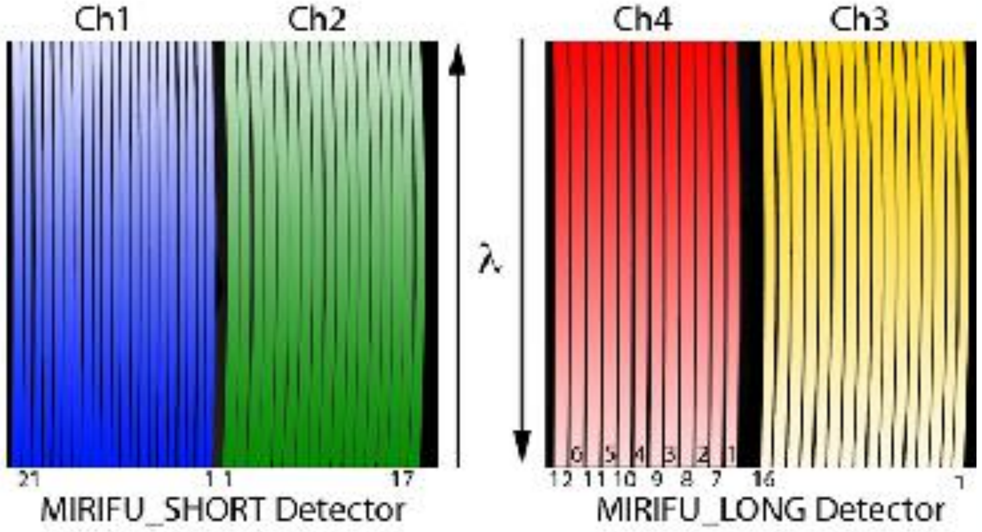


MIRI IFU example

IFU Footprint on Sky

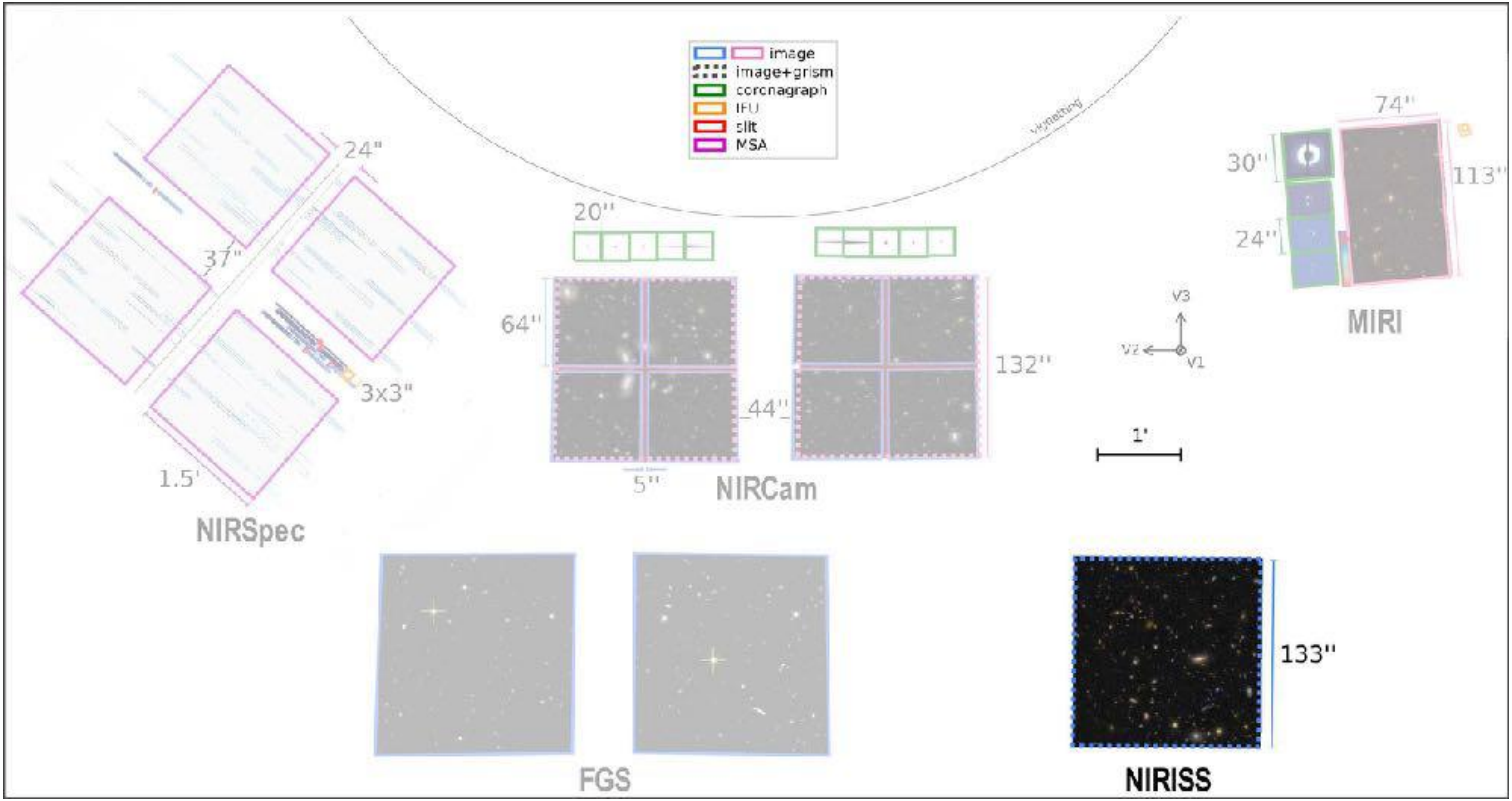


IFU Detector Layout



NIRISS Overview

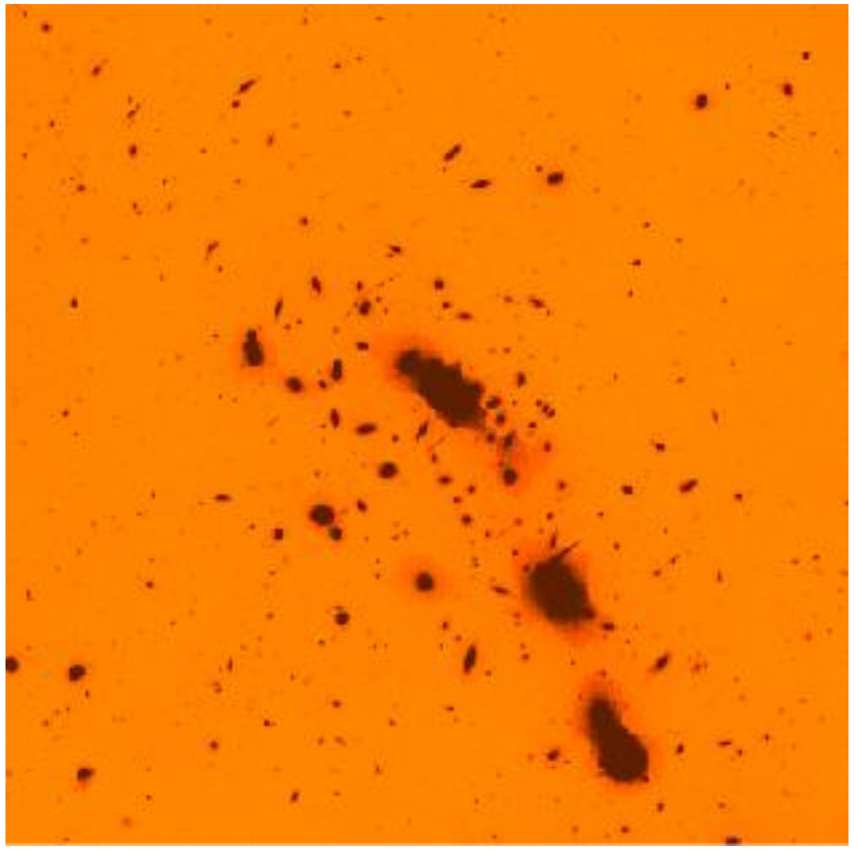
- wide field slitless spectroscopy (0.8–2.2 μm) of one 2.2'×2.2' field
- two identical R = λ/Δλ ~ 150 grisms with perpendicular dispersion
- acts as a 3rd detector when used in imaging in parallel with NIRCam (2x larger pixels)



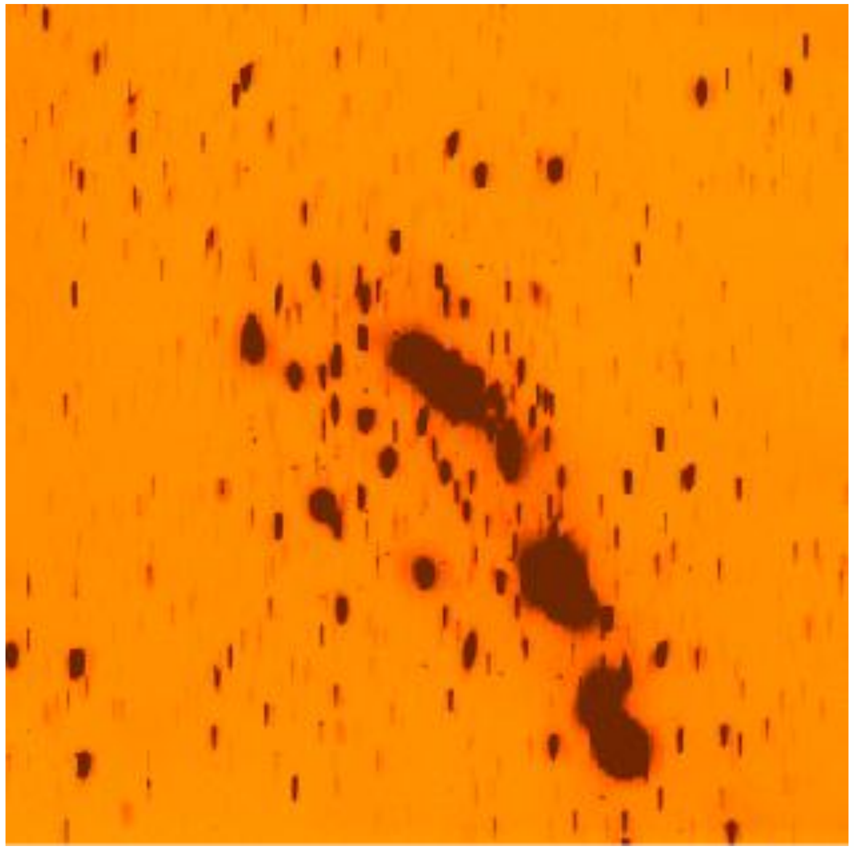
NIRISS example

massive lensing cluster MACS J0416.1–2403

- direct image

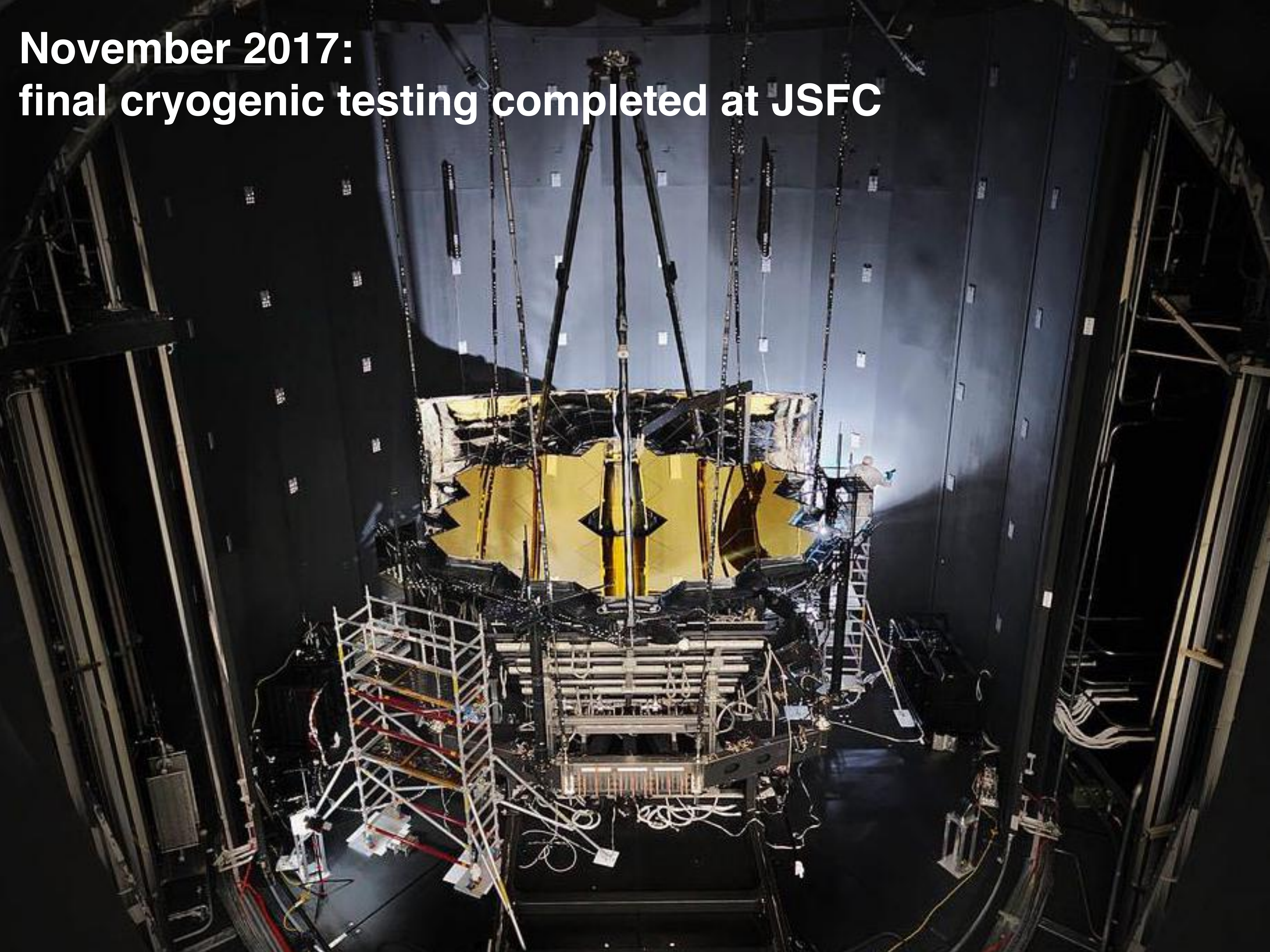


- column dispersed



- row dispersed

November 2017:
final cryogenic testing completed at JSFC

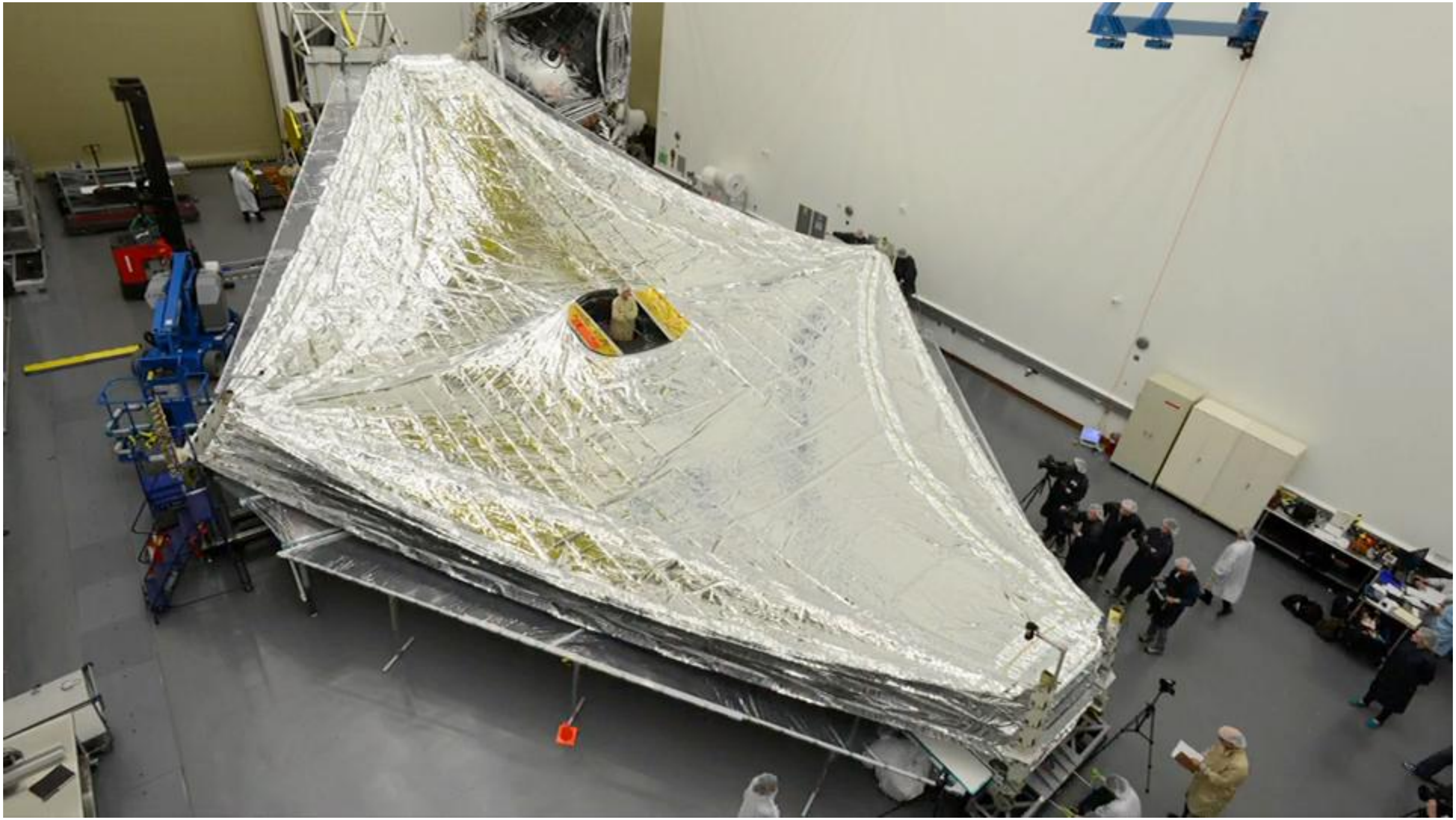


Feb 2, 2018:
arrival at Northrop Grumman (CA)

Feb 2, 2018:
arrival at Northrop Grumman (CA)


THROP GRUMMAN
JLG

JWST sunshield testing



JWST’s First year of science operations

- Calibration (5 months)
- Early Release Science Observations (ERS)
- Guaranteed Time Observations (GTO)
- General Observing Program (GO)

“Cycle 1”

13 ERS Programs were selected in 2017

ERS Programs have **no exclusive access period** - Enjoy!

(Exo-)Planetary:

Observations of the Jovian System (De Pater)
The Transiting Exoplanet ERS Program (Batalha)
High Contrast Imaging of Exoplanets with JWST (Hinkley)

Stellar:

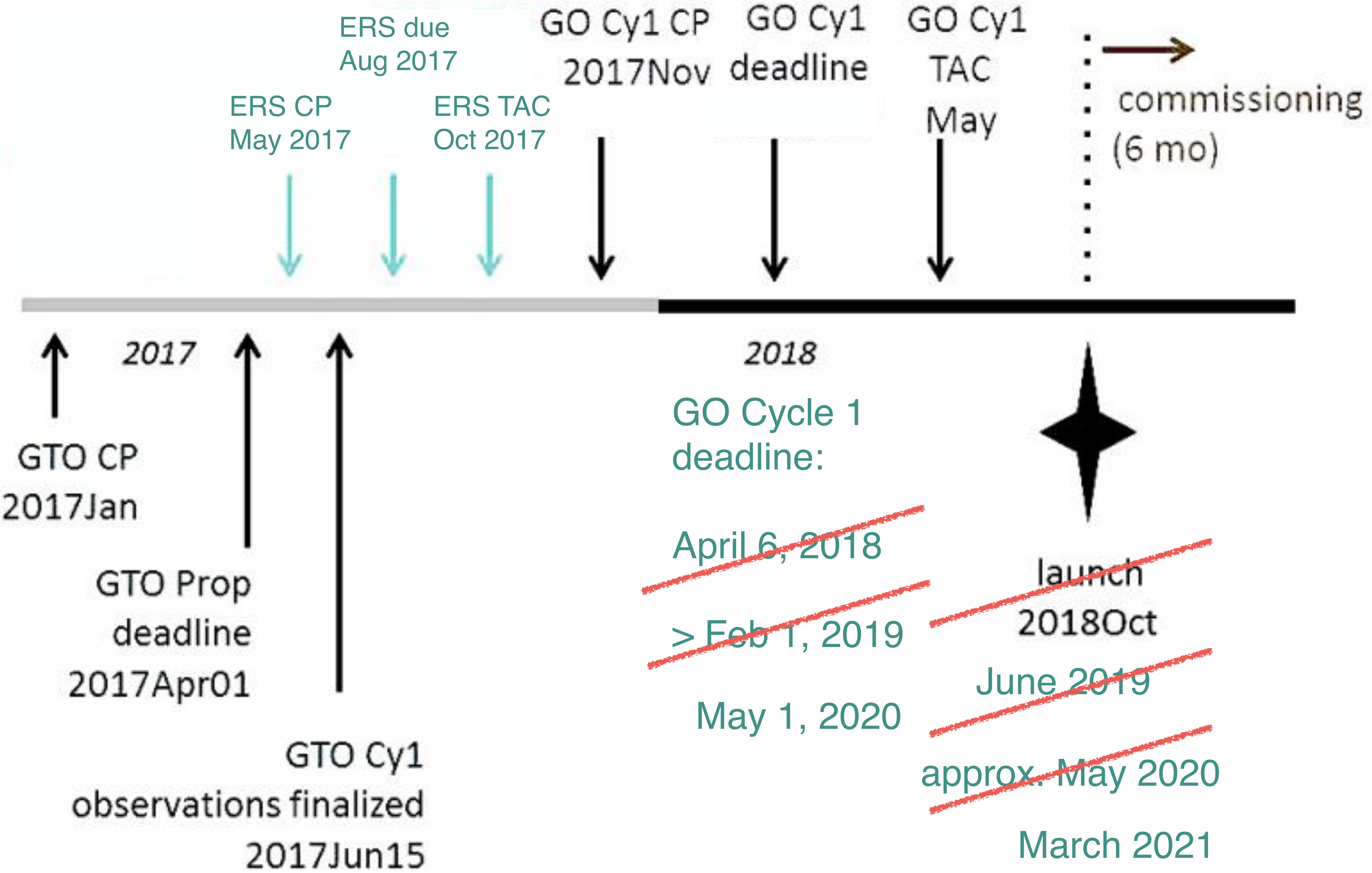
Resolved Stellar Populations ERS Program (Weisz)
Radiative Feedback from Massive Stars (Berne)
Chemical Evolution of Ices during Star Formation (McClure)
Decoding Smoke Signals in the Glare of a W-R Binary (Lau)

Galaxy evolution:

Imaging Spectroscopy of Quasar Hosts (Wylezalek)
Nuclear Dynamics of a Nearby Seyfert with NIRSpec IFU (Bentz)
Through the Looking GLASS (Treu)
The Starburst-AGN Connection in Merging LIRGs (Armus)
The Cosmic Evolution ERS Survey (Finkelstein)
Extremely Magnified Panchromatic Lensed Arcs (Rigby)

https://jwst.stsci.edu/observing-programs/approved-ers-programs/

Webb *Cycle 1 Proposal Schedule*



ERS CP
May 2017

ERS due
Aug 2017

ERS TAC
Oct 2017

GO Cy1 CP
2017Nov

GO Cy1
deadline

GO Cy1
TAC
May

commissioning
(6 mo)

2017

2018

GTO CP
2017Jan

GTO Prop
deadline
2017Apr01

GTO Cy1
observations finalized
2017Jun15

GO Cycle 1
deadline:

~~April 6, 2018~~

~~> Feb 1, 2019~~

May 1, 2020

~~launch~~
2018Oct

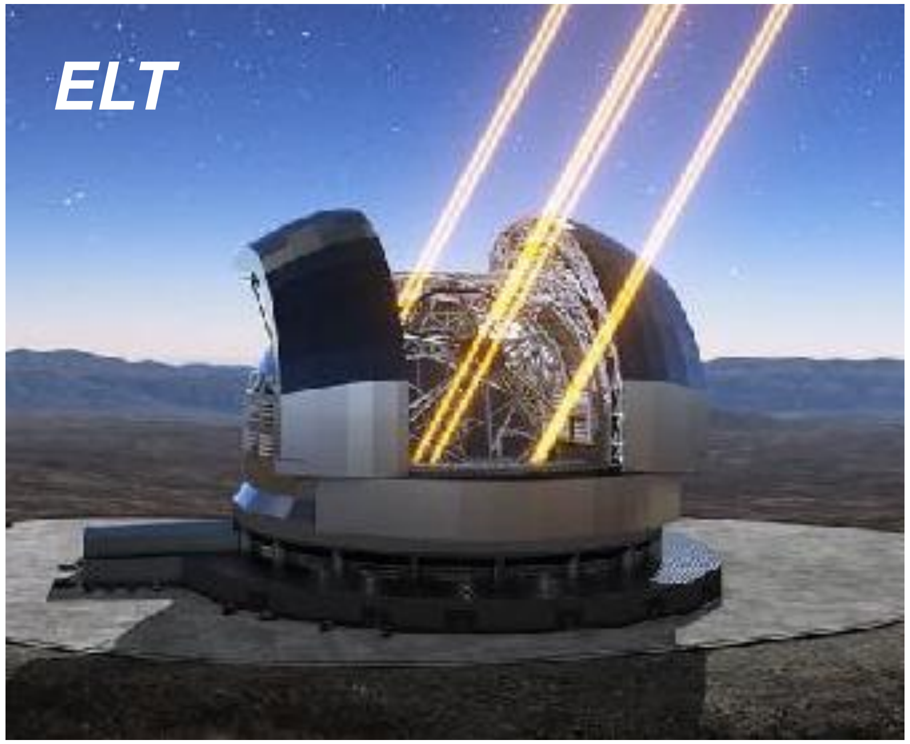
~~June 2019~~

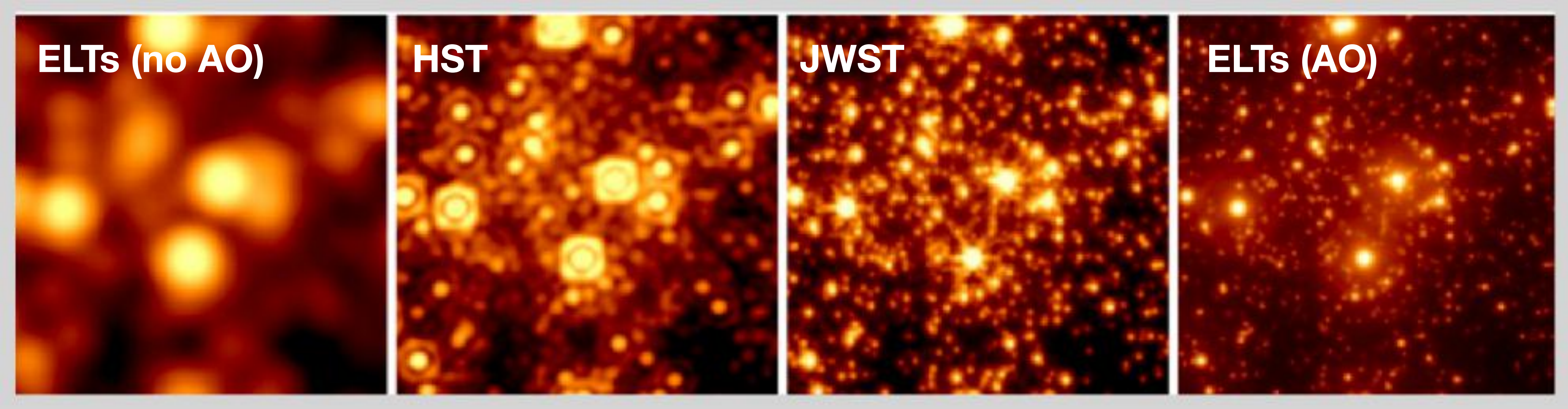
~~approx. May 2020~~

March 2021

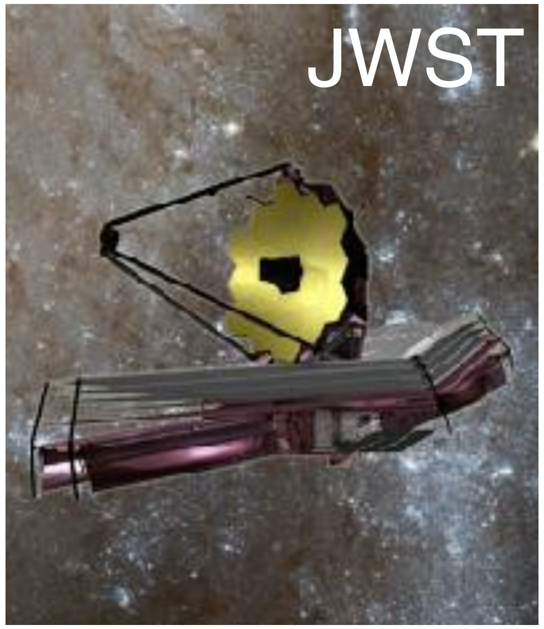
first science observations: ~ 2021/2022

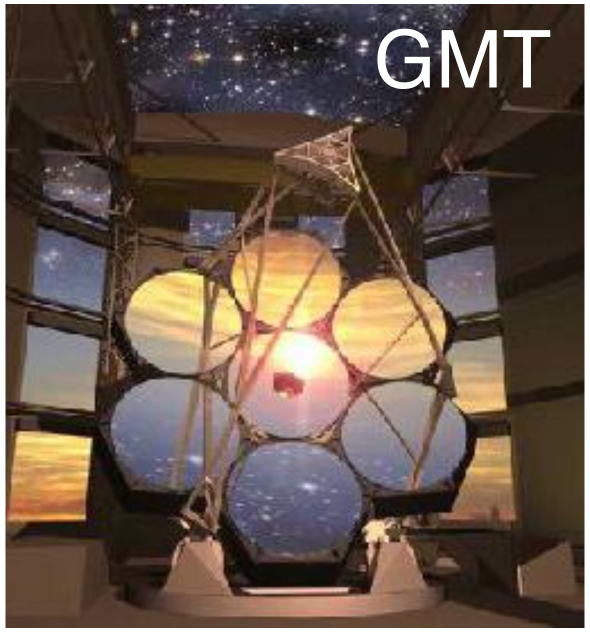
Too big to fail?

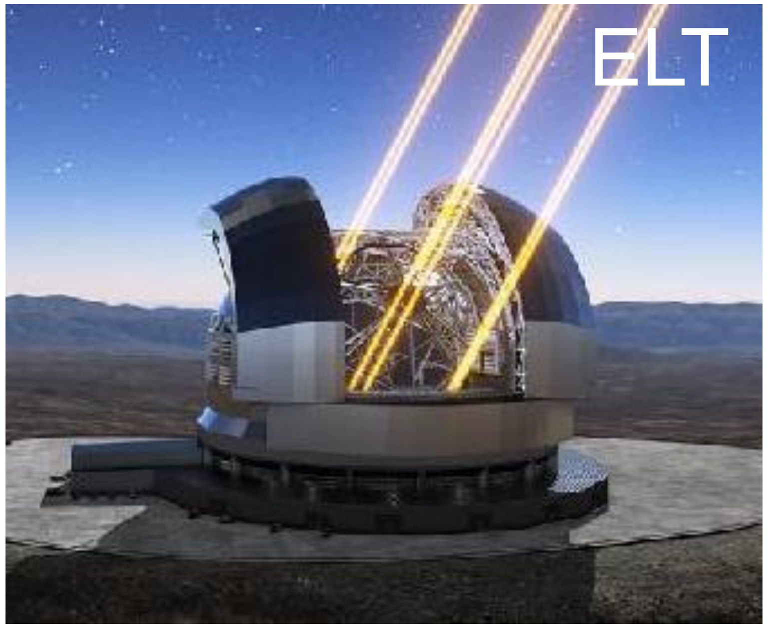




HST versus JWST versus GMT/ELT







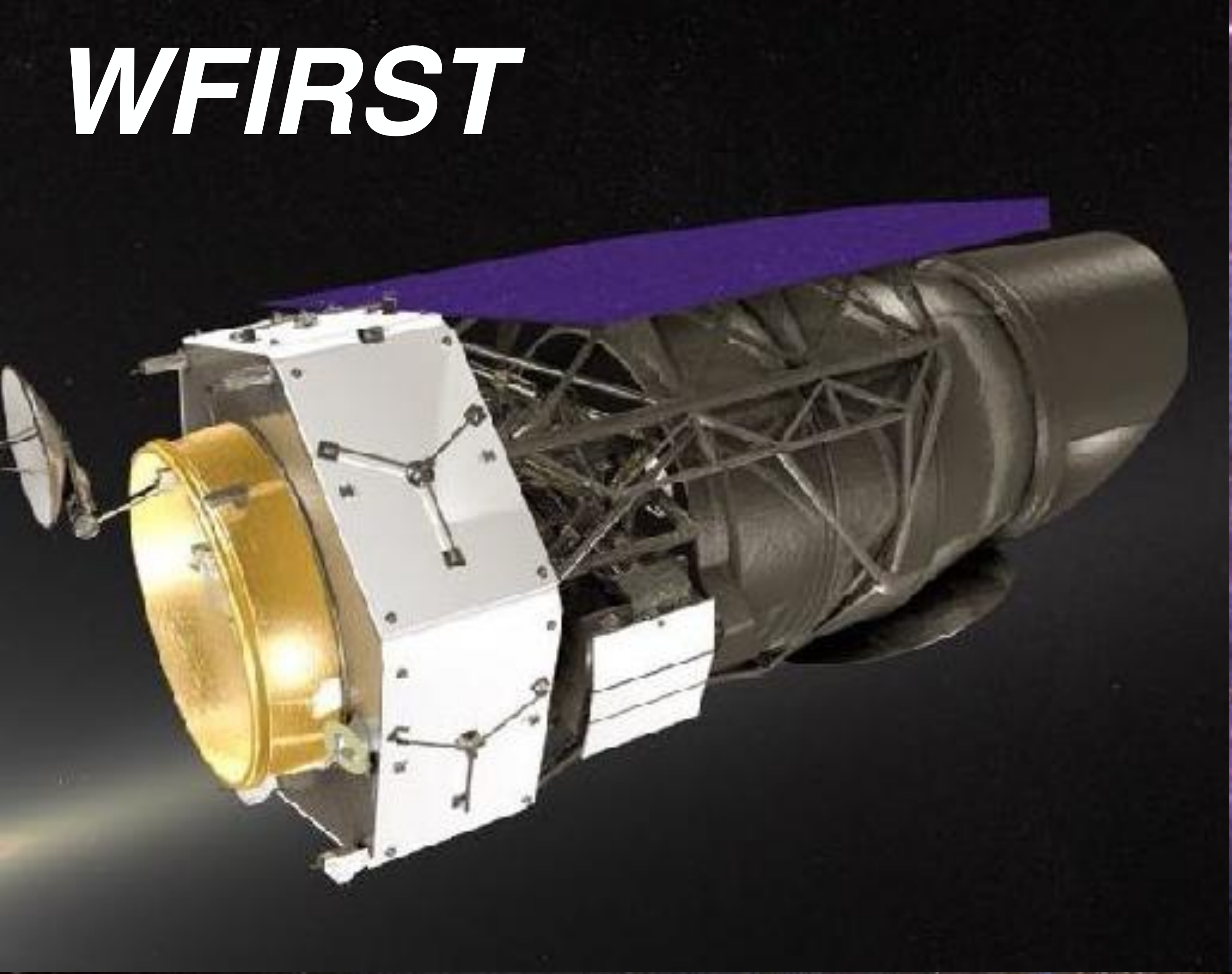
D_{prim}	2.4 m	6.5 m	22 m	35 m
A_{eff}	4.5 m^2	6 x HST	14 x JWST	34 x JWST
diff-psf	0.1”	0.03”	0.01”	0.005”
year	1990	~2021	~2024	~2024

imaging **0.7—1.7 μm → ELTs are comparable or better than JWST**

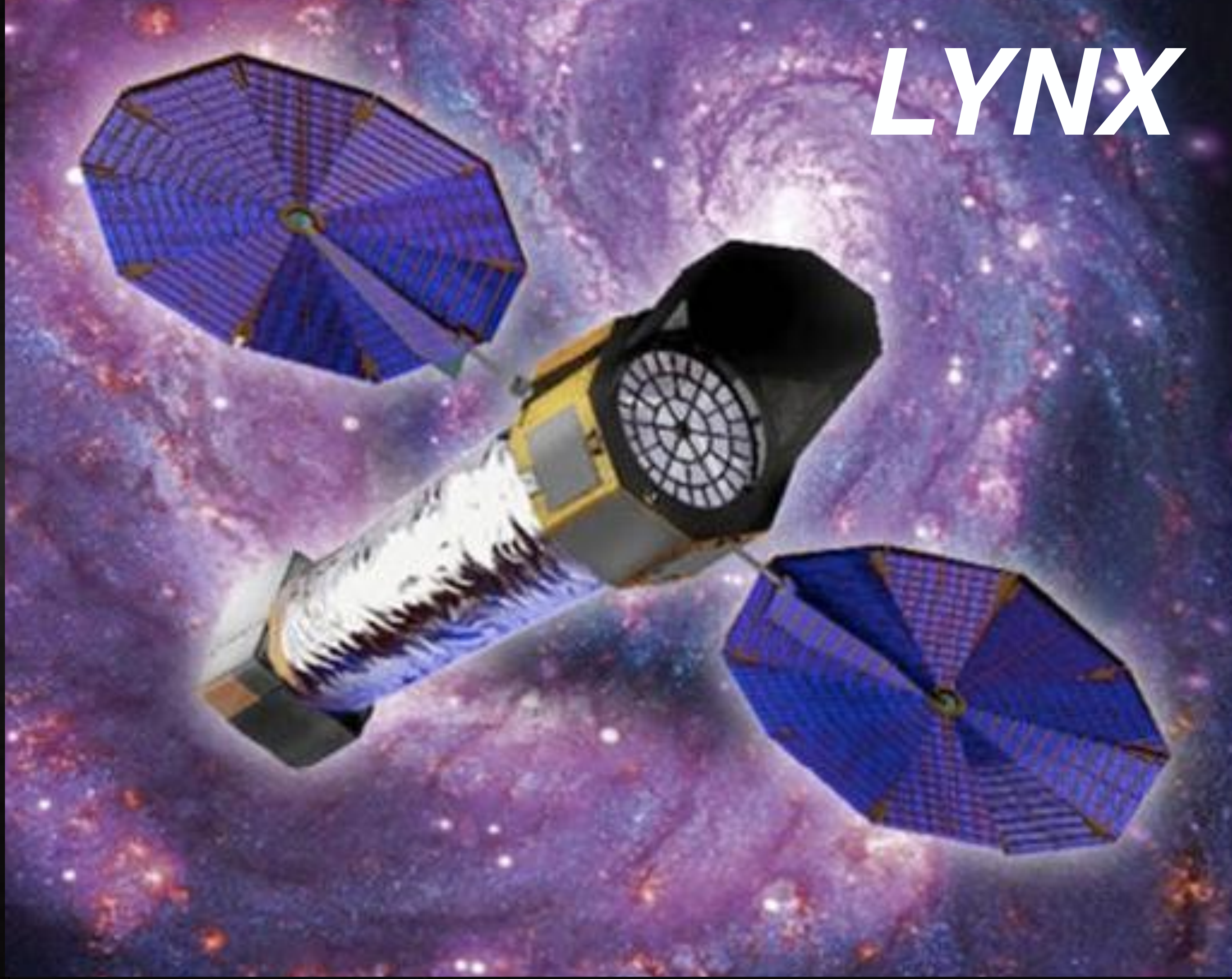
1.7—28 μm → JWST unique

spectroscopy **0.7—1.7 μm → ELTs superior (high spectral resolution + coll. area)**

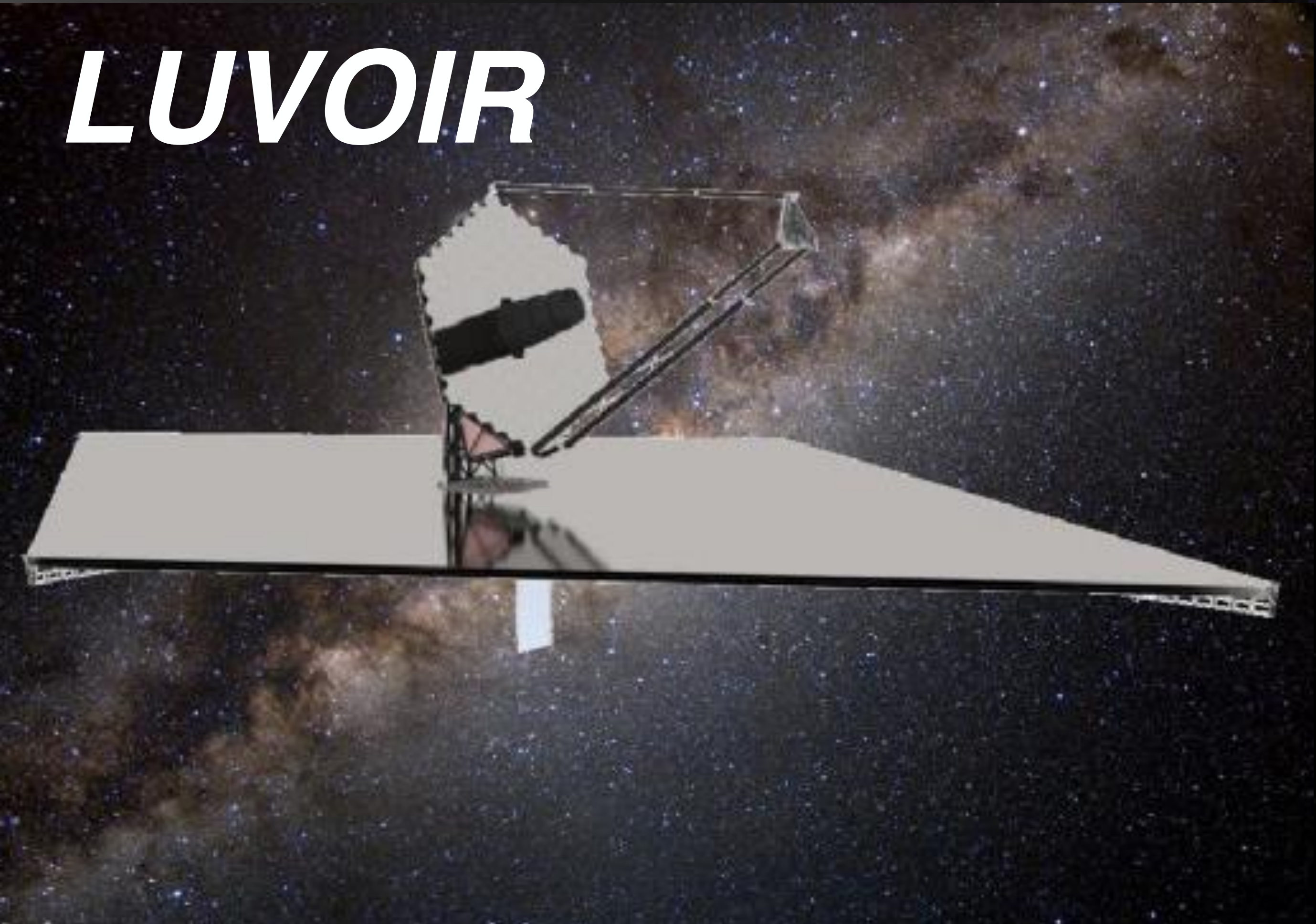
1.7—28 μm → JWST unique



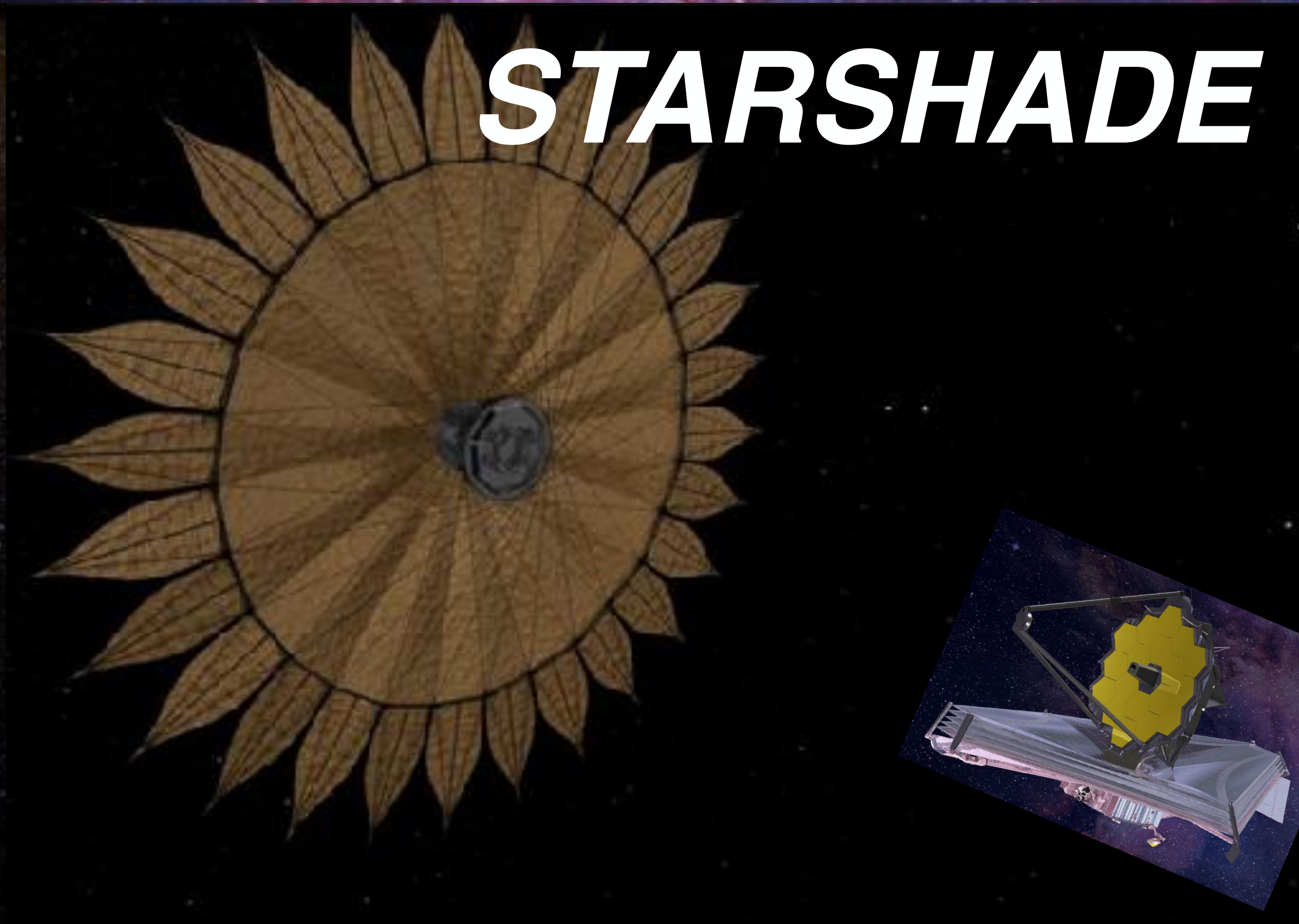
WFIRST



LYNX



LUVOIR



STARSHADE

Deployment of the James Webb Space Telescope (~2021)