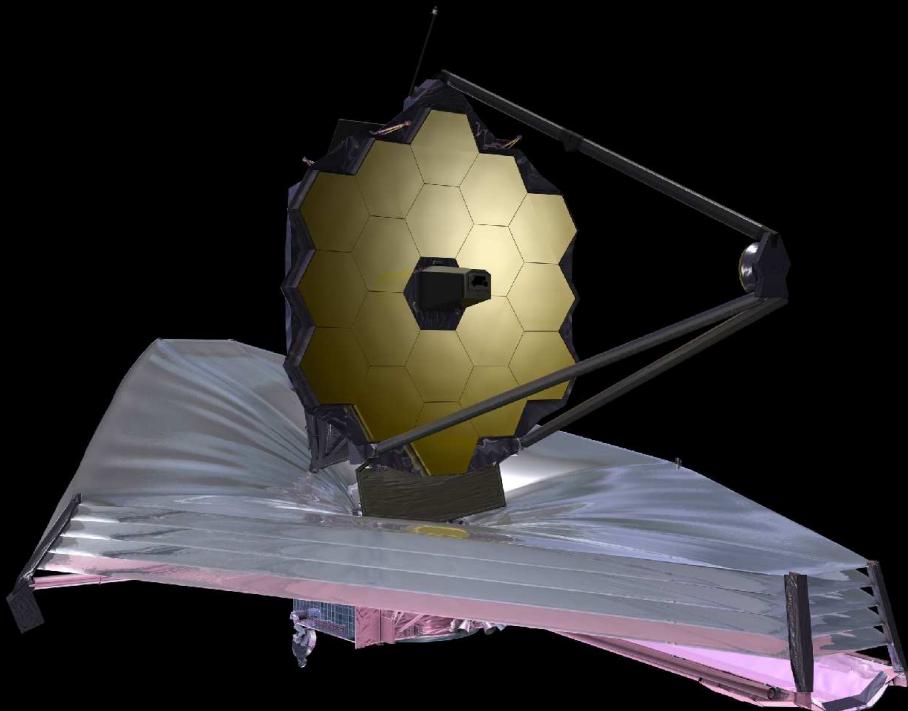


# JWST status as of 2021, and some of its first science programs: Faint object time domain, cluster lensing & caustic transits

Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist

GTO team: T. Ashcraft, S. Cohen, R. Jansen, V. Jones, B. Joshi, D. Kim, B. Smith, F. Timmes, C. White (ASU), M. Alpaslan (NYU), D. Coe, N. Grogin, N. Hathi, A. Koekemoer, N. Pirzkal, A. Riess, R. Ryan, L. Strolger (STScI), C. Conselice, I. Smail (UK), W. Brisken, J. Condon, W. Cotton, K. Kellermann, R. Perley (NRAO), J. Diego, T. Broadhurst, (Spain), S. Driver, R. Livermore, M. Marshall, A. Robotham, S. Wyithe (OZ), K. Duncan, H. Rottgering (Leiden), S. Finkelstein, R. Larson (UT), G. Fazio, M. Ashby, P. Maksym (CfA), B. Frye, M. Rieke, C. Willmer (UofA), H. Hammel (AURA), G. Hasinger (ESA), A. Kashlinsky, S. Milam, A. Straughn (GSFC), W. Keel (U-AL), P. Kelly (U-MN), P. S. Rodney (U-SC), M. Rutkowski (MNSU), H. Yan (U-MO), A. Zitrin (Israel).



- Today, the JWST science remains as compelling as it was  $\sim$ 20 years ago.
- In fact, the JWST science is far more exciting today than we could have imagined or planned for  $\sim$ 20 years ago.

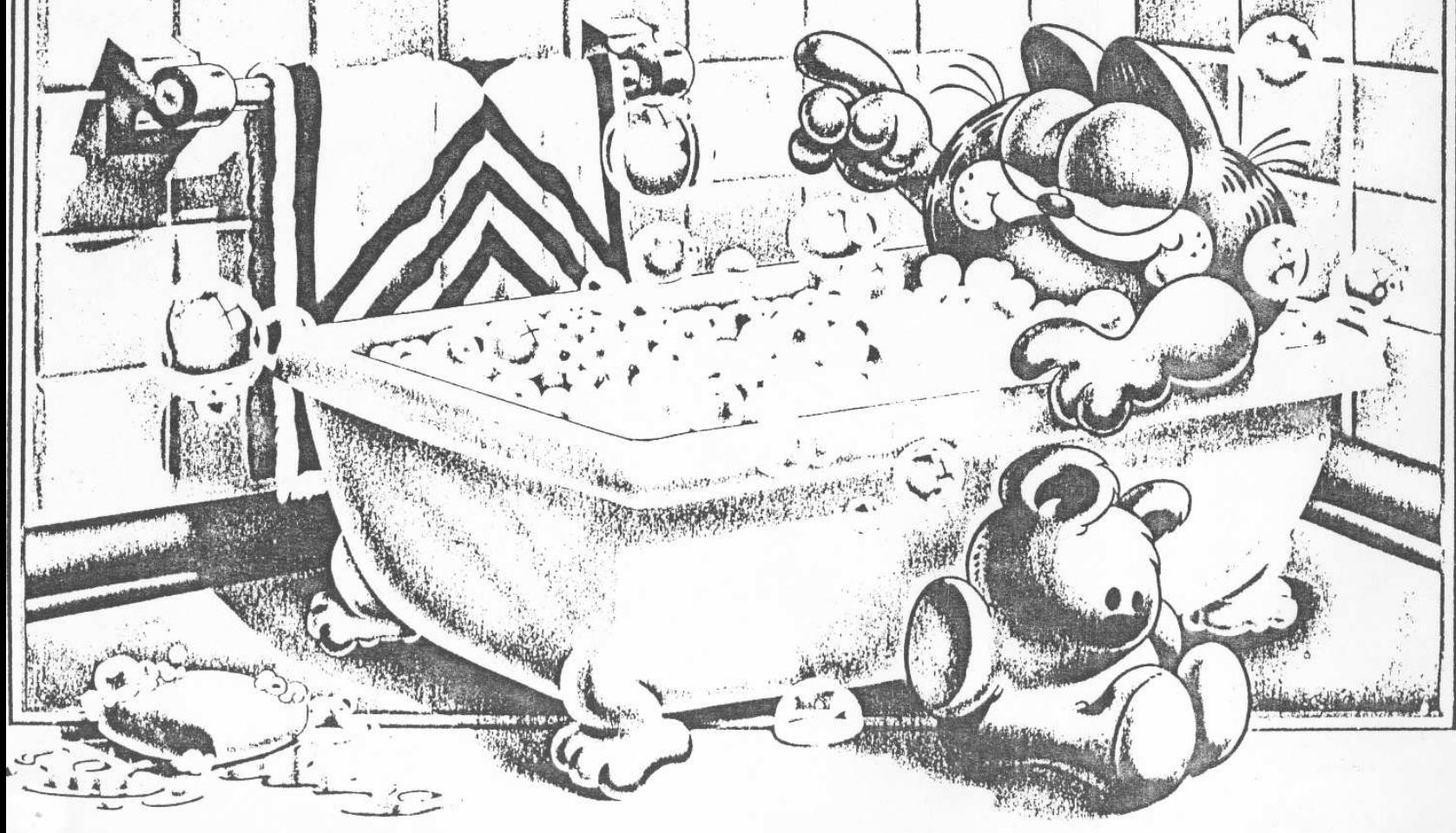
*Theoretical Physics Colloquium, ASU, Tempe, AZ (via Zoom; Wednesday, December 1, 2021)*

Talk is on: [http://www.asu.edu/clas/hst/www/jwst/jwsttalks/asuTheoreticalPhysics21\\_jwst.pdf](http://www.asu.edu/clas/hst/www/jwst/jwsttalks/asuTheoreticalPhysics21_jwst.pdf)

## Outline & Conclusions

- (1) Update on the James Webb Space Telescope (JWST), 2021.
- (2) JWST Time-Domain Field in the NEP Continuous Viewing Zone:
  - Weak AGN Variability (*e.g.*, SF–AGN connection; support LyC studies);
  - Very high redshift supernovae incl Pair Instability Supernovae (PISN).
  - Dark sky in NEP TDF: CIB-fluctuations constrain First Light sources.
  - The JWST North Ecliptic Pole CVZ area will be a Community Field for Time Domain science over 5–14 years (max JWST propellant life): first JWST epoch public rightaway + data products ASAP.
- (3) Monitor the best lensing clusters for possible JWST caustic transits of Pop III stars and their stellar-mass black hole accretion disks at  $z \gtrsim 7$ .
  - Limits to the SKY-SB from First Stars & Stellar-Mass Black Holes  $\implies$
  - JWST may detect Pop III objects directly monitoring  $\gtrsim 3$  lensing clusters.

JWST is like a hot bath. It feels good while you're in it; but the longer you stay, the more wrinkled you get.



WARNING: Both Hubble and James Webb are 30–40+ year projects:  
You will feel wrinkled before you know it ... :)

**JWST primary  
mirror**



**Hubble primary  
mirror**

JWST  $\simeq 2.5 \times$  larger than Hubble, so at  $\sim 2.5 \times$  larger wavelengths:  
JWST has the same resolution in the near-IR as Hubble in the optical.

# THE JAMES WEBB SPACE TELESCOPE

## JWST LAUNCH

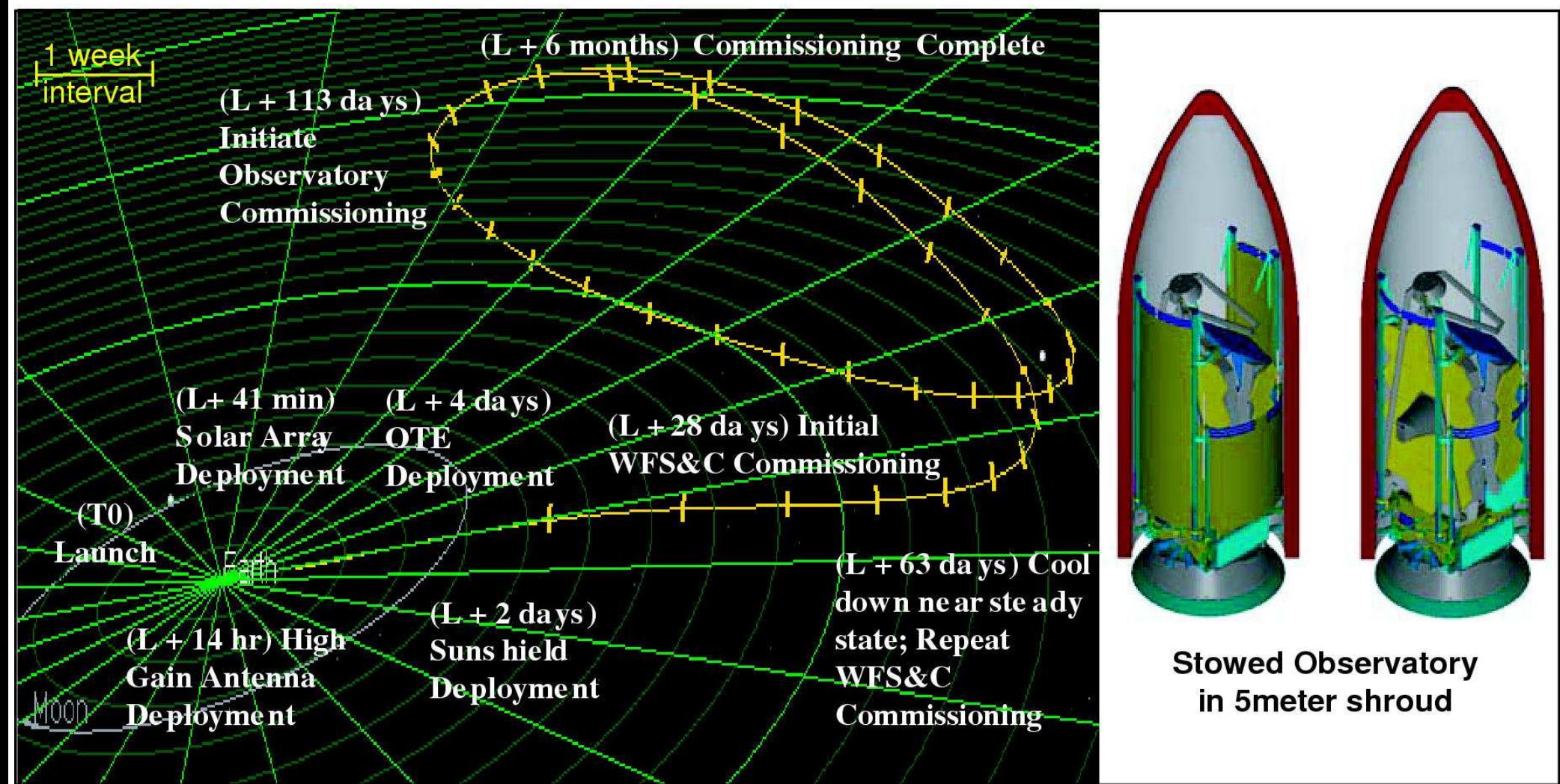
- LAUNCH VEHICLE IS AN ARIANE 5 ROCKET, SUPPLIED BY ESA
- SITE WILL BE THE ARIANESPACE'S ELA-3 LAUNCH COMPLEX NEAR KOUROU, FRENCH GUIANA



ARIANESPACE - ESA - NASA

- The JWST launch weight will be  $\lesssim 6500$  kg, and it will be launched to L2 with an ESA Ariane-V launch vehicle from Kourou in French Guiana.

## (1a) How will JWST travel to its L2 orbit?



- After launch on Dec. 22, 2021 with an ESA Ariane-V, JWST will orbit around the Earth–Sun Lagrange point L2, 1.5 million km from Earth.
- JWST can cover the whole sky in segments that move along with the Earth, observe  $\gtrsim 70\%$  of the time, and send data back to Earth every day.

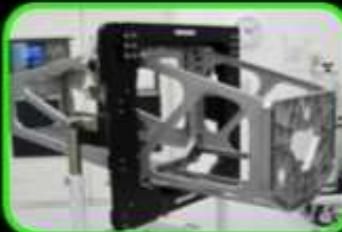


# JWST Hardware Status

Primary Mirror Segment



Aft Optics System



PM Flight Backplane



Tertiary Mirror



Fine Steering Mirror

Secondary Mirror Pathfinder Strut



ISIM Flight Bench



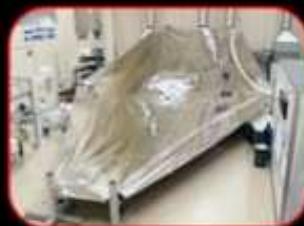
Secondary Mirror Hexapod



Secondary Mirror



Membrane Mgmt



Pathfinder Membrane



Spacecraft computer Test Unit

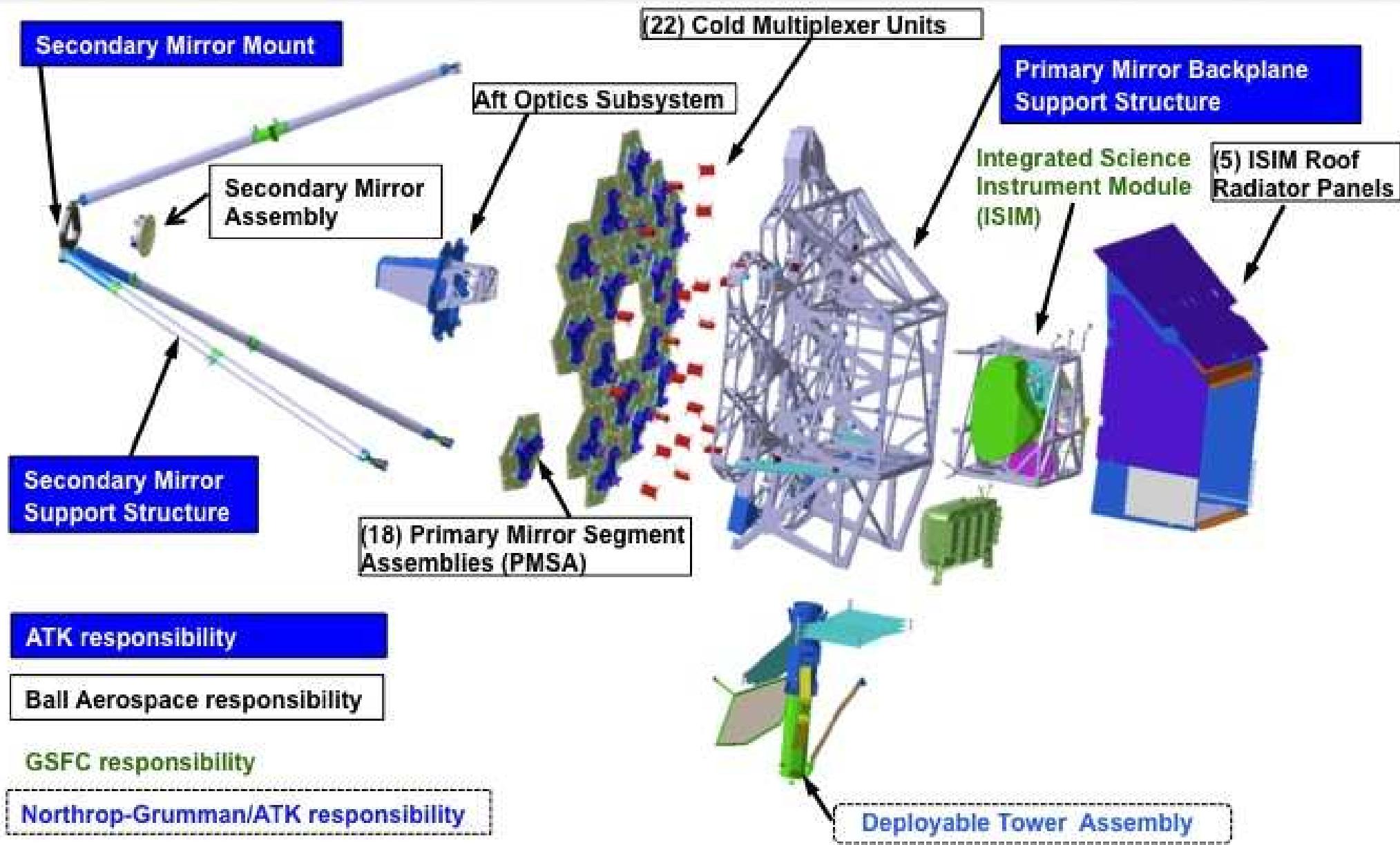


Mid-boom Test

Spring 2021: 100% of launch mass designed and built ( $\gtrsim 99.5\%$  weighed).



# TELESCOPE ARCHITECTURE



3/31/11

2014–2021: Complete system integration at GSFC and Northrop.



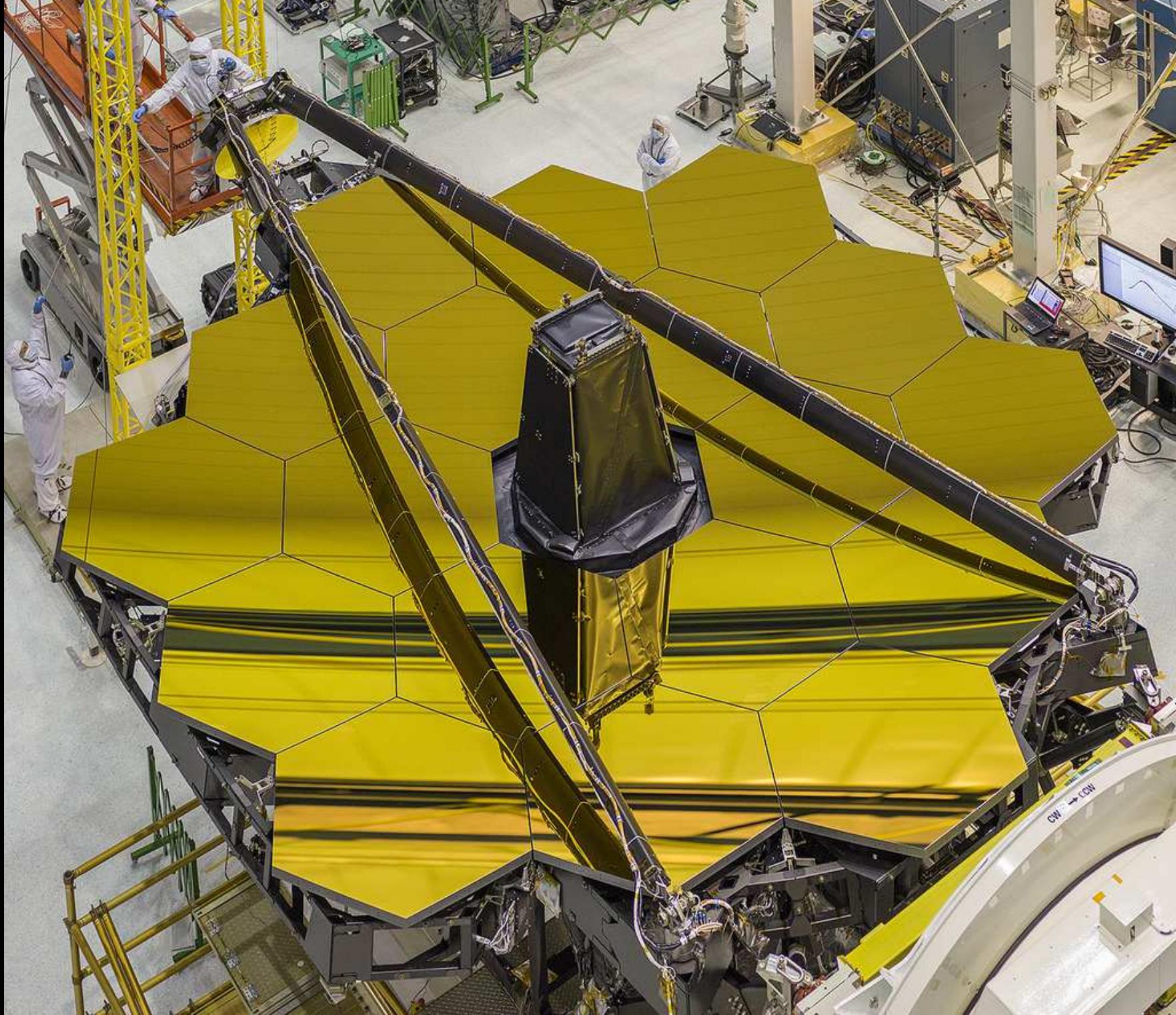
NASA team-work to take JWST mirror covers off!



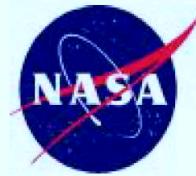
JWST being tilted into the right position



Webb mirrors finally mounted and ready!



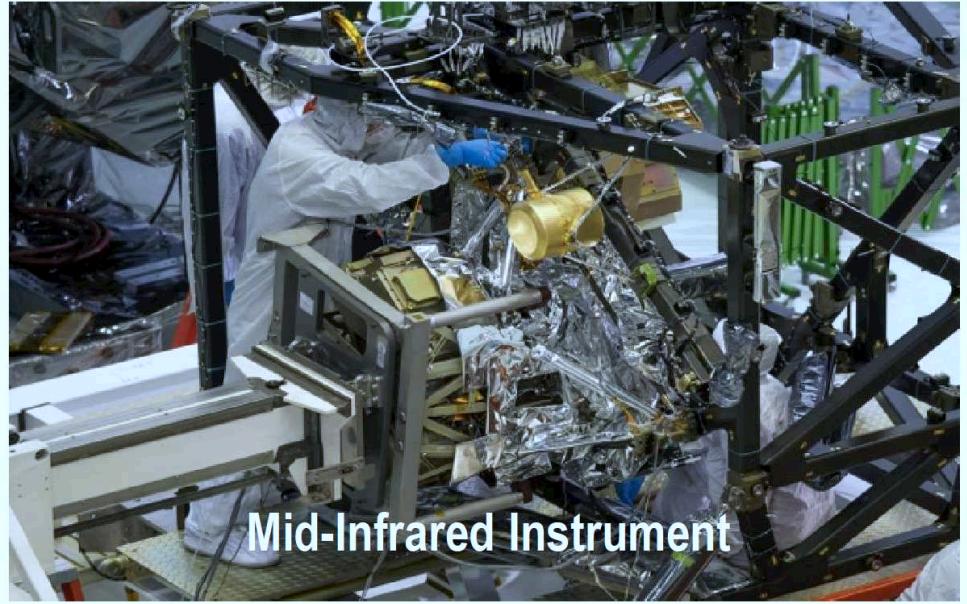
JWST stowed for final instrument mounting



# All Instruments Integrated



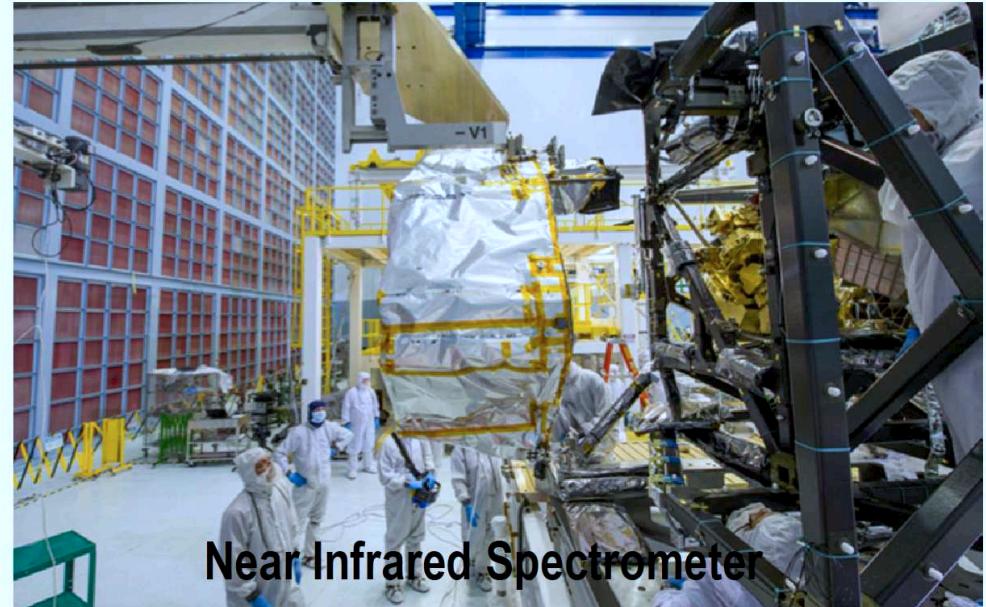
Fine Guidance Sensor



Mid-Infrared Instrument

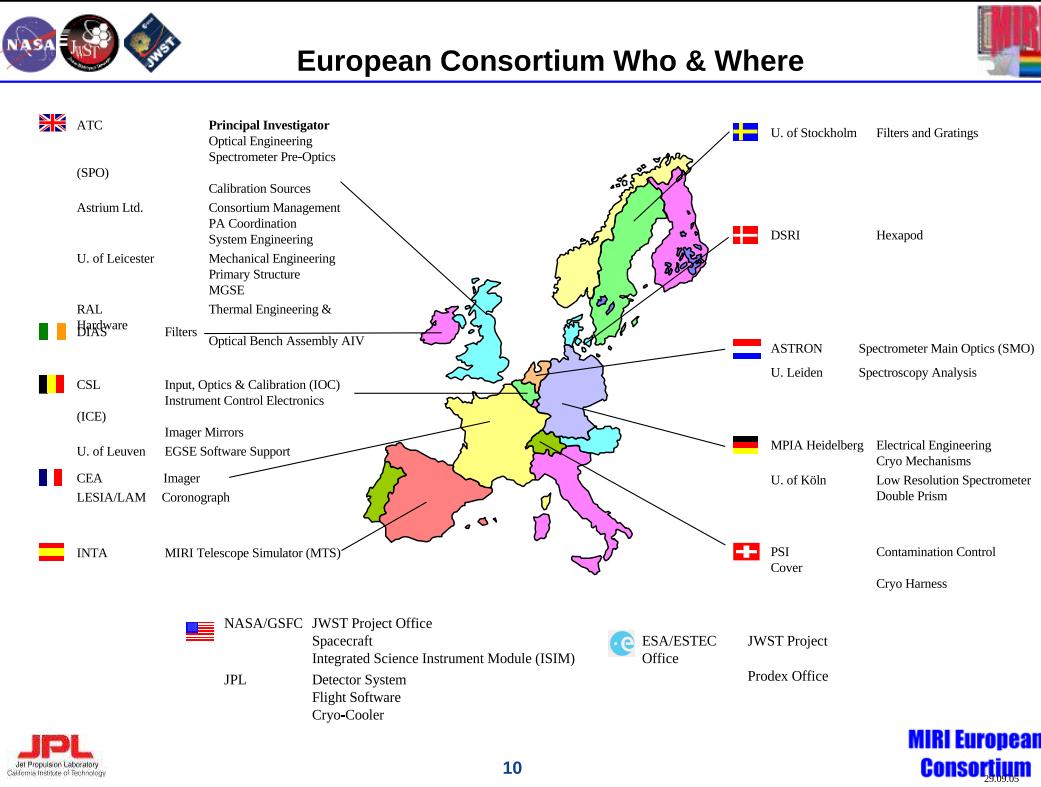
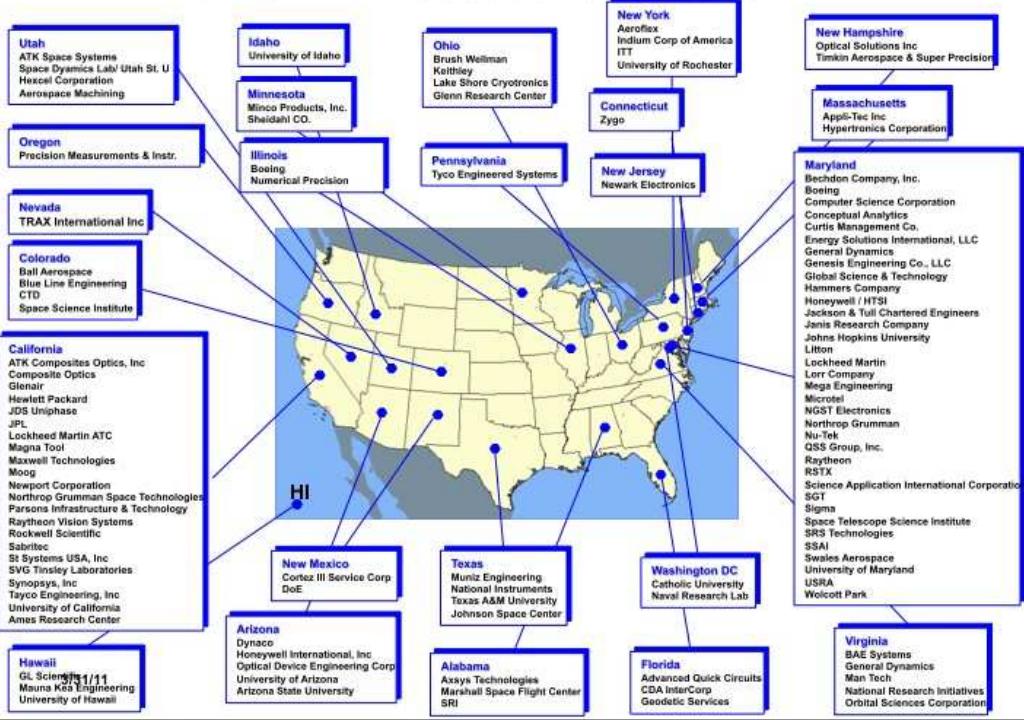


Near Infrared Camera



Near Infrared Spectrometer

# JWST: A Product of the Nation

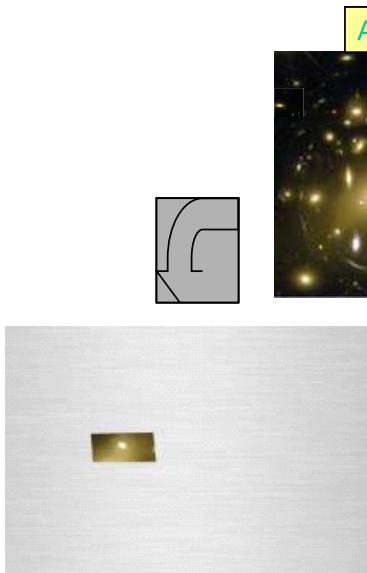


10

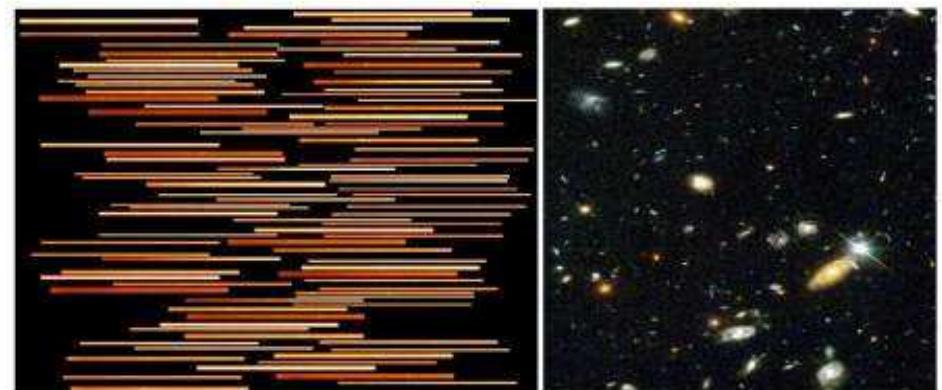
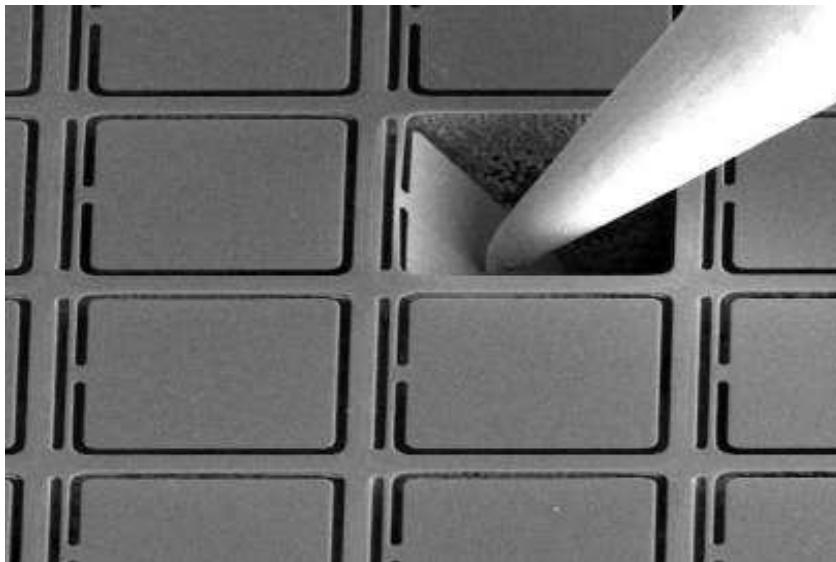
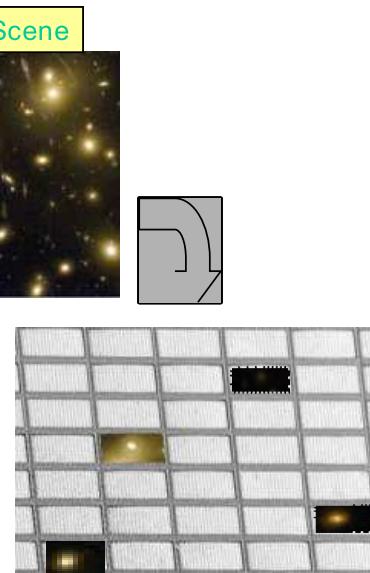
MIRI European Consortium  
29.09.05

- JWST hardware made in 27 US States: 100% of launch-mass finished.
- Ariane V Launch & NIRSpec provided by ESA; & MIRI by ESA & JPL.
- JWST Fine Guider Sensor + NIRISS provided by Canadian Space Agency.
- JWST NIRCam made by UofA and Lockheed.

# Micro Shutters

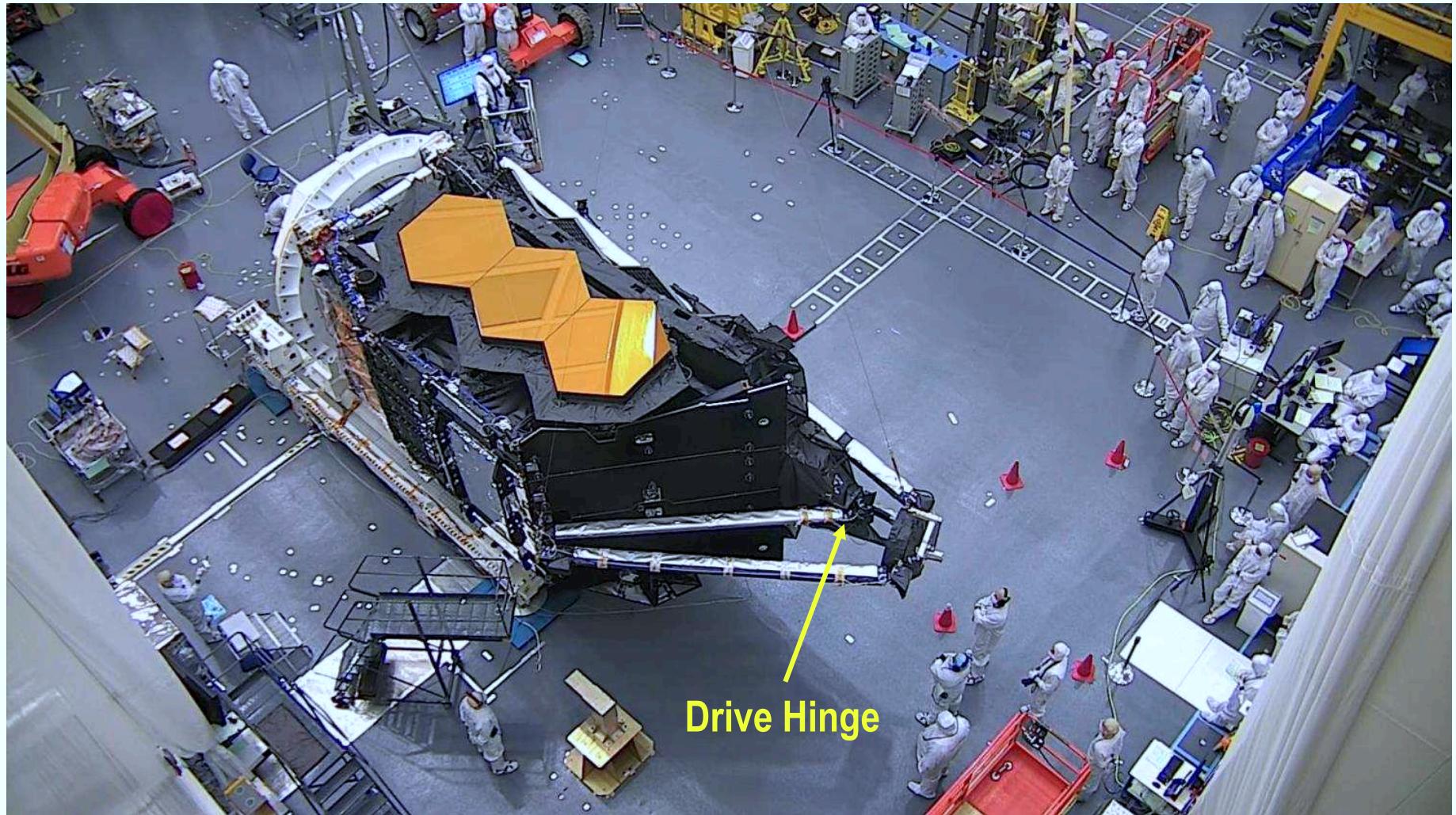


Metal Mask/Fixed Slit





# SMSS Deployment Sequence (1)

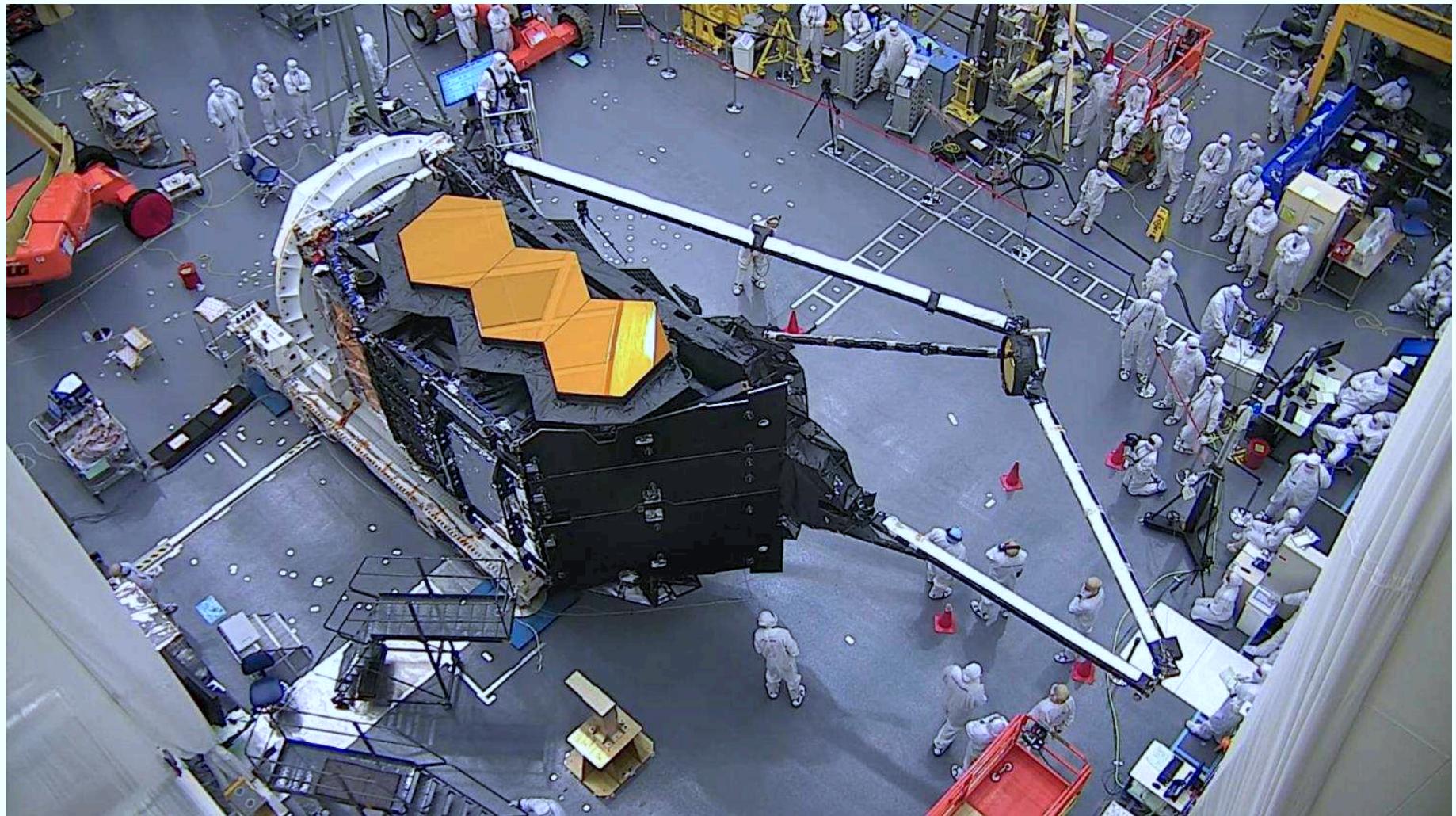


190812 JWST Monthly Telecon 8

July 2019: Full 1-G deployment of JWST secondary mirror (SM) .



## SMSS Deployment Sequence (2)

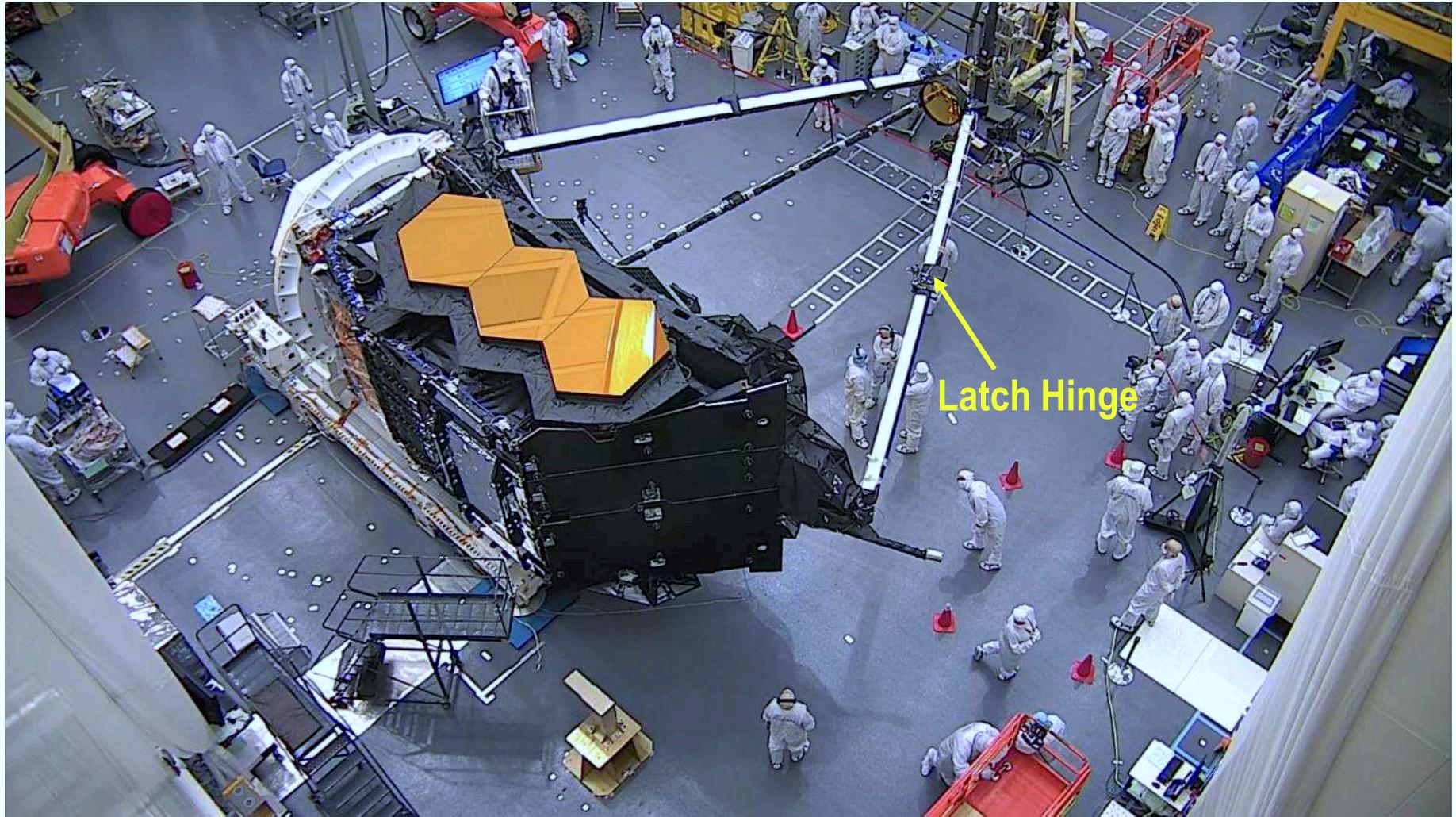


190812 JWST Monthly Telecon 9

July 2019: Full 1-G deployment of JWST secondary mirror (SM) ..



## SMSS Deployment Sequence (3)



190812 JWST Monthly Telecon 10

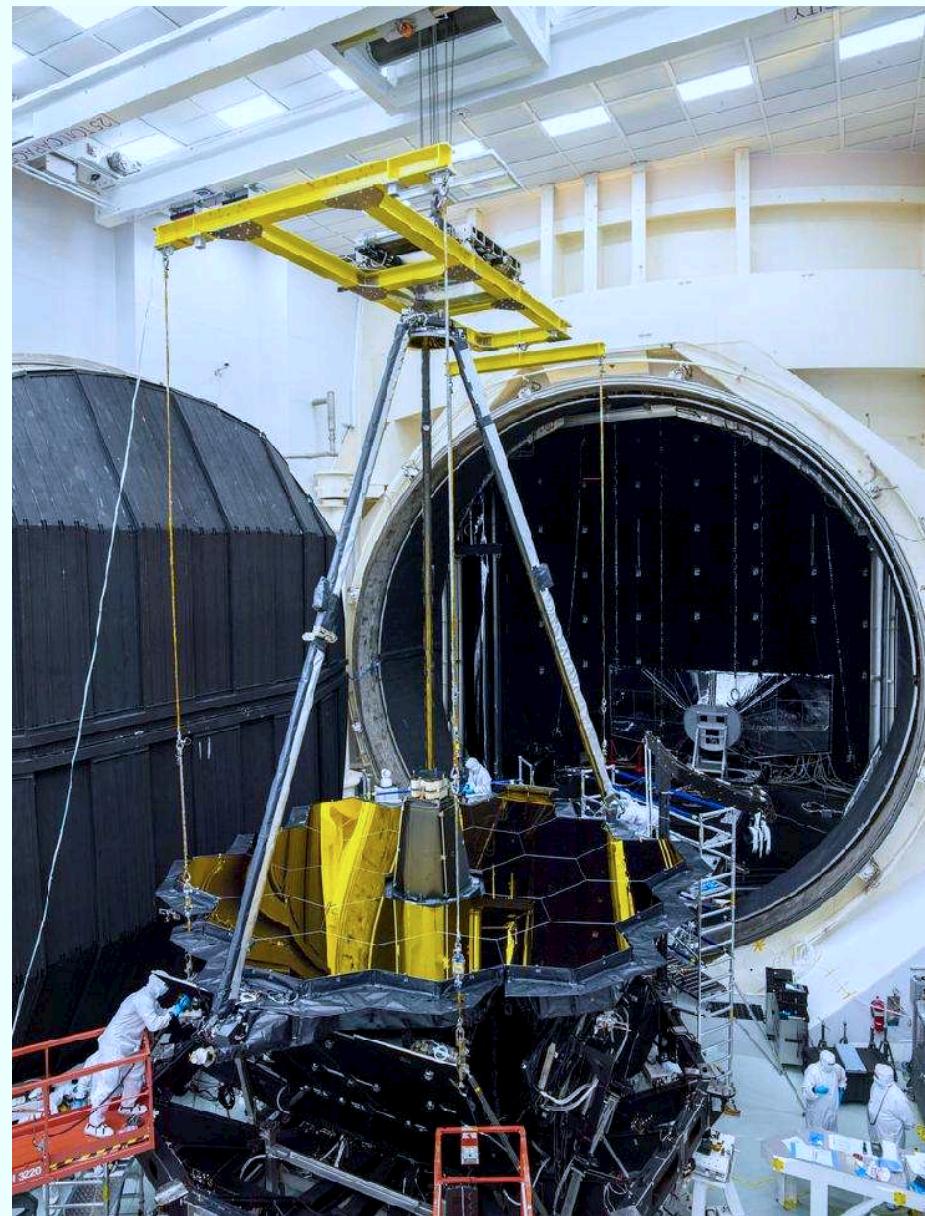
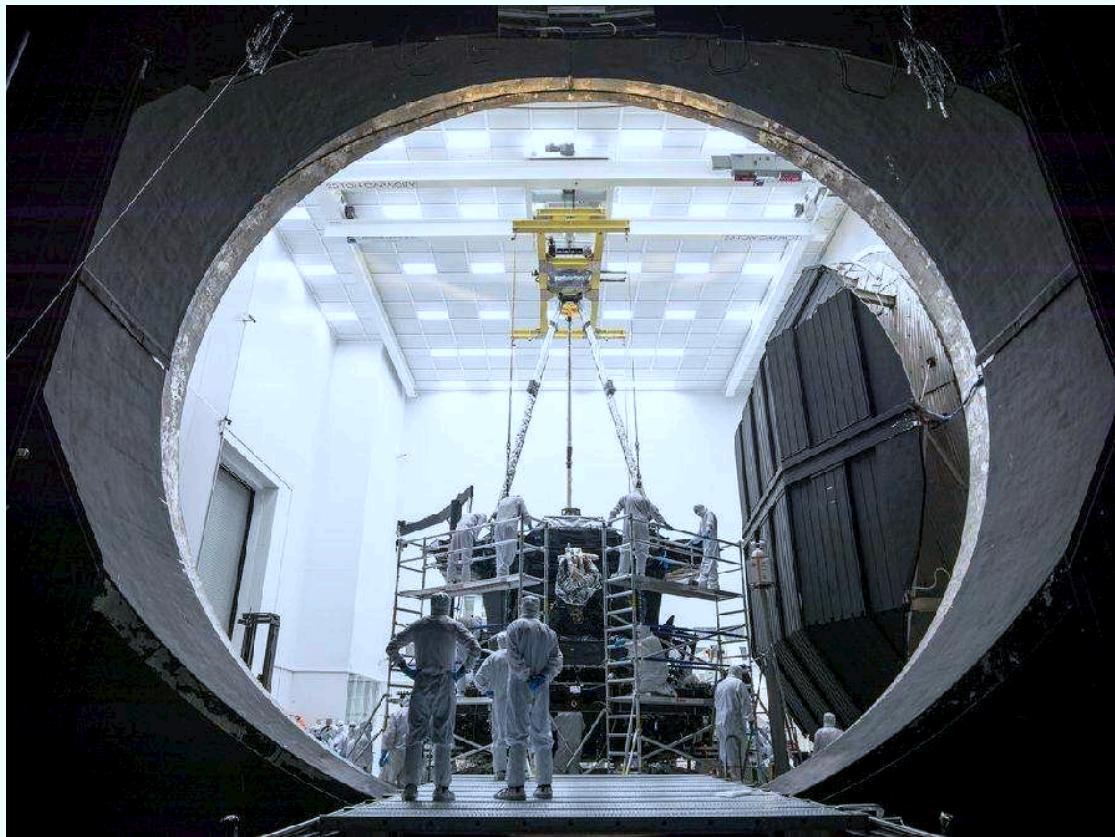
July 2019: Full 1-G deployment of JWST secondary mirror (SM) ...



JWST in enclosure at Johnson Space Center in Houston.

# Program Update: OTIS

NORTHROP GRUMMAN

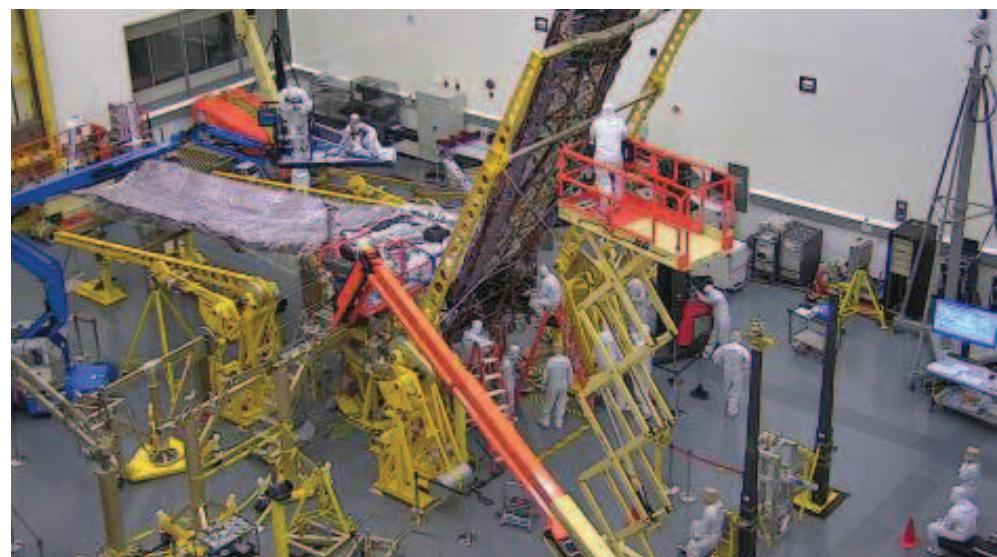


170612 JWST Monthly Telecon 29

JWST going into Chamber A at Johnson Space Center in Houston.

# Program Updates: Spacecraft and Sunshield

NORTHROP GRUMMAN

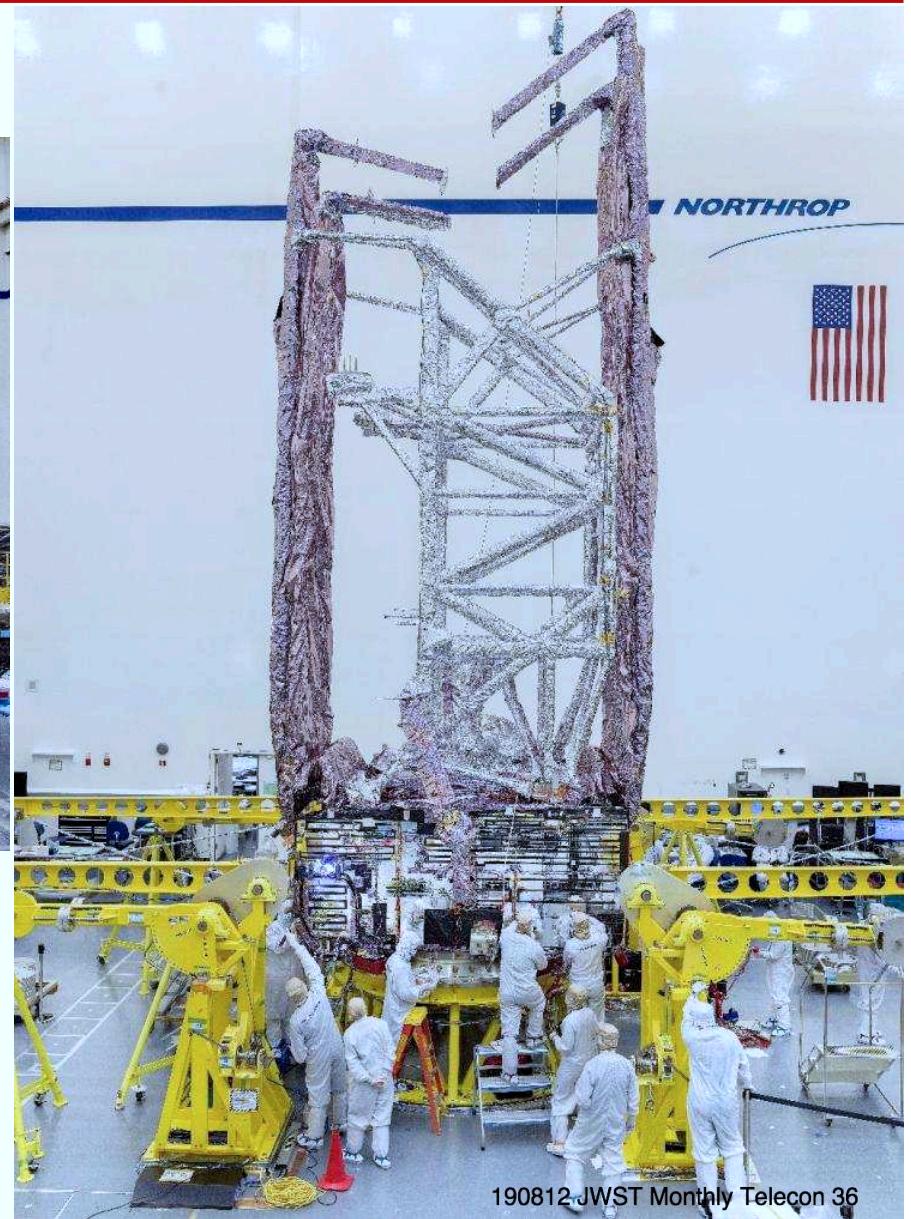


JWST Flight Sunshield assembled and tested at Northrop.



# SCE to Elephant Stand

NORTHROP GRUMMAN



Aug. 2019: Stowed flight sunshield before integration with JWST OTE.



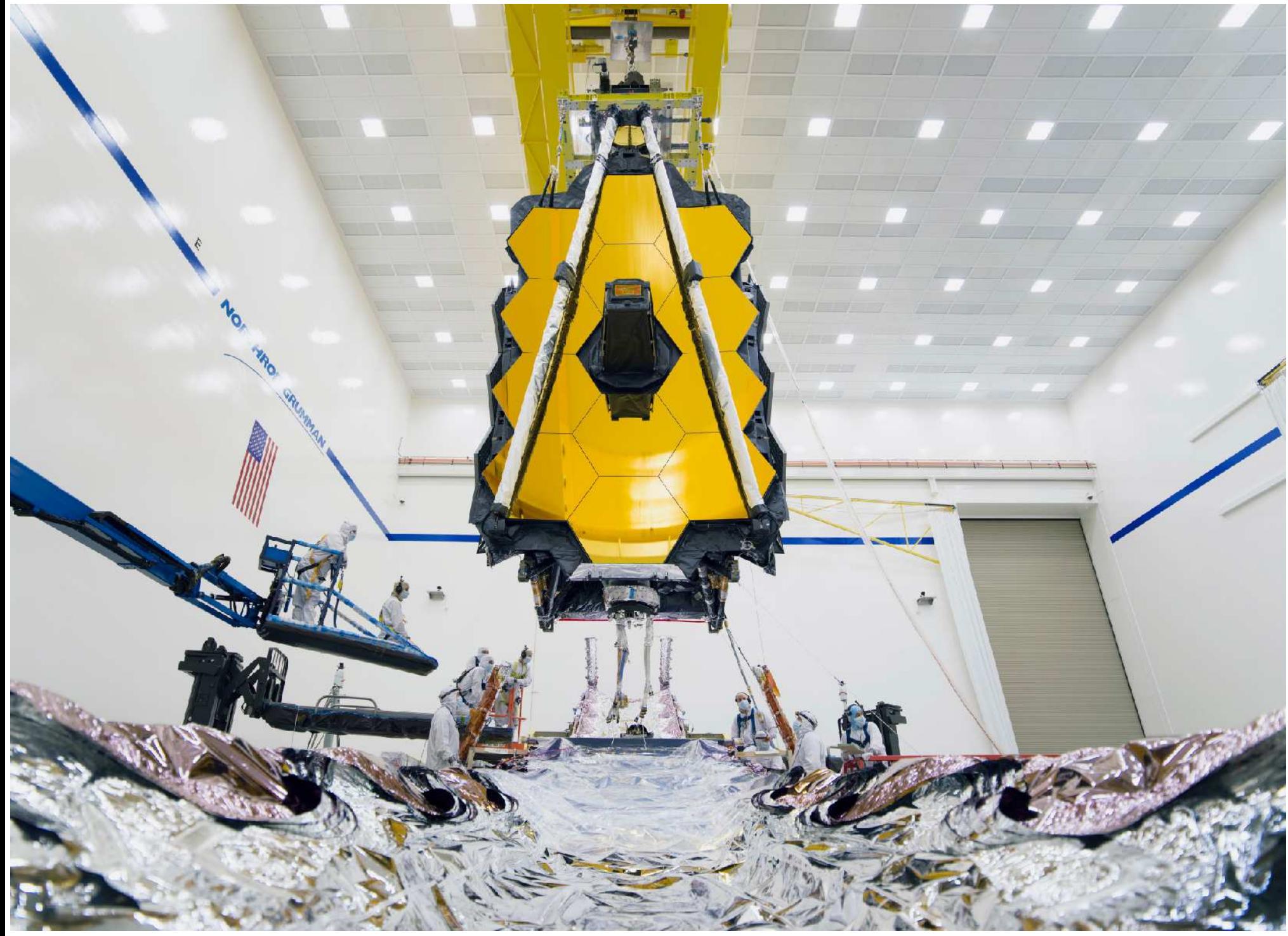
# SMSS Deployment

NORTHROP GRUMMAN



190812 JWST Monthly Telecon 39

Aug. 2019: OTE before final integration with Sunshield & spacecraft.



August 2019: JWST OTE+ISIM lowered into Sunshield+Spacecraft



August 2019: JWST OTE+ISIM integrated with Sunshield+Spacecraft!



August 2019: JWST OTE+ISIM integrated with Sunshield and Spacecraft!



# Meet the JWST Observatory 1



See NASA Press Release here:

<https://www.nasa.gov/feature/goddard/2019/nasa-s-james-webb-space-telescope-has-been-assembled-for-the-first-time>

190909-JWST Monday Telecon 11

August 2019: JWST OTE+ISIM integrated with Sunshield and Spacecraft!



# Solar Array Deployment 1

Five Panel Sunshield

Stowed

Offloading System



200511 JWST Monthly Telecon 12

May 2020: Ready for Solar Array deployment test



# Solar Array Deployment 2



200511 JWST Monthly Telecon 13

May 2020: Solar Array deployment with gravity off-loading



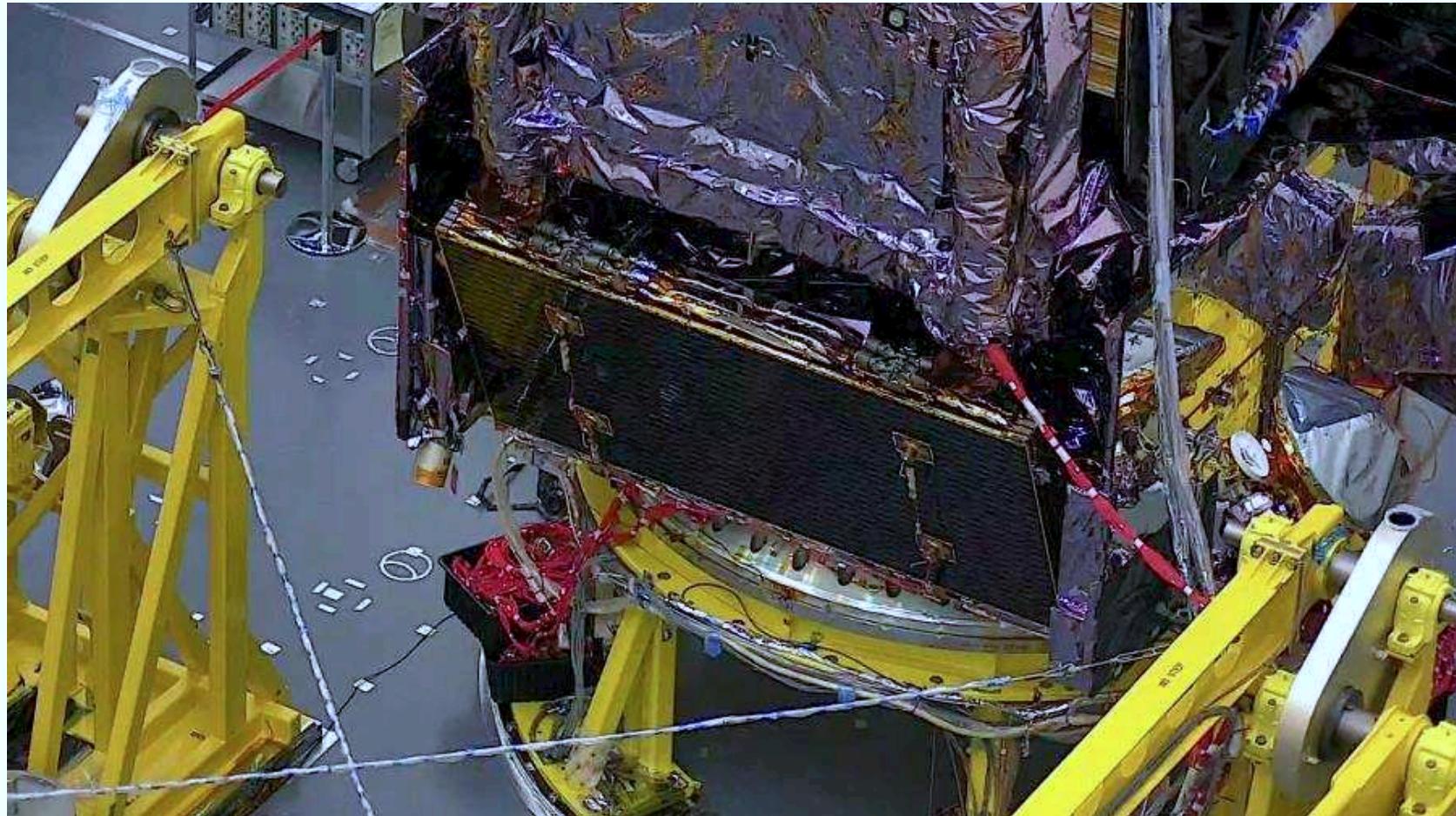
# Solar Array Deployment 3



200511 JWST Monthly Telecon 14

May 2020: Solar Array fully deployed and motor tested in 1G

## 7/26/20: Solar Array Installed for Environments



5

Approved for Public Release; NG20-1503  
200810 JWST Monthly Telecon Man.

May 2020: Solar Array as installed on JWST Observatory



## 5/28/20: DTA Deployment



Approved for Public Release; NG20-106  
200608 JWST Monthly Telecon 26

June 2020: Deployable Tower Assembly test



## 5/28/20: DTA Deployment



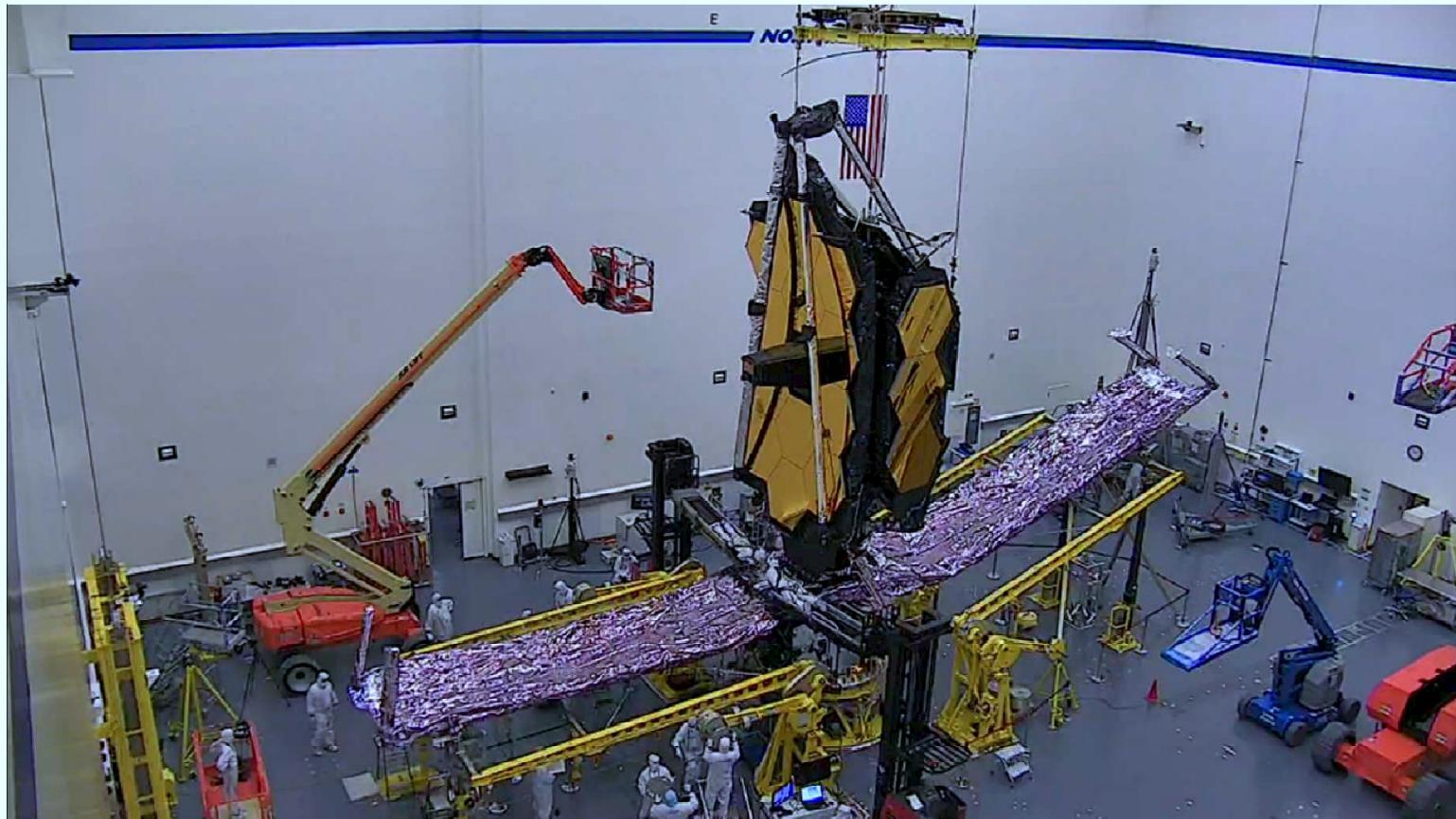
Approved for Public Release; NG20-106  
200608 JWST Monthly Telecon 27

June 2020: Deployable Tower Assembly test with gravity off-loading.



NORTHROP  
GRUMMAN

## 5/29/20: DTA Deployment



Approved for Public Release; NG20-106  
200608 JWST Monthly Telecon 28

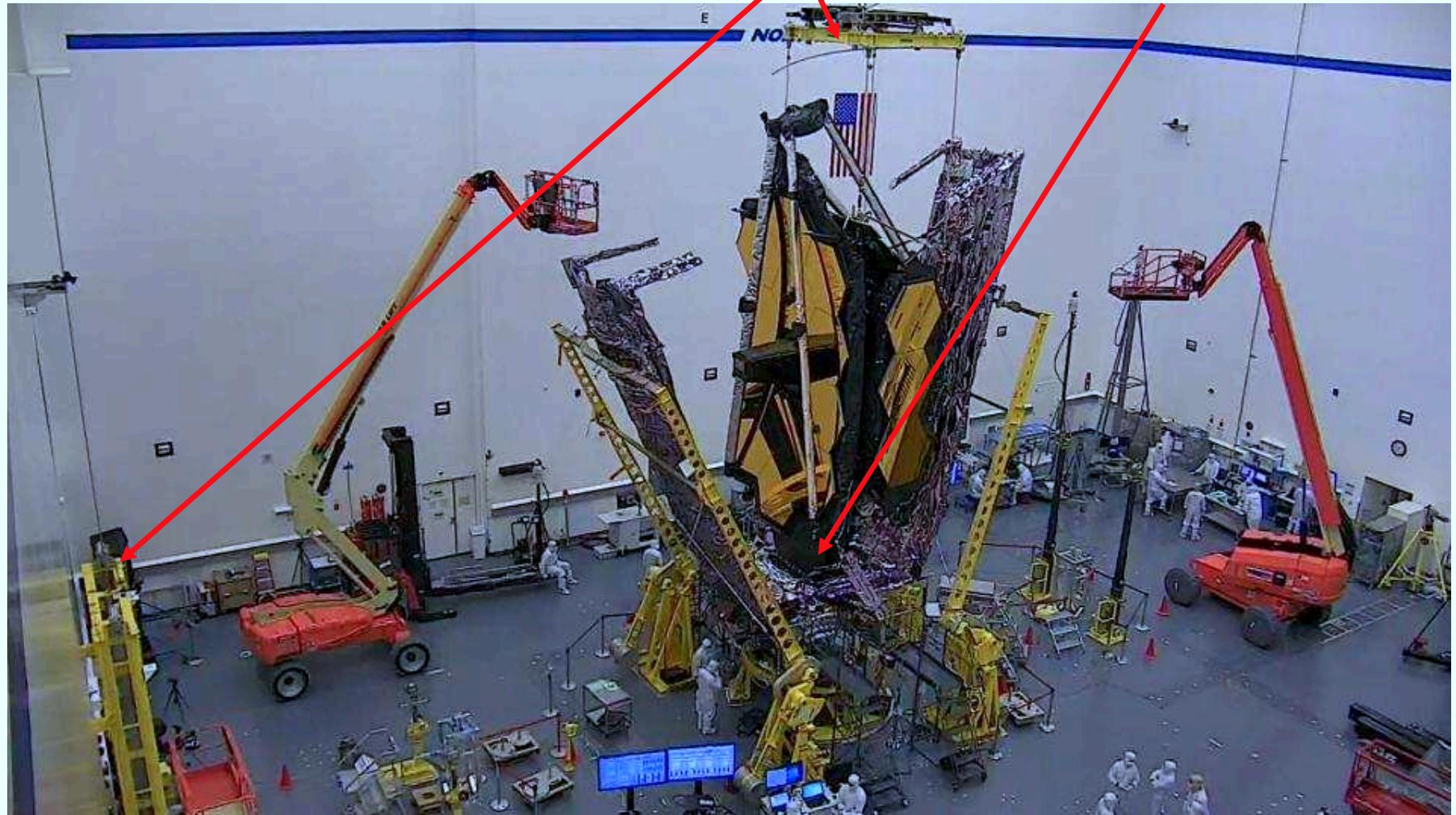
June 2020: Deployable Tower Assembly motor tested in 1G



# DTA Stow 1

Offloading System

Deployable Tower Assembly



200713 JWST Monthly Telecon 9

July 2020: Deployable Tower Assembly stow for launch



# DTA Stow 2

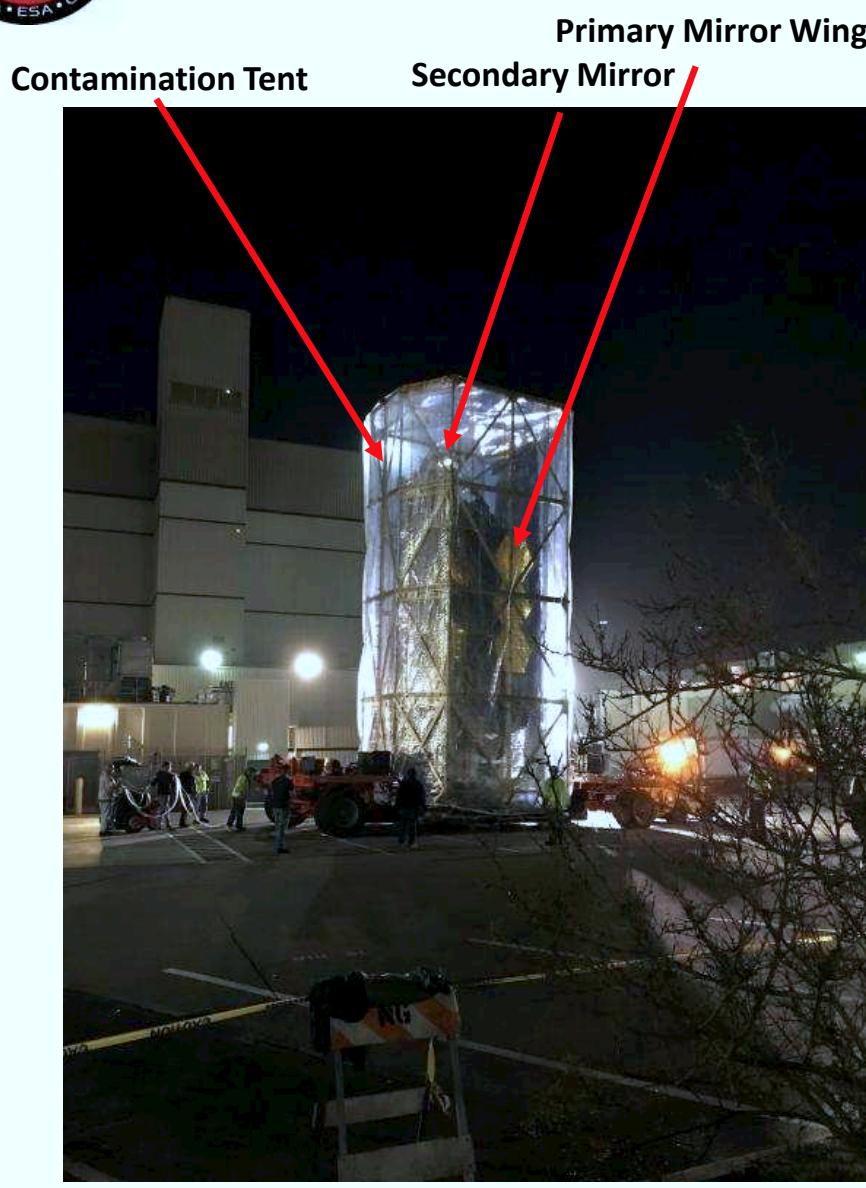


200713 JWST Monthly Telecon 10

July 2020: Deployable Tower Assembly stowed for launch



# Transport to the Large Acoustic Test Facility



En route through the Space Park, Credit: NGSS



Arriving at the LATF Airlock, Credit: NGSS  
200914 JWST Monthly Telecon 12

Aug 2020: Transport of JWST into Northrop acoustic chamber

Oct. 2020: JWST acoustic tests completed without (further) hick ups!



# Venting Patch Installation



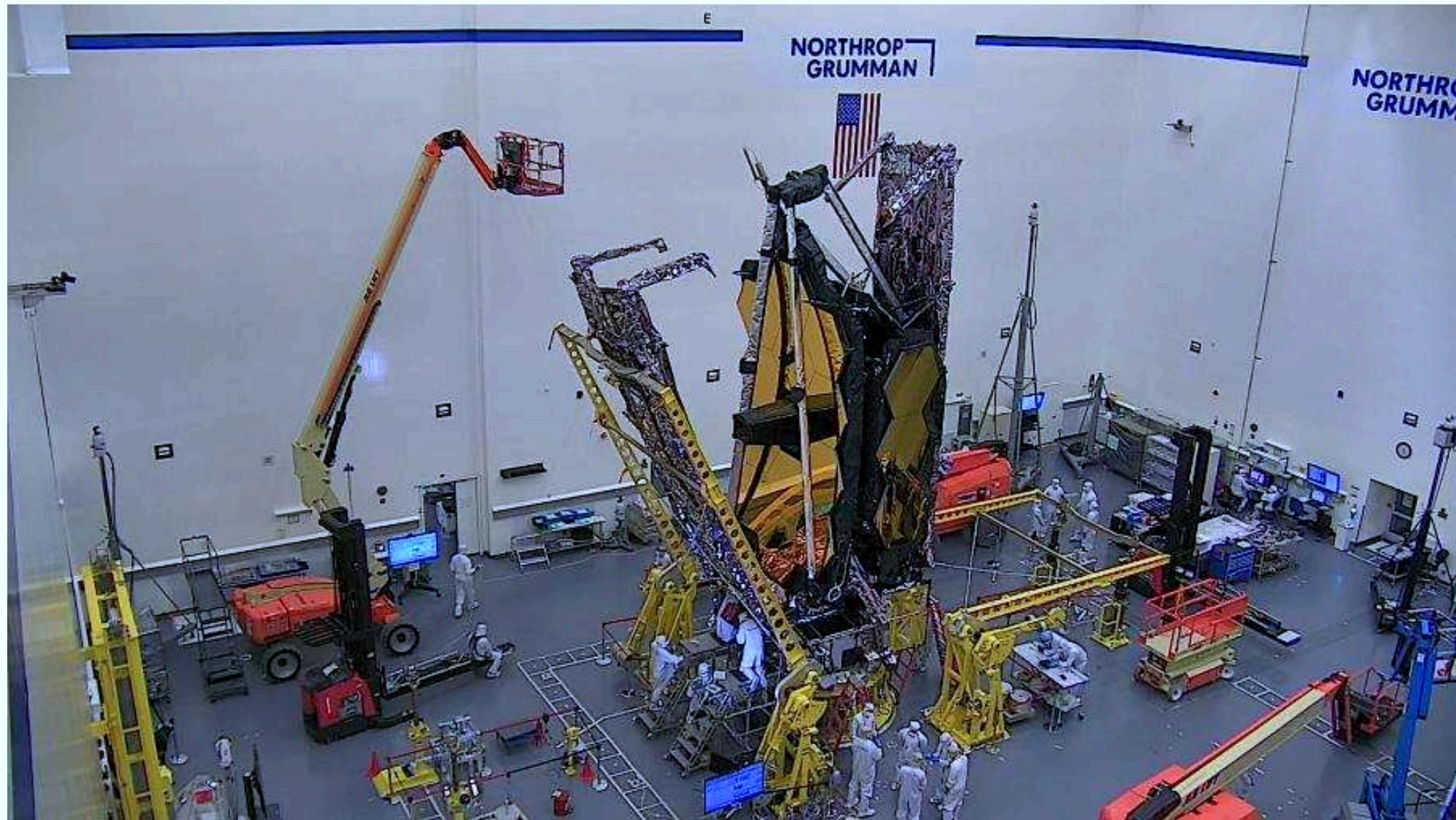
210308 JWST Telecon 16

Spring 2021: Venting patch installation before final Sunshield folding.

# 7/13/21: AFT UPS Full Stow



# 7/13/21: AFT UPS Full Stow





(beautiful)  
**The James Webb  
Space Telescope**

**Stowed for Launch**



210913 JWST Monthly Telecon 18

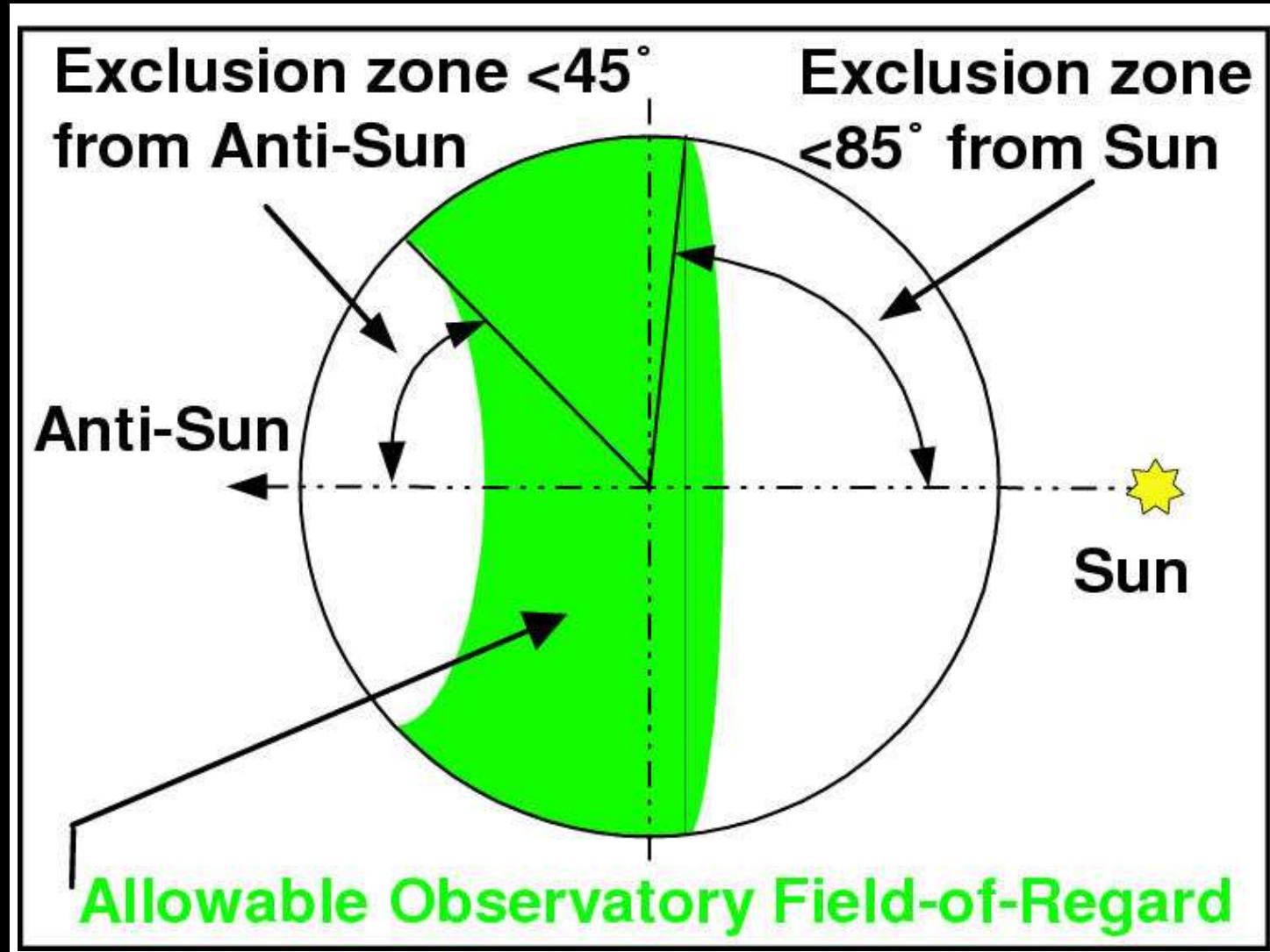
Sept. 2021: JWST ready and stowed for shipping to Kourou

NASA Readies James Webb Space Telescope for December Launch



Sept. 9, 2021: NASA/ESA declare official Kourou launch date: December 2021!

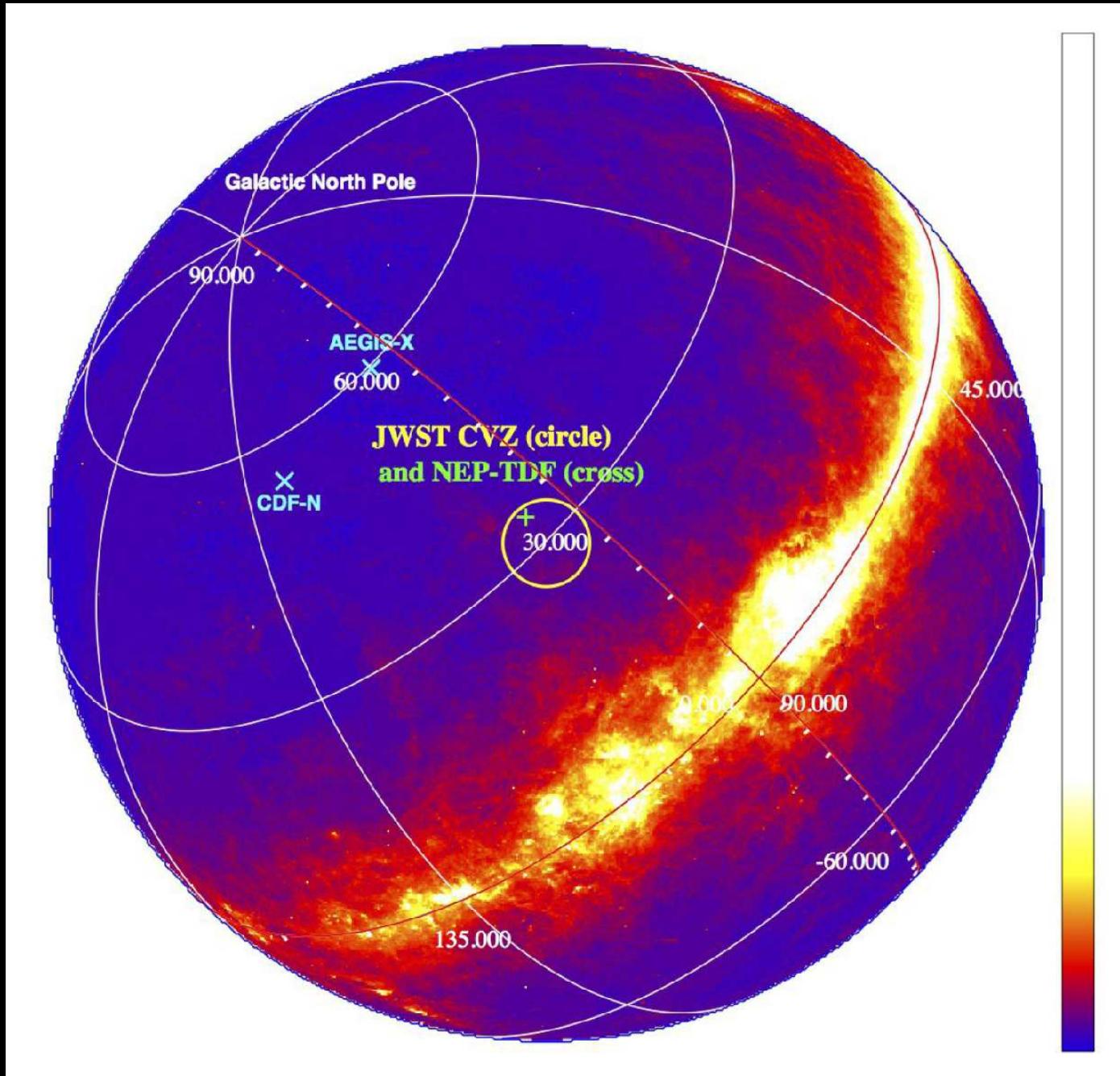
## (2) JWST Continuous Viewing Zones (CVZs): North & South Ecliptic Poles.



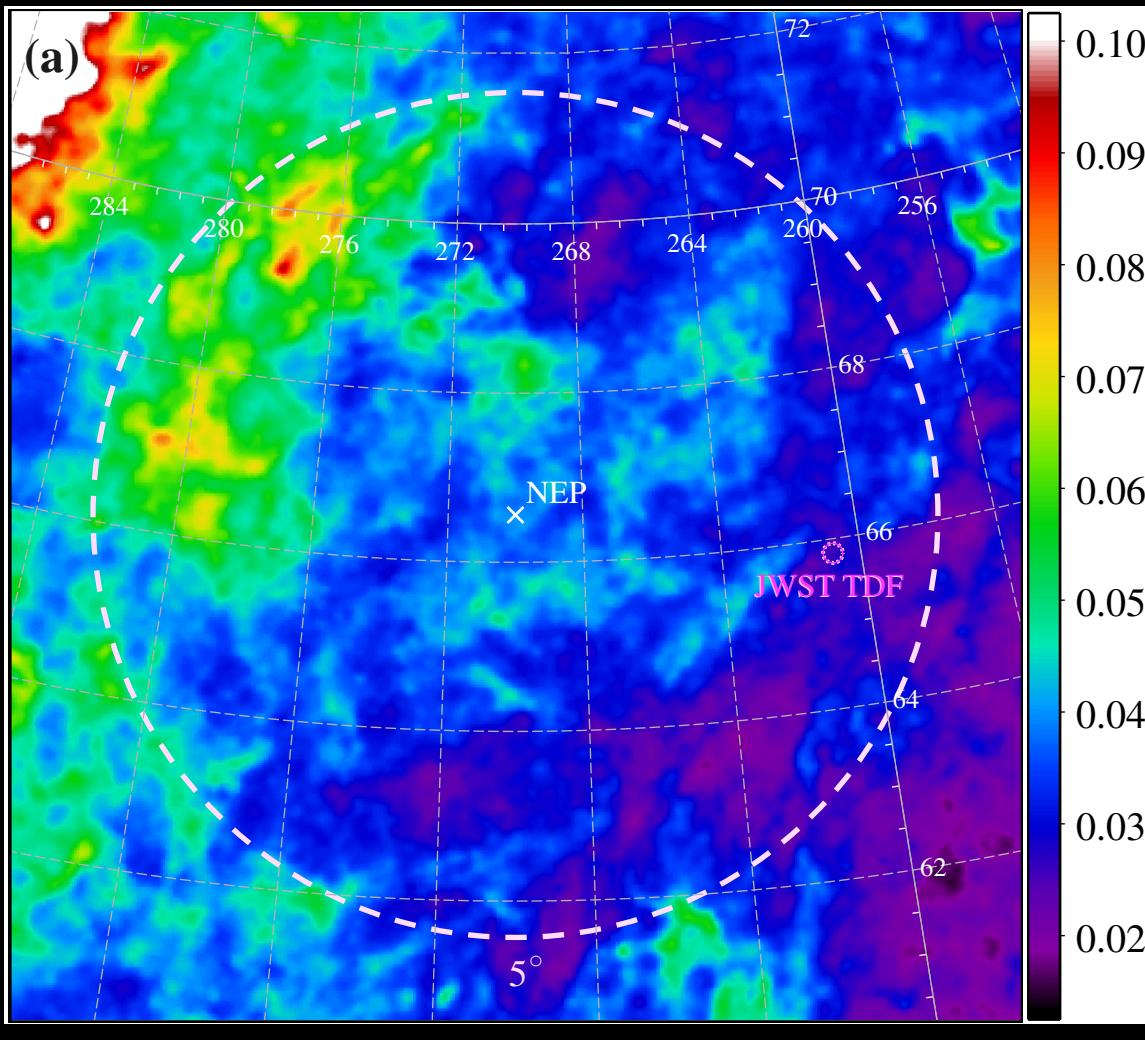
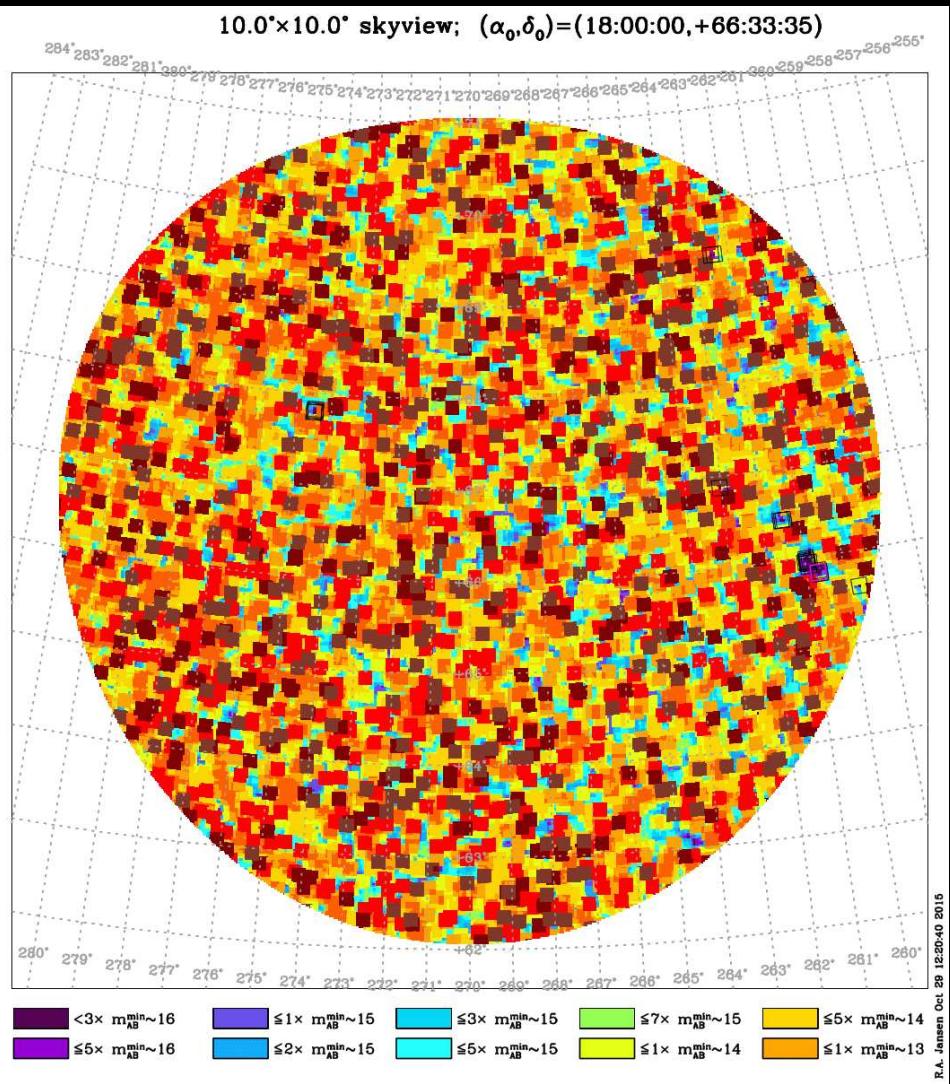
Accessible by JWST 365 days/yr: *only* the NEP & SEP CVZ ( $r \lesssim 5^\circ$ ):

- NEP has great regions for far-extragalactic science. SEP contains LMC.
- CVZs great for parallax, proper motions, high redshift variability, etc.
- JWST NEP survey also provides multi-ORIENT grism spectral separation.

## (2) JWST Continuous Viewing Zones (CVZs): North & South Ecliptic Poles.



Location of the JWST NEP TDF in our Galaxy ( $b^{II} \simeq 33^\circ$ ).

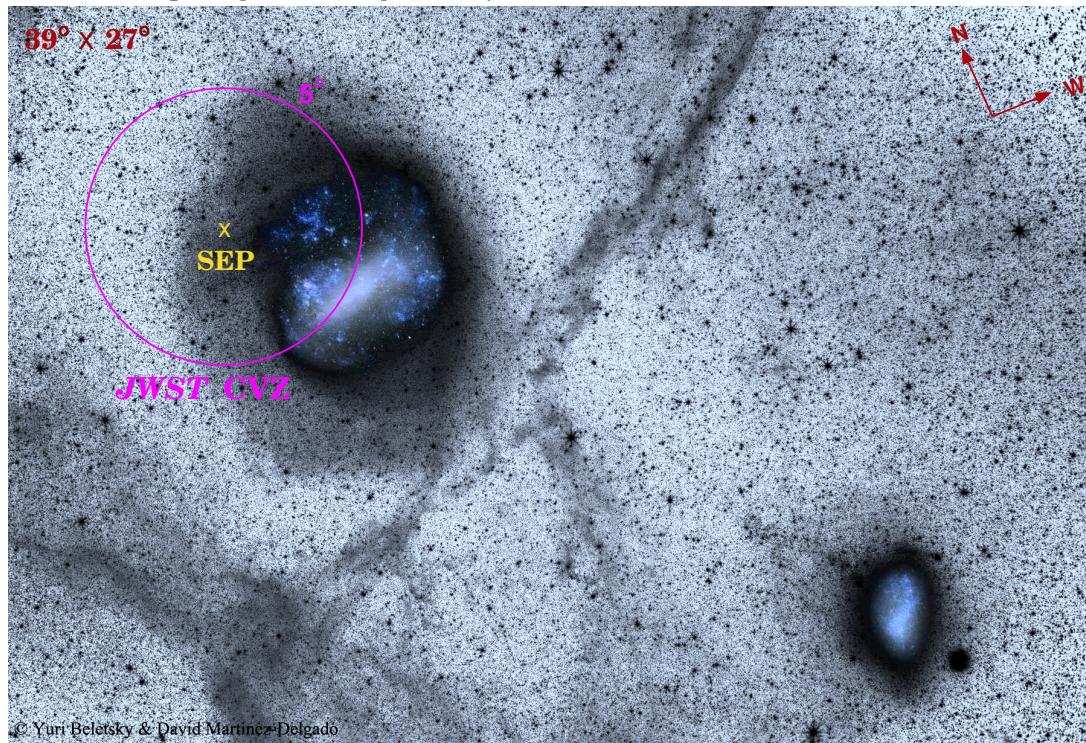


[LEFT]: *WISE*  $4\mu\text{m}$  bright star density: Very few regions (purple) without bright stars ( $AB \lesssim 16$ ) to minimize persistence in JWST images

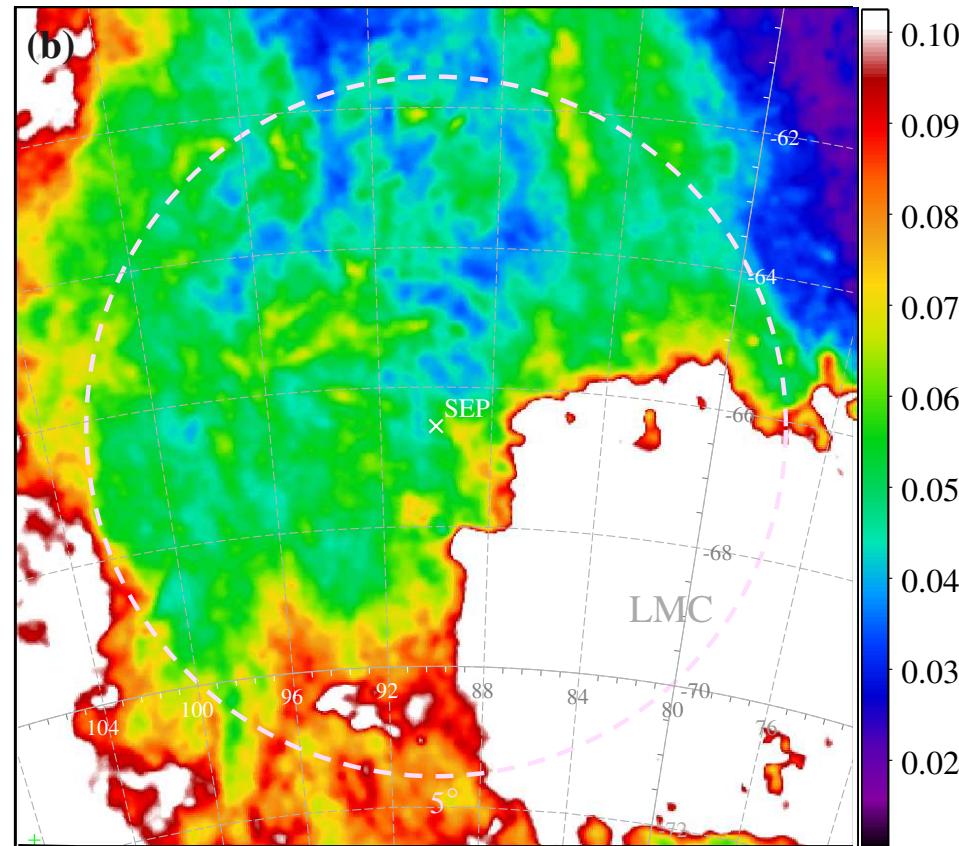
(Jansen & Windhorst, 2018, PASP, 130, 124001).

[RIGHT]:  $E(B-V)$  map (Schlegel<sup>+</sup> 1998) in same NEP-region ( $b^{II} \simeq 33^\circ$ ). Cleanest  $r=7'$  region for JWST has modest extinction:  $E(B-V) \lesssim 0.028m$ .

Deep Image of the Magellanic System with southern JWST CVZ indicated.



Besla, G., Martínez-Delgado, D., van der Marel, R., Beletsky, Y., et al. 2016, ApJ 825, 20



[LEFT] Map of LMC+SMC (Besla et al. 2016, ApJ, 825, 20).

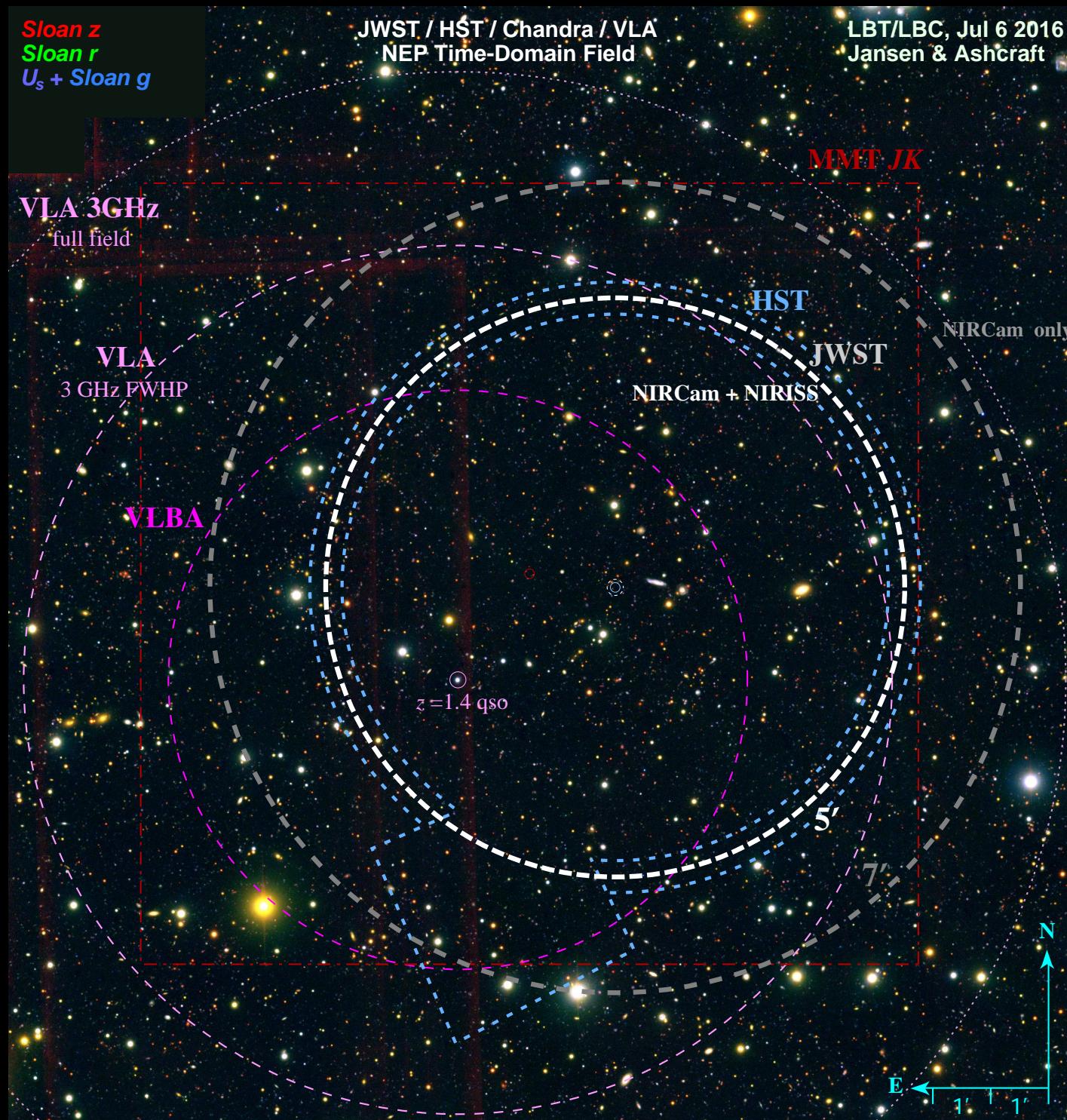
[RIGHT]:  $E(B-V)$  map (Schlegel et al. 1998) in SEP-region.

- SEP will be good for CVZ studies of LMC and its outskirts.
- SEP/LMC can be a counter-target for NEP surveys: offsets accumulated angular momentum, and so help save JWST propellant/lifetime.
- JWST should observe and monitor bottom of IMF in LMC at SEP.

Sloan z  
Sloan r  
 $U_s + \text{Sloan } g$

JWST / HST / Chandra / VLA  
NEP Time-Domain Field

LBT/LBC, Jul 6 2016  
Jansen & Ashcraft

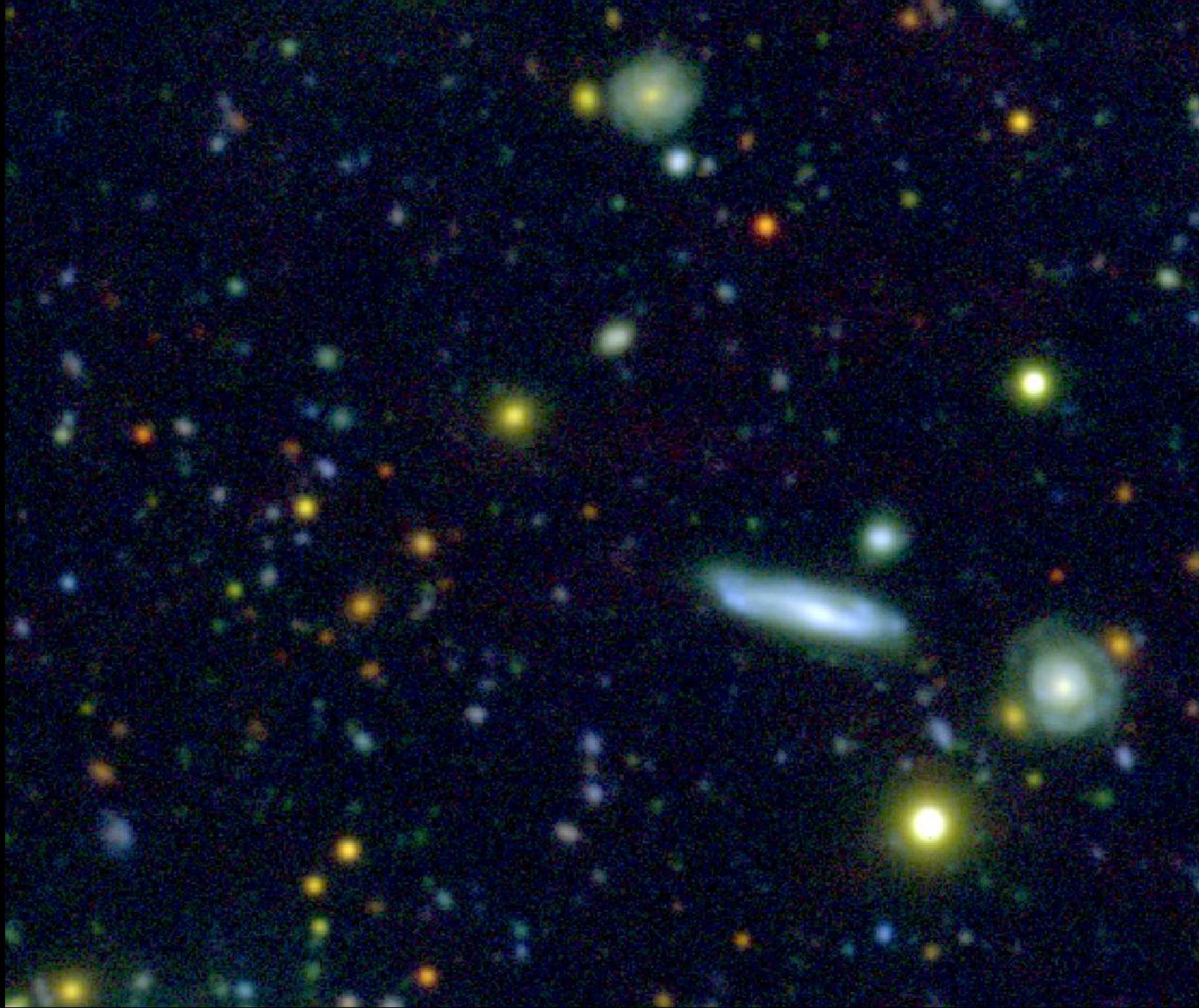


$r=7'$  JWST NEP Time-Domain Field is free of bright ( $\text{AB} \lesssim 16$ ) stars.

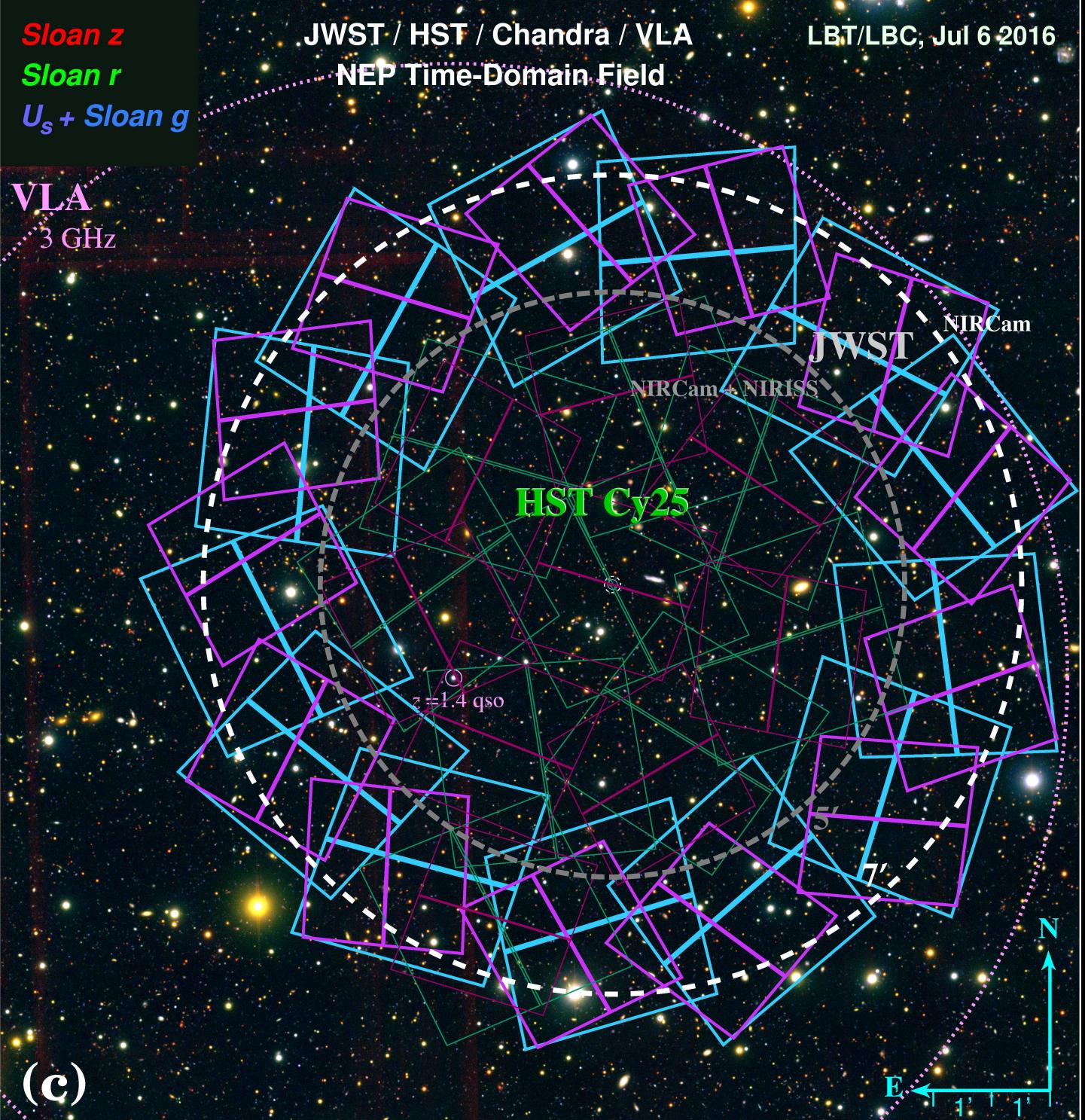
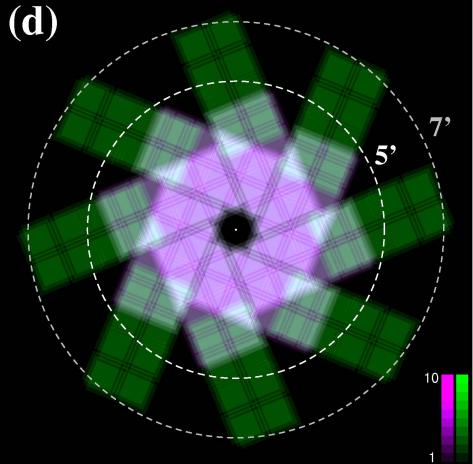
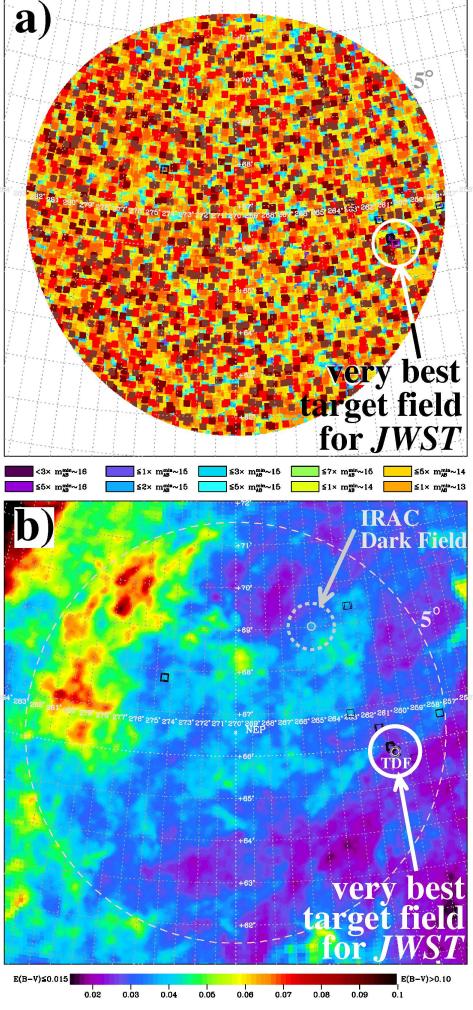
**Table 1: JWST NEP Time-Domain Field multiwavelength community investment**

Telescope	PI	Status	Depth
<i>NuSTAR</i> 3–24 keV	F. Civano	extant / in progress	687 ks / 780 ks; $>50$ cts
<i>Chandra/ACIS-I</i> 0.2–10 keV	W.P. Maksym	extant; 238 sources	444 ks; $\sim 1 \times 10^{-16}$ cgs
"	"	in progress / approved	456 ks / 900 ks
<i>XMM-Newton</i> 0.5–2.0 keV	F. Civano/M. Ward/N. Cappelluti	approved / proposed	40 ks / 800 ks; $3 \times 10^{-16}$ cgs
<i>HST/WFC3+ACS</i>	R.A. Jansen	extant; inner 9' diameter region	36 CVZ orbits;
<i>F275W,F435W,F606W</i>	"	GO 15278, GO 16252	$m \sim 27.2, 28.2, 29$ mag
"	"	in progress; annulus to $r \sim 7.8'$	52 CVZ orbits; "
<i>LBT/LBC U<sub>sp</sub>griz</i>	R.A. Jansen	extant; wide-field (2 epochs)	11 hrs; $m \sim 26.5$ –26.0 mag
<i>Subaru/HSC giz,nb816,nb921</i>	G. Hasinger / E. Hu	extant; wide-field	5 hrs; $m \sim 25.5$ –25.1 mag
<i>GTC/HiPERCAM ugriz</i>	V. Dhillon	extant; $r < 5'$	16×1 hr; $m \sim 27$ mag
<i>TESS</i> (0.6–1.0 $\mu$ m bandpass)	G. Berriman & B. Holwerda	in progress; ultra wide-field	357 days; low-SB xtd
<i>MMT/MMIRS YJHK<sub>s</sub></i>	C.N.A. Willmer	extant	60 hrs; $m \sim 23$ –24 mag
<i>JWST/NIRCam+NIRISS</i> 0.8–5 $\mu$ m + 1.75–2.23 $\mu$ m	R.A. Windhorst / H.B. Hammel	<i>guaranteed time</i> GTO #1176, #1255	~49 hrs total; $m < 29$ –28.5 mag
<i>JCMT/SCUBA-2</i> 850 $\mu$ m	I. Smail / M. Im	in progress; $\geq 93$ sources	31 hrs; rms $\sim 1$ mJy
<i>SMA</i> 0.87 mm	G. Fazio	approved pilot; lost to protests	37.5 hrs; rms $\sim 0.9$ mJy
<i>IRAM/Nika2</i> 1.2, 2 mm	S.H. Cohen	in progress	30 hrs; rms $\sim 2$ mJy
<i>VLA</i> 3(2–4) GHz	R.A. Windhorst / W. Cotton	extant; $\sim 2500$ sources	47 hrs; rms $\sim 0.9$ $\mu$ Jy
<i>VLBA</i> 4.7 GHz	W. Brisken	extant; $\sim 128$ targets	147 hrs; rms $\sim 3$ $\mu$ Jy
<i>LOFAR</i> 150 MHz	R. van Weeren	extant; ultra-wide field	72 hrs; rms $\sim 0.12$ mJy
<i>J-PAS</i> (56 narrow-band spectroph.)	S. Bonoli / R. Dupke	extant; ultra-wide field	48 hrs; $m \sim 21.5$ –22.5 mag
<i>MMT/Binospec</i> (mos)	C.N.A. Willmer	extant; 1378 spectra/799 redshifts	26 hrs; $m \sim 22.5$ –24 mag
<i>MMT/MMIRS</i> (mos)	C.N.A. Willmer	approved	$m < 22$ , $z > 0.4$

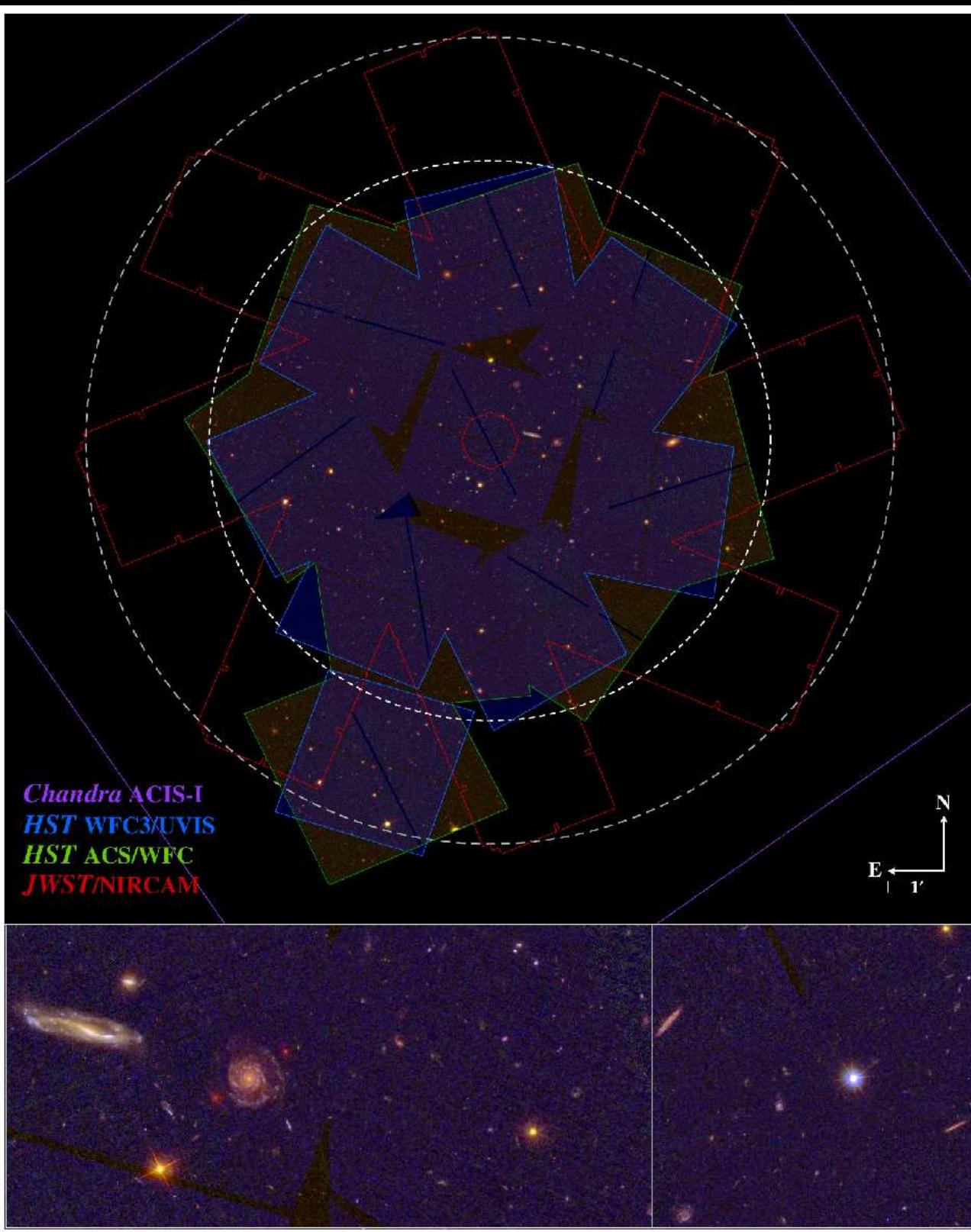
Panchromatic JWST NEP TDF data available or in progress as of 2021.  
 IDS GTO pgm focus on ground-based data supporting the JWST NEP TDF.



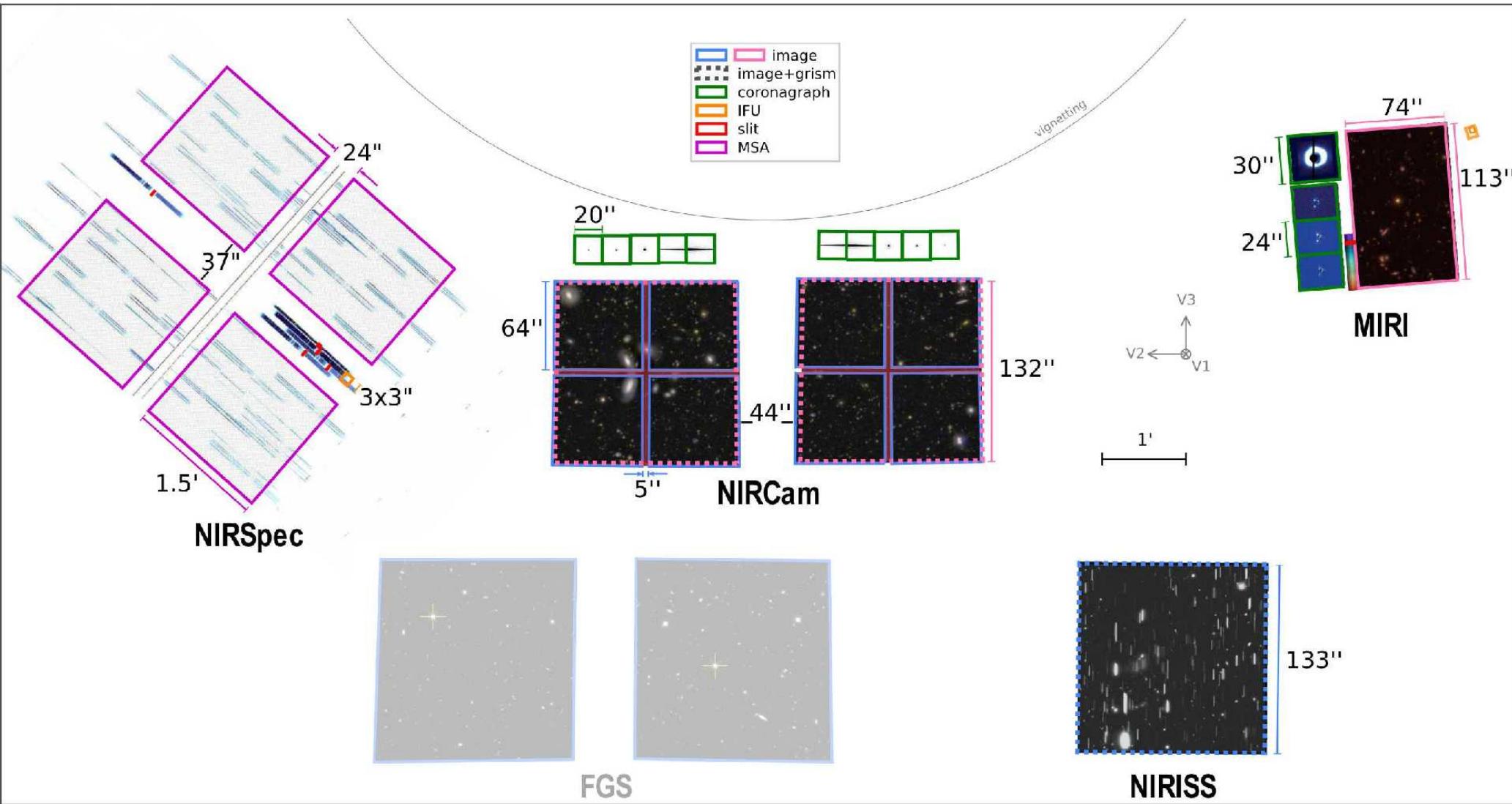
At  $r \lesssim 7'$ , JWST NEP TDF is a clean extragalactic survey field (LBT).  
To  $AB \lesssim 26$  mag, get many faint Galactic brown dwarfs and high-z dropouts.



JWST NEP TDF with HST Cy 25–28 ACS+WFC3 mosaics overlaid.



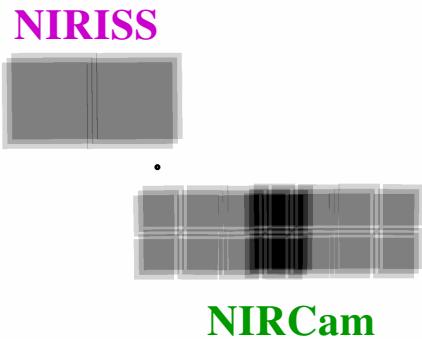
## (2) NIRCam + NIRISS-parallels optimally cover the JWST NEP TDF.



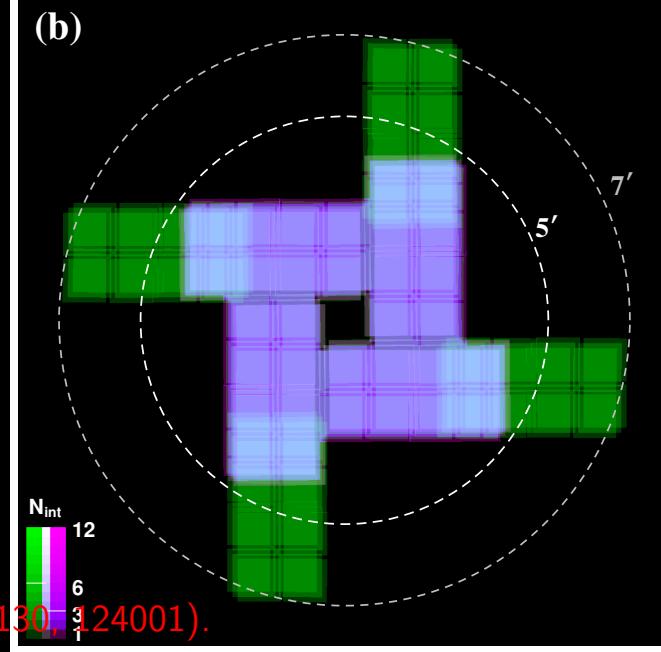
- Most-used JWST instrument pairs implemented for science parallels.
- CVZ enables overlapping *dark-sky* NIRCam + NIRISS-parallel mosaics.
- JWST NIRISS grism science (parallel to NIRCam) is essential!

# Exposure Maps of NEP JWST-Windmill & GO-Extensions:

(a)

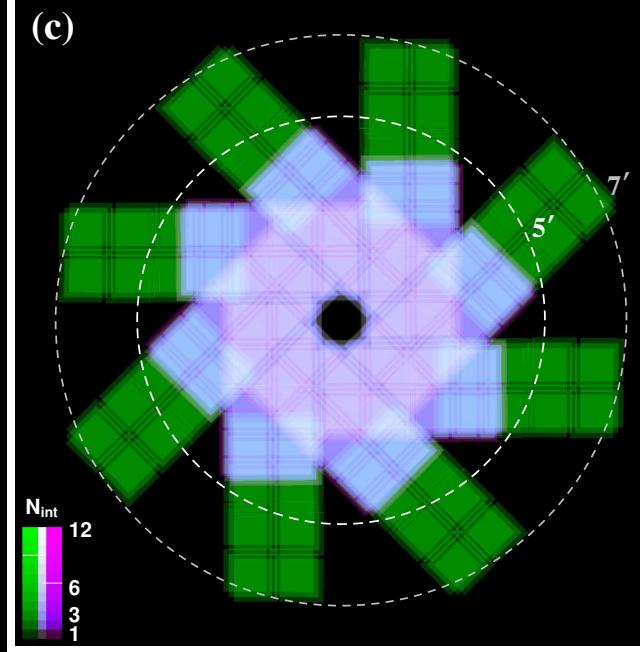


(b)



From: Jansen & Windhorst (2018, PASP, 130, 124001).

(c)



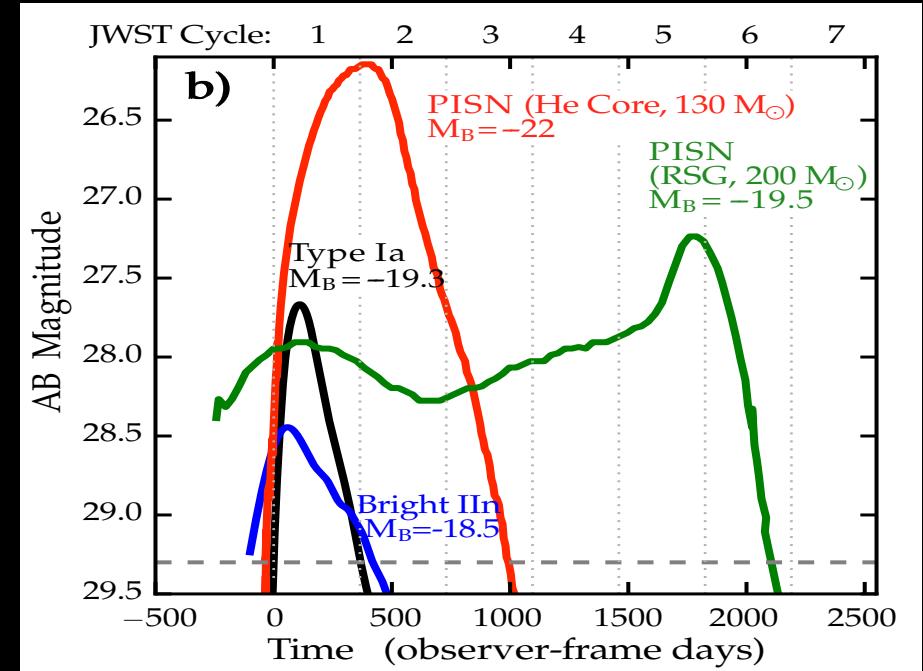
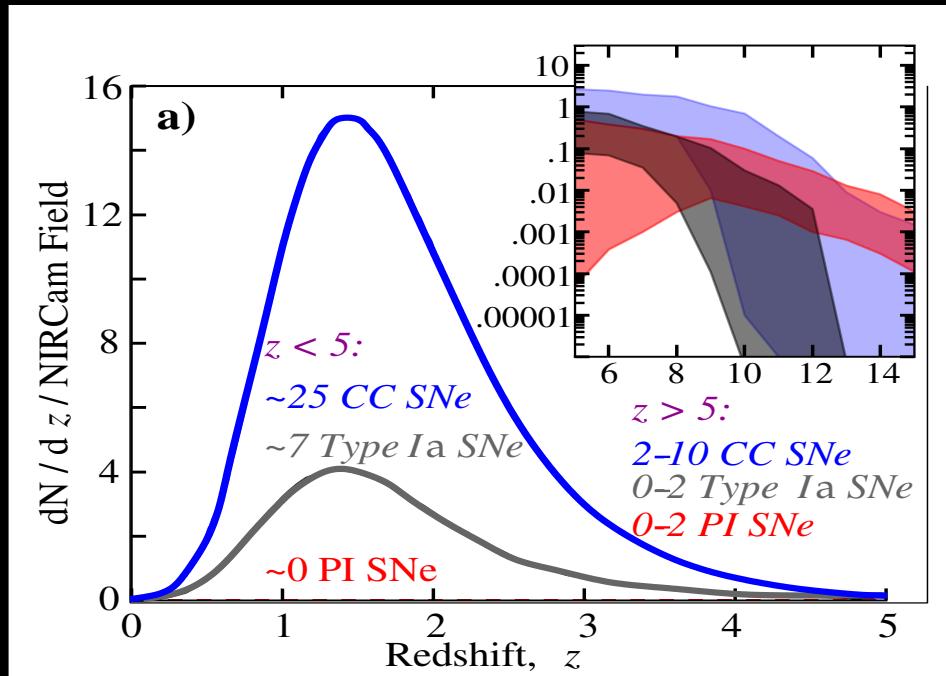
[LEFT]: Exposure map of two contiguous areas: NIRCam primary (green) + NIRISS parallel grism (purple), observable at any PA.

[MIDDLE]: Same with  $\Delta PA = 90 + 180 + 270^\circ$  added: our 50-hr GTO plan.

[RIGHT]: 8-epoch GO-Community extension in JWST Cycle  $\gtrsim 1$ .

NEP  $2.0\mu\text{m}$  sky *always* dark:  $0.24 \pm 0.03 \text{ MJy/sr}$  (GOODS  $\simeq 0.19 - 0.35$ ).

- NEP: time-domain imaging to AB  $\lesssim 29$  & grism spectra to AB  $\lesssim 28$  mag.



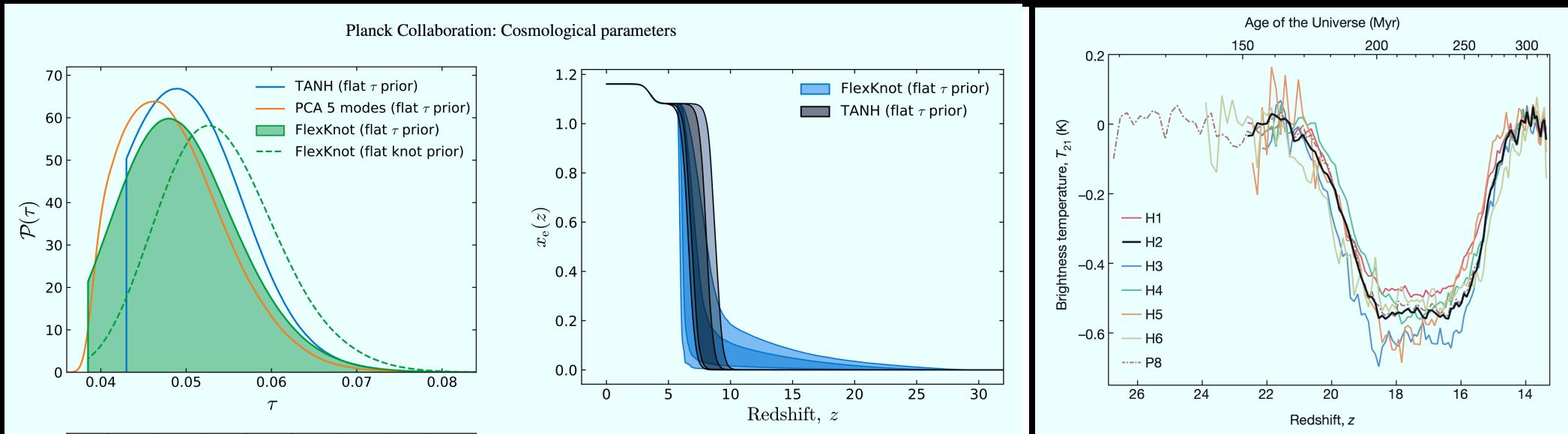
[LEFT] Projected Supernova yield for a single JWST/NIRCam field:  
JWST NEP TDF provides  $\sim 16 \times$  more high-z SNe than 1 NIRCam:

- JWST NEP will detect *all* Type Ia SNe to  $z \lesssim 5$  (Rodney et al. 2015),
- + 90% of all Core Collapse (CC) SNe to  $z \lesssim 1.5$  (Strövelger et al. 2015).

[RIGHT] Simulated light curves for SNe types at  $z=7$ : JWST may detect (rare) Pair Instability SuperNovae (PISN; Kasen et al. 2011).

- 7-yr timescale of PISN: Must start NEP field in JWST Cycle 1.
- NEP can monitor SNe (+hosts) as often as needed, including at  $z \gtrsim 5$ .

### (3a) Limits to the Sky-SB from Pop III objects: First Stars



Two Reionization/First Light constraints remain seemingly at odds:

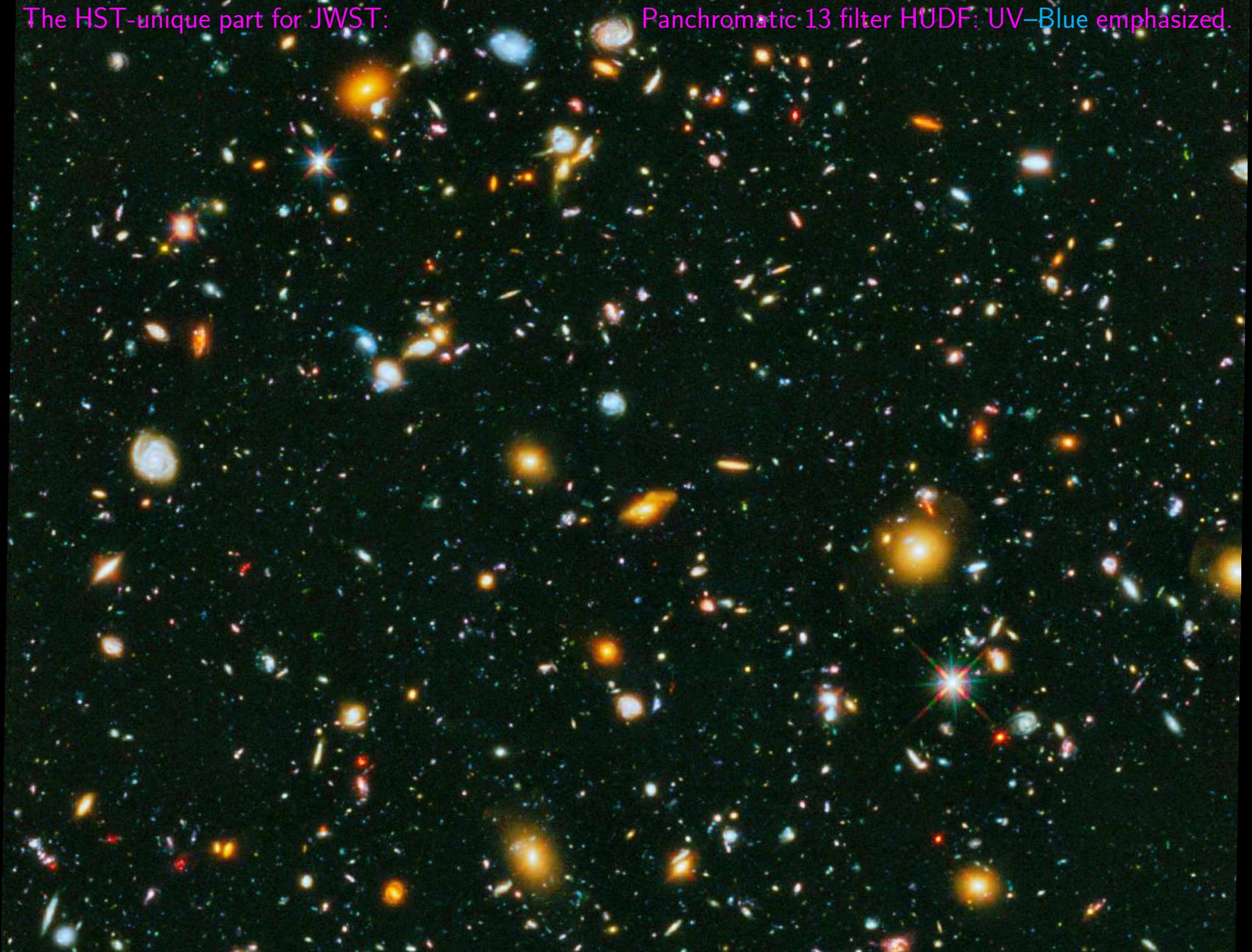
[LEFT 2]: Planck 2018 VI (astro-ph/1807.06209v1): ● CMB polarization optical depth  $\tau \simeq 0.054 \pm 0.007 \Rightarrow z_{reion} \simeq 7.7 \pm 0.7$  (age 670 Myr).

[RIGHT]: Bowman et al. EDGES result (2018, Nature, 555, 67):

- Possible global 78 MHz HI-signal at  $z \simeq 17 \pm 2$  (age 225 Myr).
- How can we reconcile this in context of the First Stars?
- What does this mean for First Dust, and the first (BH) binary stars?

The HST-unique part for JWST:

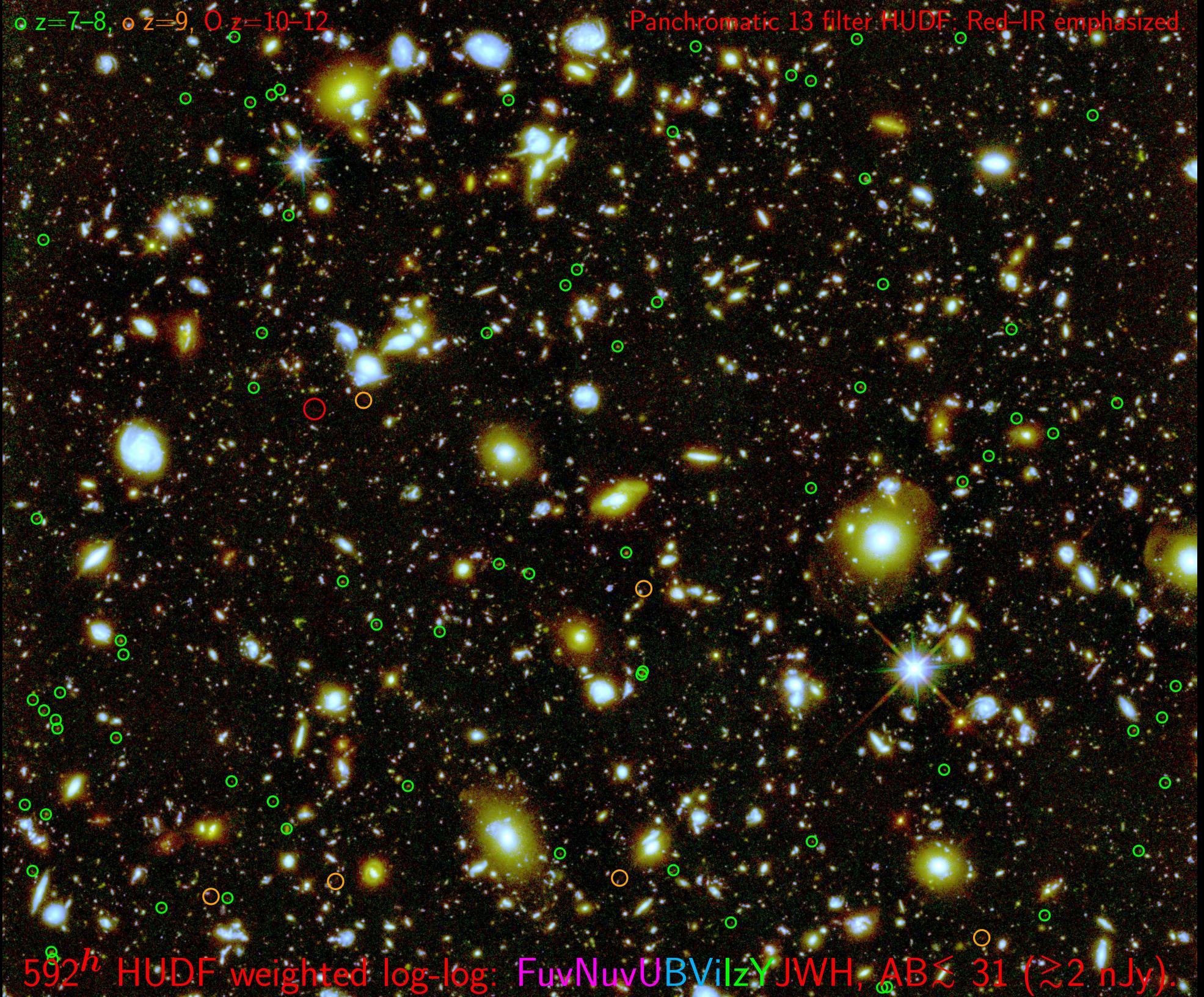
Panchromatic 13 filter HUDF: UV–Blue emphasized.



$592^h$  HUDF weighted log-log: F<sub>UV</sub>N<sub>UV</sub>U<sub>BV</sub>i<sub>Lz</sub>Y<sub>JWH</sub>, AB $\lesssim$ 28–31 ( $\gtrsim$ 2 nJy).

○  $z=7-8$ , ○  $z=9$ , ○  $z=10-12$ .

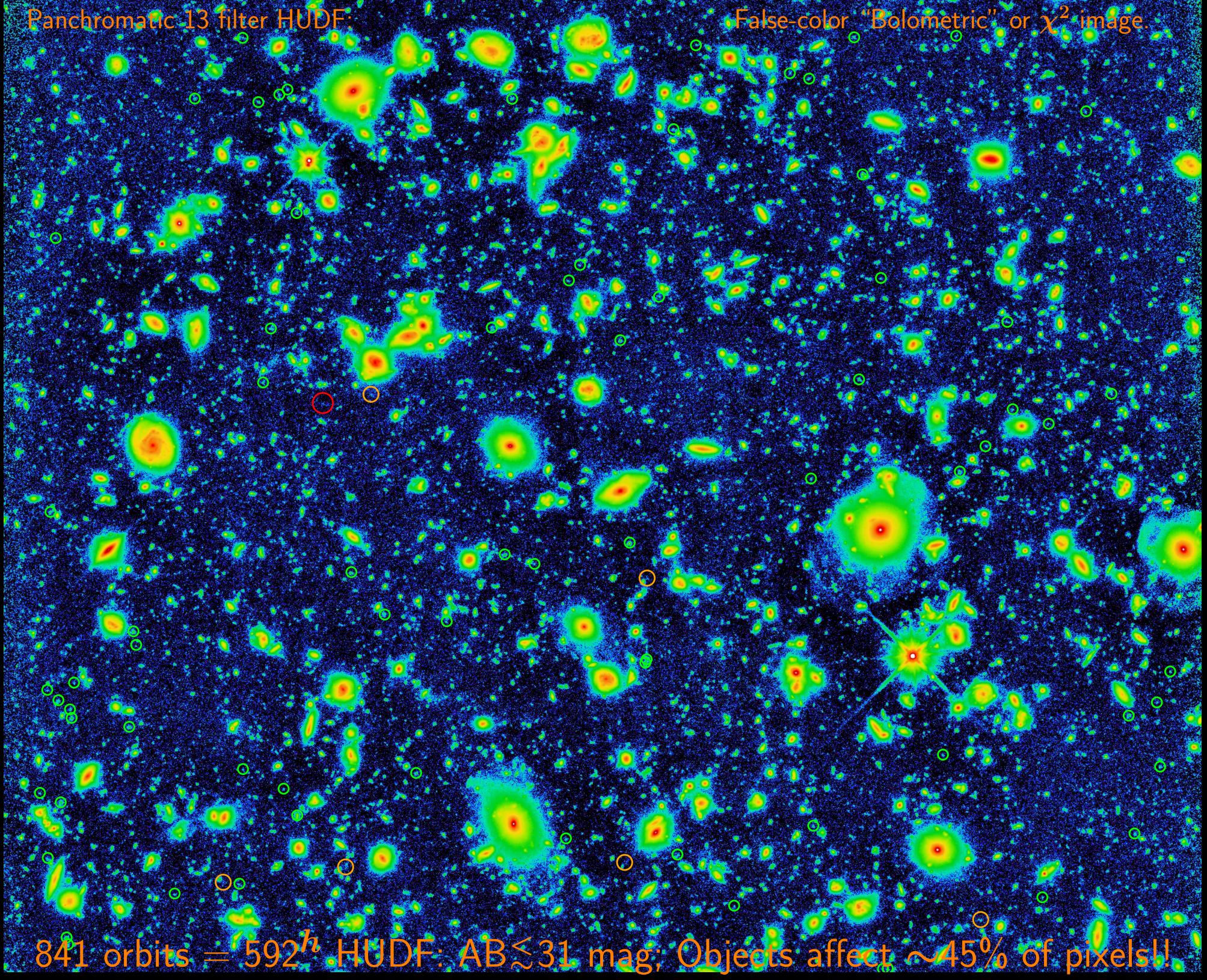
Panchromatic 13 filter HUDF: Red-IR emphasized.



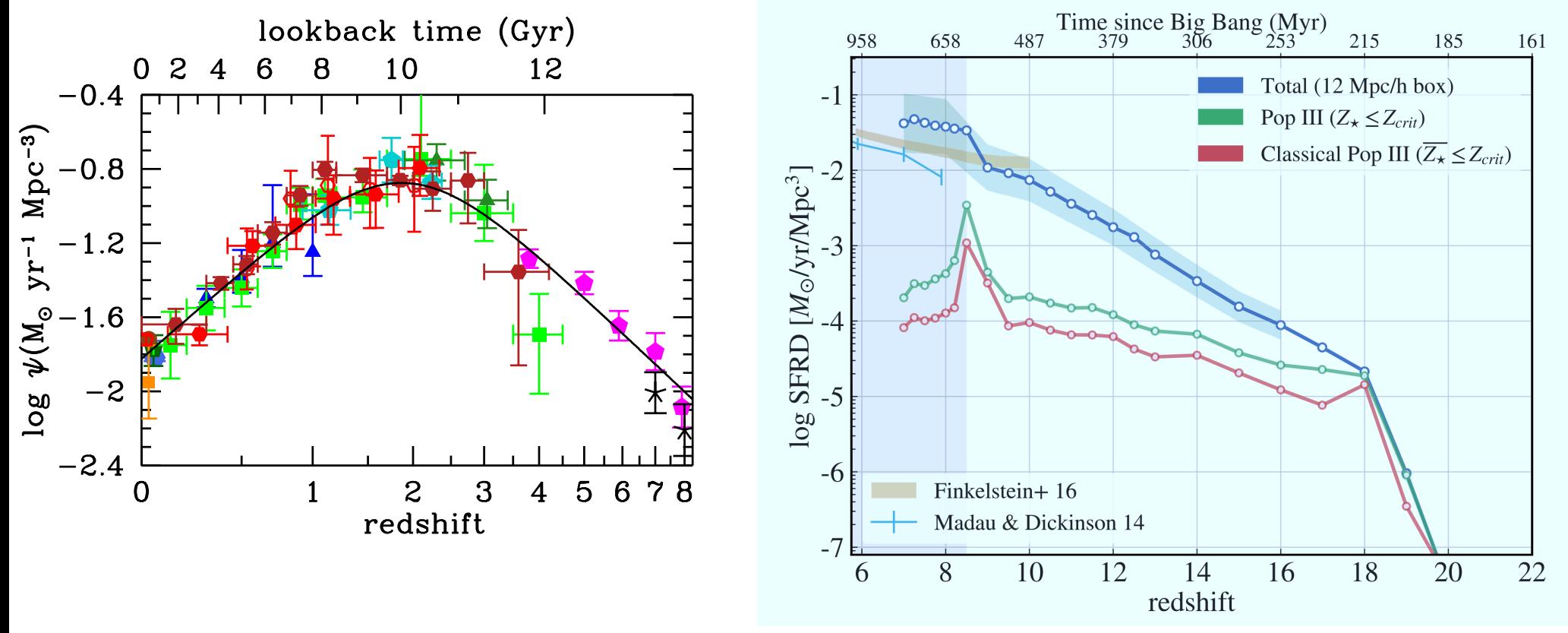
$592^h$  HUDF weighted log-log: F<sub>UV</sub>N<sub>UV</sub>U<sub>BV</sub>I<sub>zYJWH</sub>, AB  $\lesssim 31$  ( $\gtrsim 2$  nJy).

Panchromatic 13 filter HUDF

False-color "Bolometric" or  $\chi^2$  image.



841 orbits = 592<sup>h</sup> HUDF: AB  $\lesssim$  31 mag; Objects affect  $\sim$  45% of pixels!!



Anticipated cosmic star-formation rate (SFR) at  $z \gtrsim 7$ :

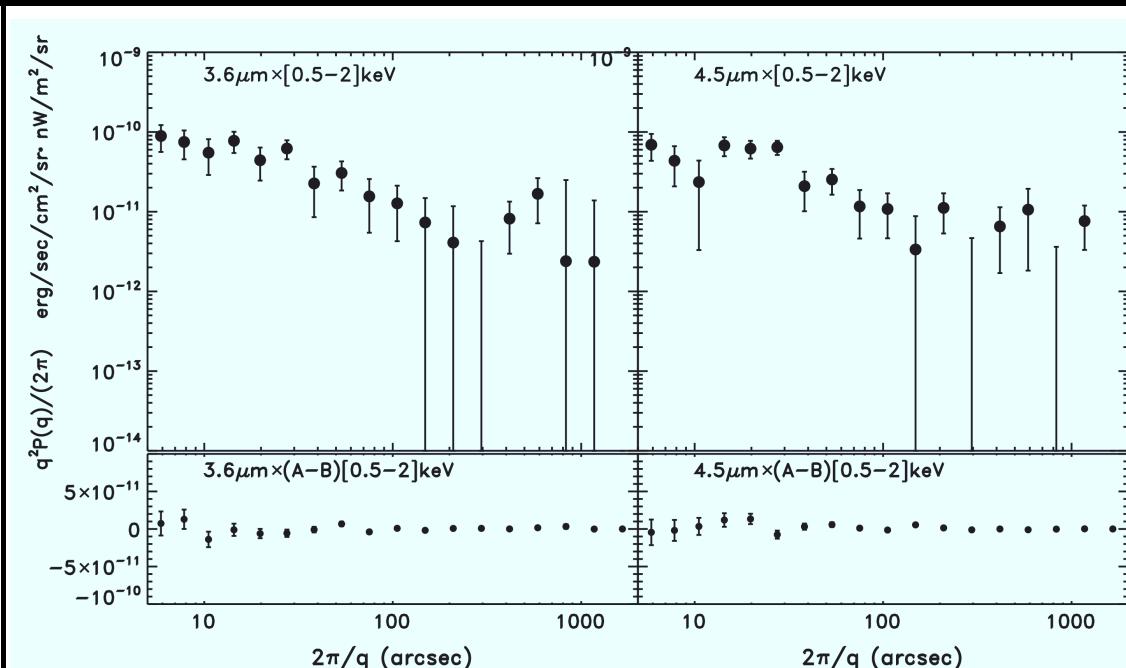
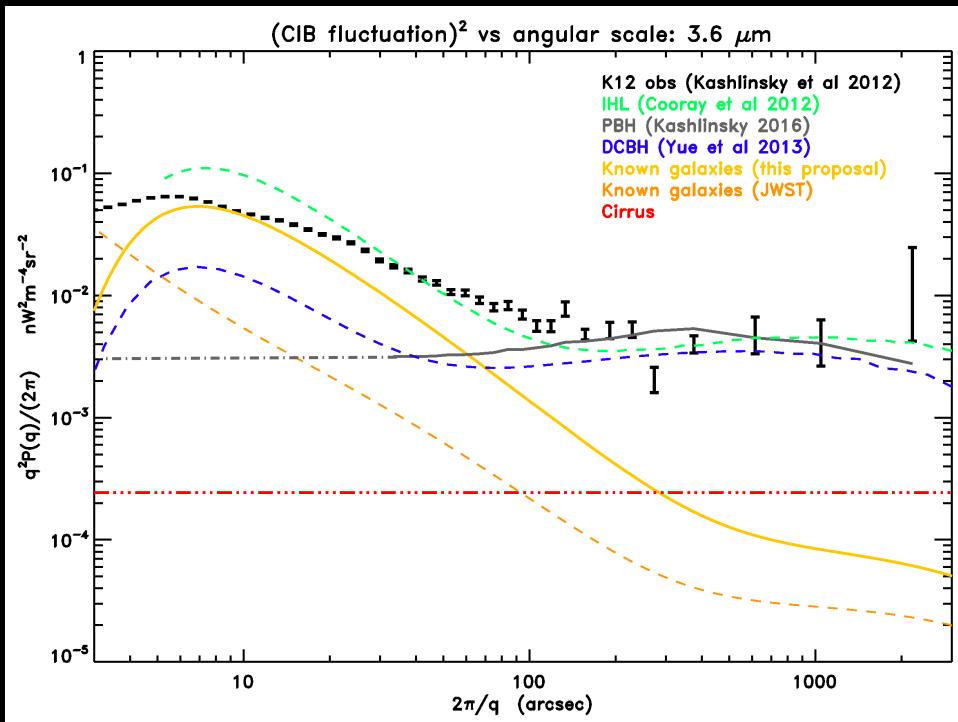
[LEFT] Observed SFH (Madau & Dickinson; 2014 ARAA, 52, 415);

[RIGHT] RAMSES models (*e.g.*, Sarmento et al. 2018, ApJ, 854 75).

⇒ Adopt this SFR from  $z \simeq 17$  to  $z \simeq 7$ , implying at the lowest masses:

- Metallicity increases from  $\sim 0$  at  $z \simeq 18$  to  $\lesssim 10^{-3}$  solar at  $z \simeq 7$ .
- Integrated SFR from  $z \gtrsim 7$  has sky-SB  $\gtrsim 31$  K-mag/arcsec $^{-2}$  (Windhorst et al. 2018), similar to the 3.6  $\mu\text{m}$  CIB sky-SB possibly from BH's.

### (3a) Limits to Pop III Sky-SB: First (Stellar-Mass?) Black Holes



[LEFT] Object-free Spitzer  $3.6\mu m$  power-spectrum constrains noise fluctuation models (Cappelluti et al. 2017; Kashlinsky et al. 2012, 2015, 2018):

Explainable by: Primordial black hole or Direct-collapse black hole models.

[RIGHT] Spitzer–Chandra cross-corr spectrum (Mitchell-Wynne et al. 2016):

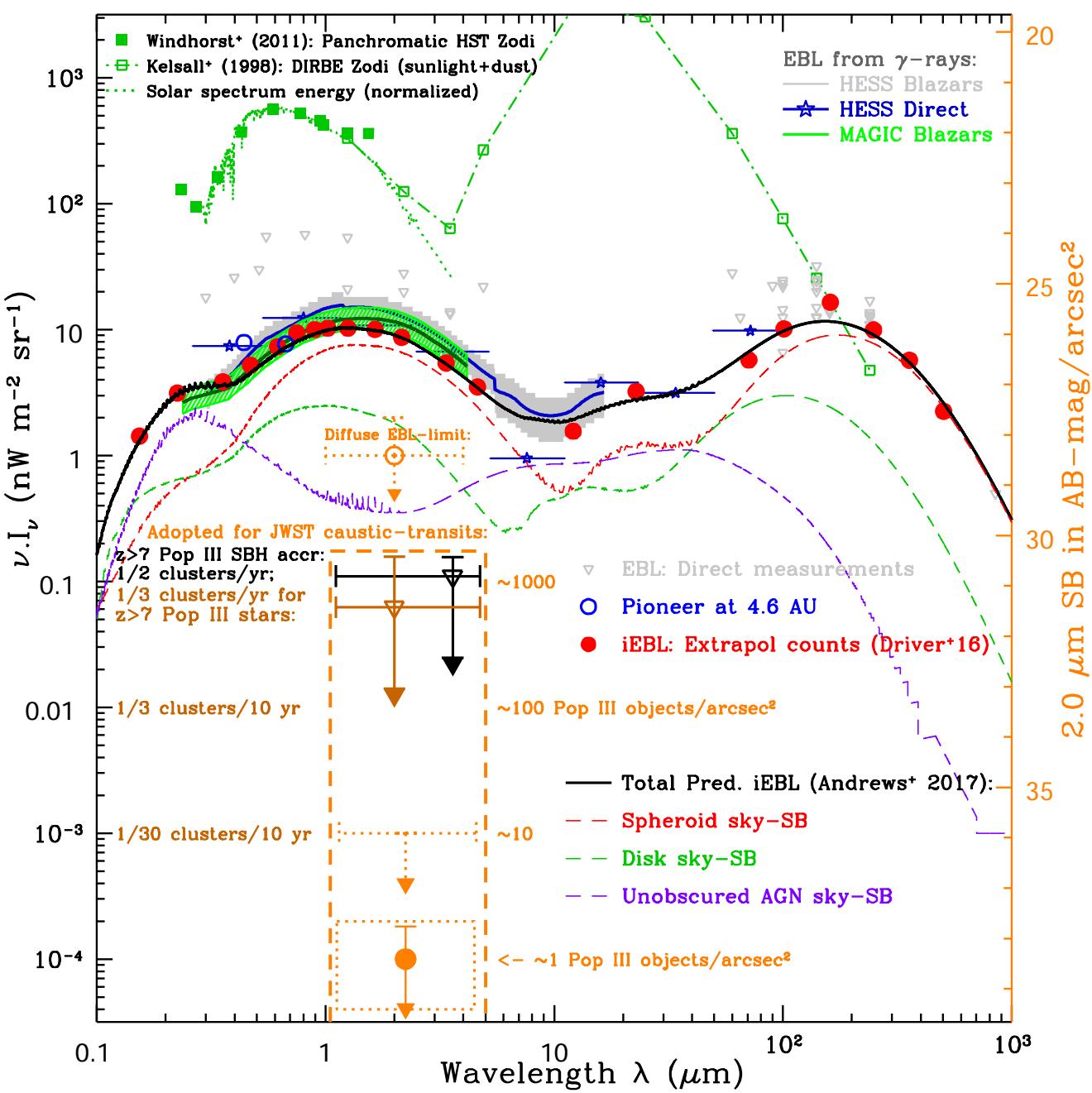
- $z \gtrsim 7$  objects have sky-SB fainter than  $31 \text{ mag}/\text{arcs}^2$ , plus likely a (stellar mass) black hole X-ray component. (Kashlinsky+ 2018; Windhorst+ 2018, ApJ, 234, 41).

# Extragalactic Background Light (Driver<sup>+</sup> 16; Windhorst<sup>+</sup> 18):

$\text{Energy(dust)} \simeq 52\% \&$   
 $\text{energy(cosmic SF)} \simeq 48\%$   
 of EBL  $\Rightarrow$  dust wins!

Diffuse  $1-4\mu\text{m}$  sky  $\lesssim 0.1 \text{ nW/m}^2/\text{sr}$   
 or  $\text{SB}(K) \gtrsim 31 \text{ mag/arcsec}^2$ :

- 1) possibly from Pop III stars at  $z \simeq 7-17$ , and/or
- 2) their stellar-mass BH accretion disks ( $z \simeq 7-8$ ).



- This can make Pop III stars or their BH accretion disks temporarily visible to JWST & ground-based 30 meter telescopes at  $\text{AB} \lesssim 28-29$  mag.
- Requires using the best lensing clusters and monitoring caustic transits.

# (3c) Possible caustic transits from Pop III stars and their BH accretion disks.

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## On the Observability of Individual Population III Stars and Their Stellar-mass Black Hole Accretion Disks through Cluster Caustic Transits

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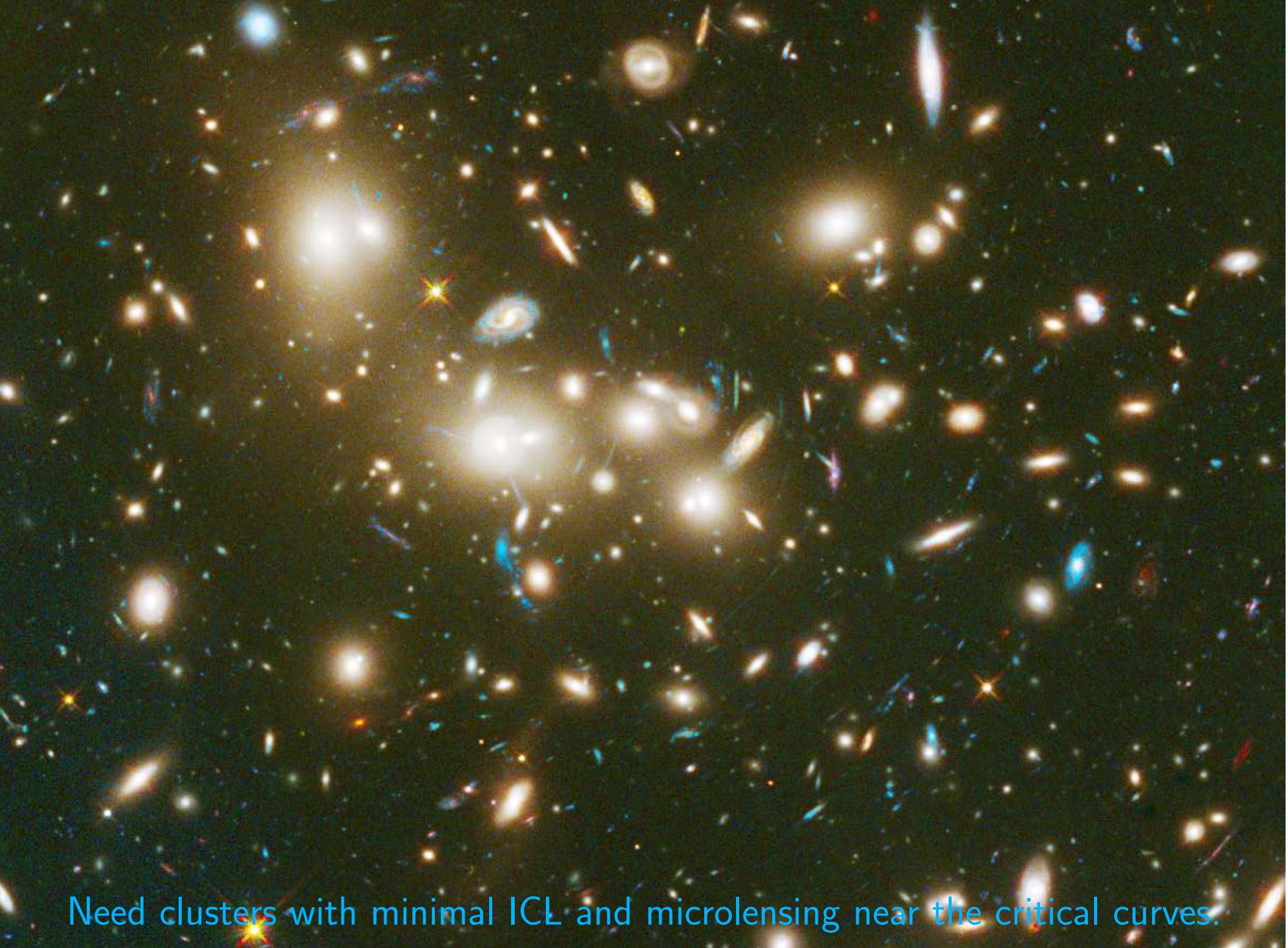
### Abstract

We summarize panchromatic Extragalactic Background Light data to place upper limits on the integrated near-infrared surface brightness (SB) that may come from Population III stars and possible accretion disks around their stellar-mass black holes (BHs) in the epoch of First Light, broadly taken from  $z \simeq 7\text{--}17$ . Theoretical predictions and recent near-infrared power spectra provide tighter constraints on their sky signal. We outline the physical properties of zero-metallicity Population III stars from MESA stellar evolution models through helium depletion and of BH accretion disks at  $z \gtrsim 7$ . We assume that second-generation non-zero-metallicity stars can form at higher multiplicity, so that BH accretion disks may be fed by Roche-lobe overflow from lower-mass companions. We use these near-infrared SB constraints to calculate the number of caustic transits behind lensing clusters that the *James Webb Space Telescope* and the next-generation ground-based telescopes may observe for both Population III stars and their BH accretion disks. Typical caustic magnifications can be  $\mu \simeq 10^4\text{--}10^5$ , with rise times of hours and decline times of  $\lesssim 1$  year for cluster transverse velocities of  $v_T \lesssim 1000 \text{ km s}^{-1}$ . Microlensing by intracluster-medium objects can modify transit magnifications but lengthen visibility times. Depending on BH masses, accretion-disk radii, and feeding efficiencies, stellar-mass BH accretion-disk caustic transits could outnumber those from Population III stars. To observe Population III caustic transits directly may require monitoring 3–30 lensing clusters to AB  $\lesssim 29$  mag over a decade.

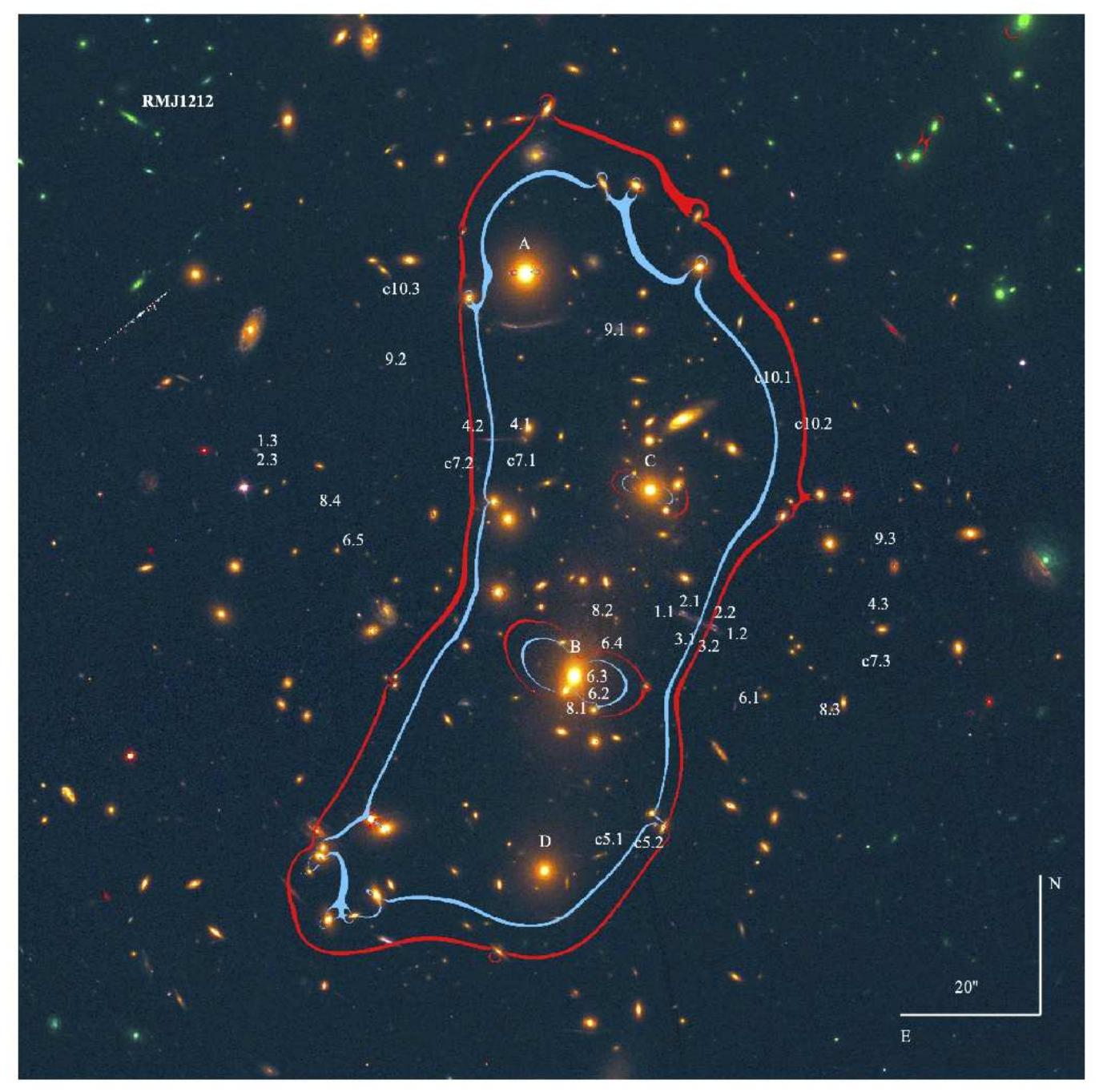
**Key words:** accretion, accretion disks – galaxies: clusters: general – gravitational lensing: strong – infrared: diffuse background – stars: black holes – stars: Population III

- JWST (and ground-based 25–39 m telescopes) may detect Pop III stars and their stellar-mass BH accretion disks *directly* to AB  $\lesssim 28\text{--}29$  mag via cluster caustic transits (Windhorst<sup>+</sup>, 2018, ApJS, 234, 41).
- JWST GO community should anticipate this and build on it.

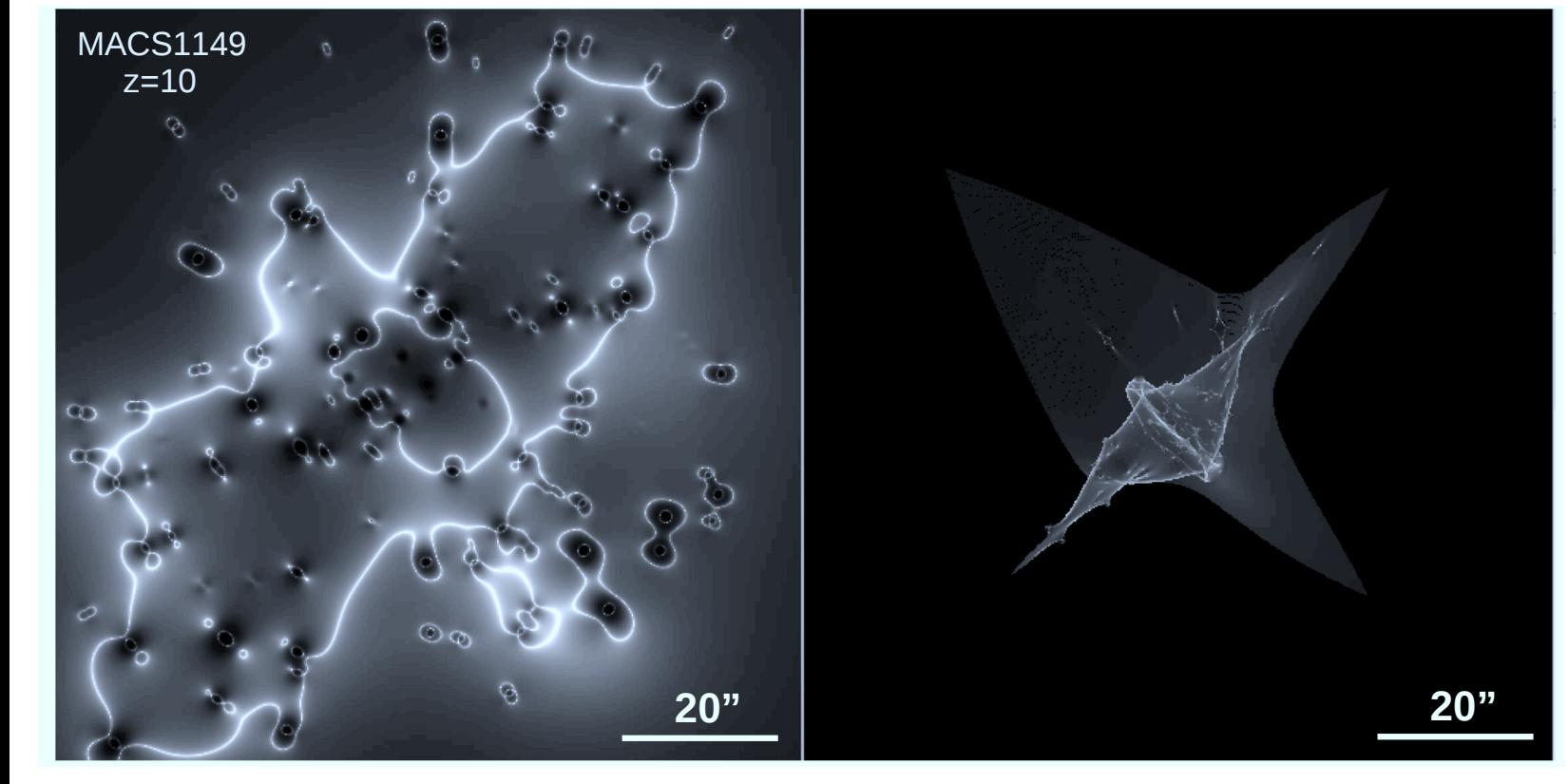
HFF A2744: JWST needs cluster caustic transits to see Pop III objects.



Need clusters with minimal ICL and microlensing near the critical curves.



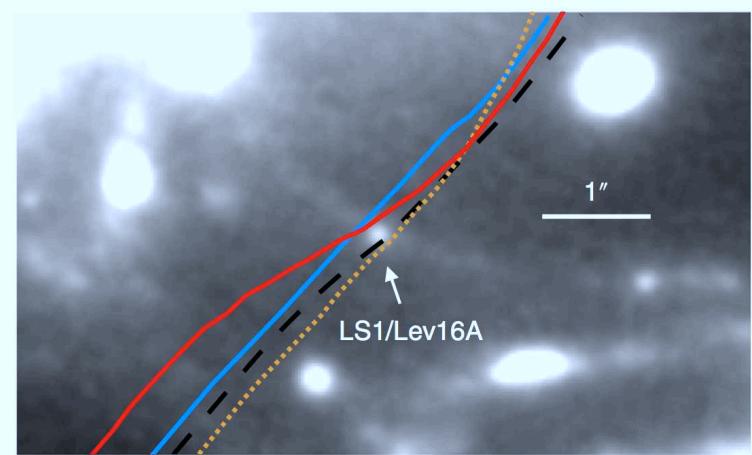
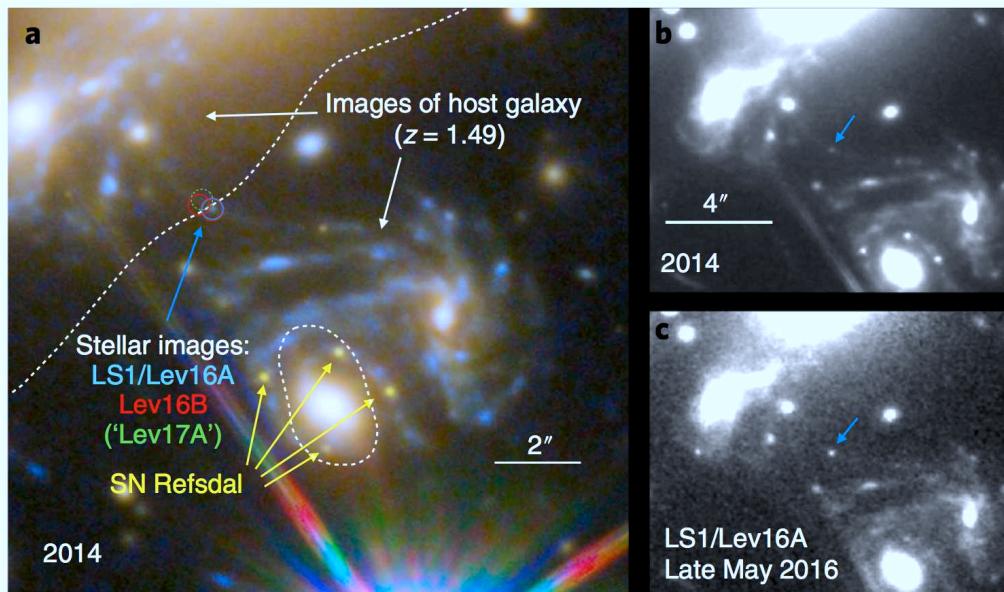
Light Traces Mass (LTM) method gives lensing clusters well suited for high-z magnifications (A. Zitrin et al. 2020, ApJ, 903, 137; astro-ph/2007.11600).



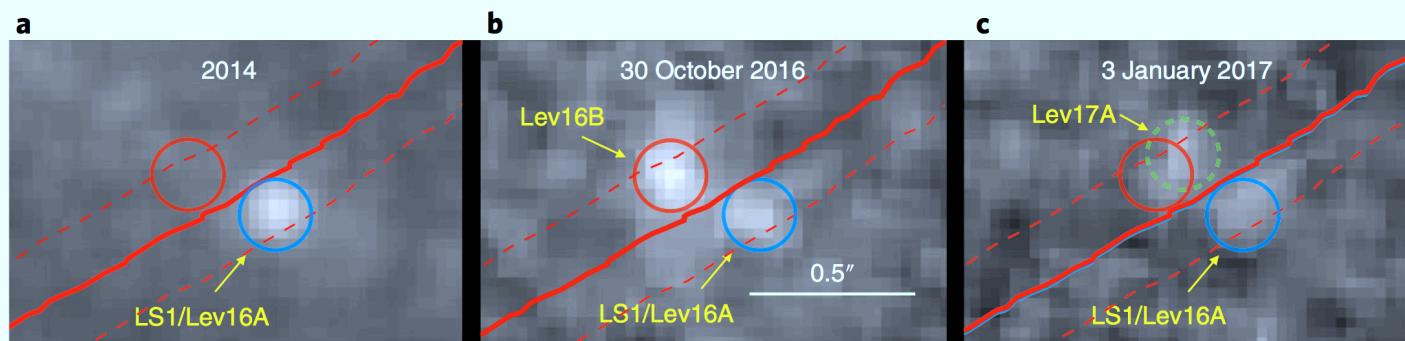
For source at  $z=10$ , critical curves for HFF cluster MACS 1149 at  $z \simeq 0.54$  [LEFT], and main cluster caustics [in the source plane; RIGHT].

- Transverse cluster (sub-component) velocities can be  $v_T \lesssim 1000$  km/s (Kelly<sup>+</sup> 2018; Nature Astr. 2, 334; Windhorst<sup>+</sup> 2018, ApJS, 234, 41).
- Main caustic magnification:  $\mu \simeq 10.(d_{caustic}/'')^{-1/2}$ . For Pop III objects at  $z \gtrsim 7$  with  $1-30 R_\odot$ ,  $\mu$  can be  $\gtrsim 10^4-10^5$  for  $\lesssim 0.4$  year!
- Must use clusters with minimal ICL near the critical curves, since ICL microlensing dilutes the main caustics (Diego<sup>+</sup> 2018, ApJ, 857, 25).

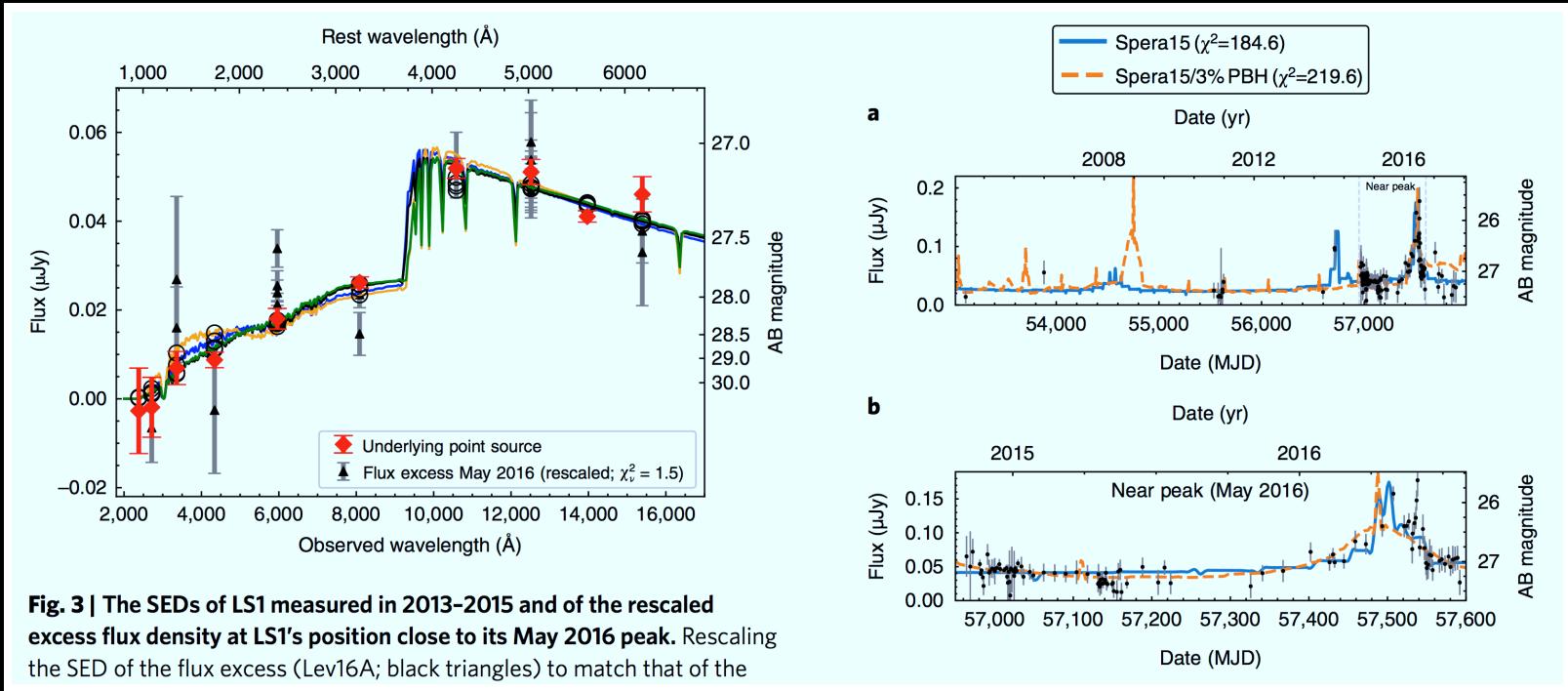
### (3c) HST observations of a B-star caustic transit at $z \approx 1.49$



**Fig. 2 | Proximity of LS1/Lev16A to the MACS J1149 galaxy cluster's critical curve for multiple galaxy-cluster lens models.** Critical curves for models with available high-resolution lens maps including ref. <sup>8</sup> (CATS;

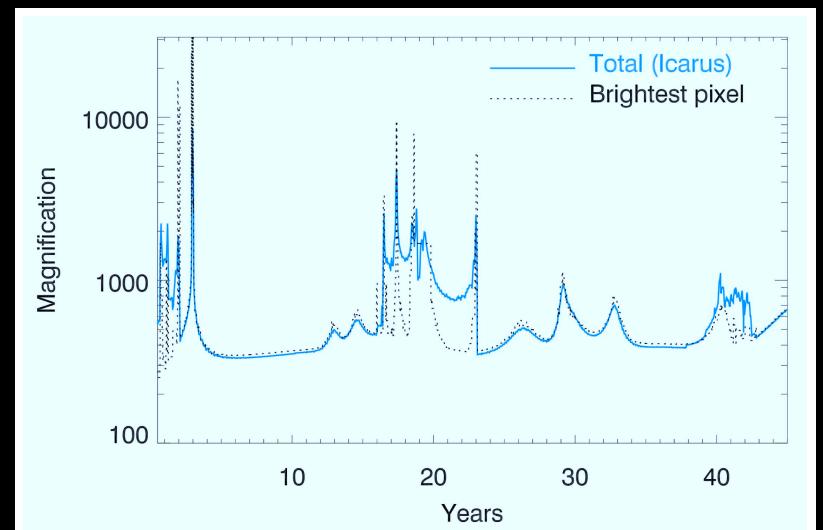
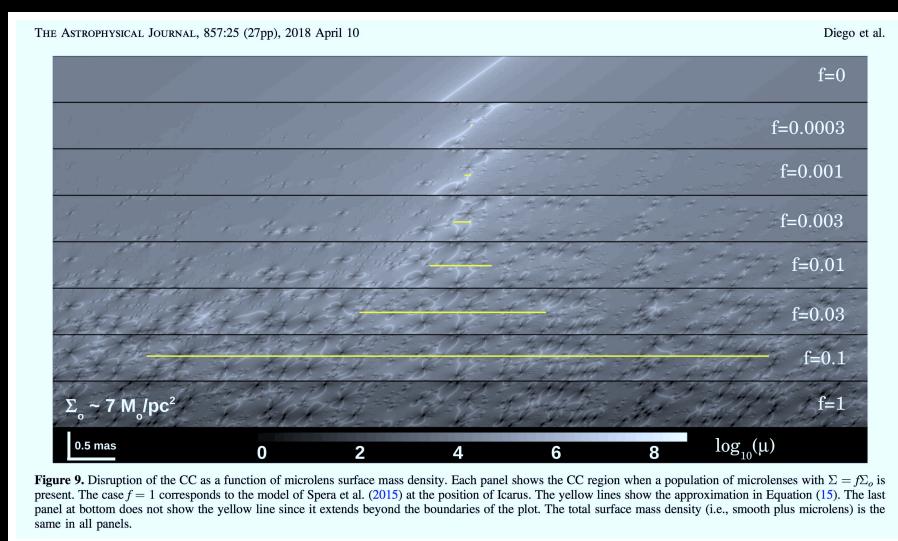


**Fig. 5 | Highly magnified stellar images located near the MACS J1149 galaxy cluster's critical curve.** **a**, LS1 in 2014; we detected LS1 when it temporarily brightened by a factor of  $\sim 4$  in late April 2016, and its position is marked by a blue circle. **b**, The appearance of a new image dubbed Lev16B on 30 October 2016, whose position is marked by a red circle. The solid red line marks the location of the cluster's critical curve from the CATS cluster model<sup>8</sup>, and the dashed red lines show the approximate  $1\sigma$  uncertainty from comparison of multiple cluster lens models<sup>5-10</sup>. Lev16B's position is consistent with the possibility that it is a counterimage of LS1. **c**, The candidate named Lev17A at the location of the green dashed circle had a  $\sim 4\sigma$  significance detection on 3 January 2017. If a microlensing peak, Lev17A must correspond to a different star.

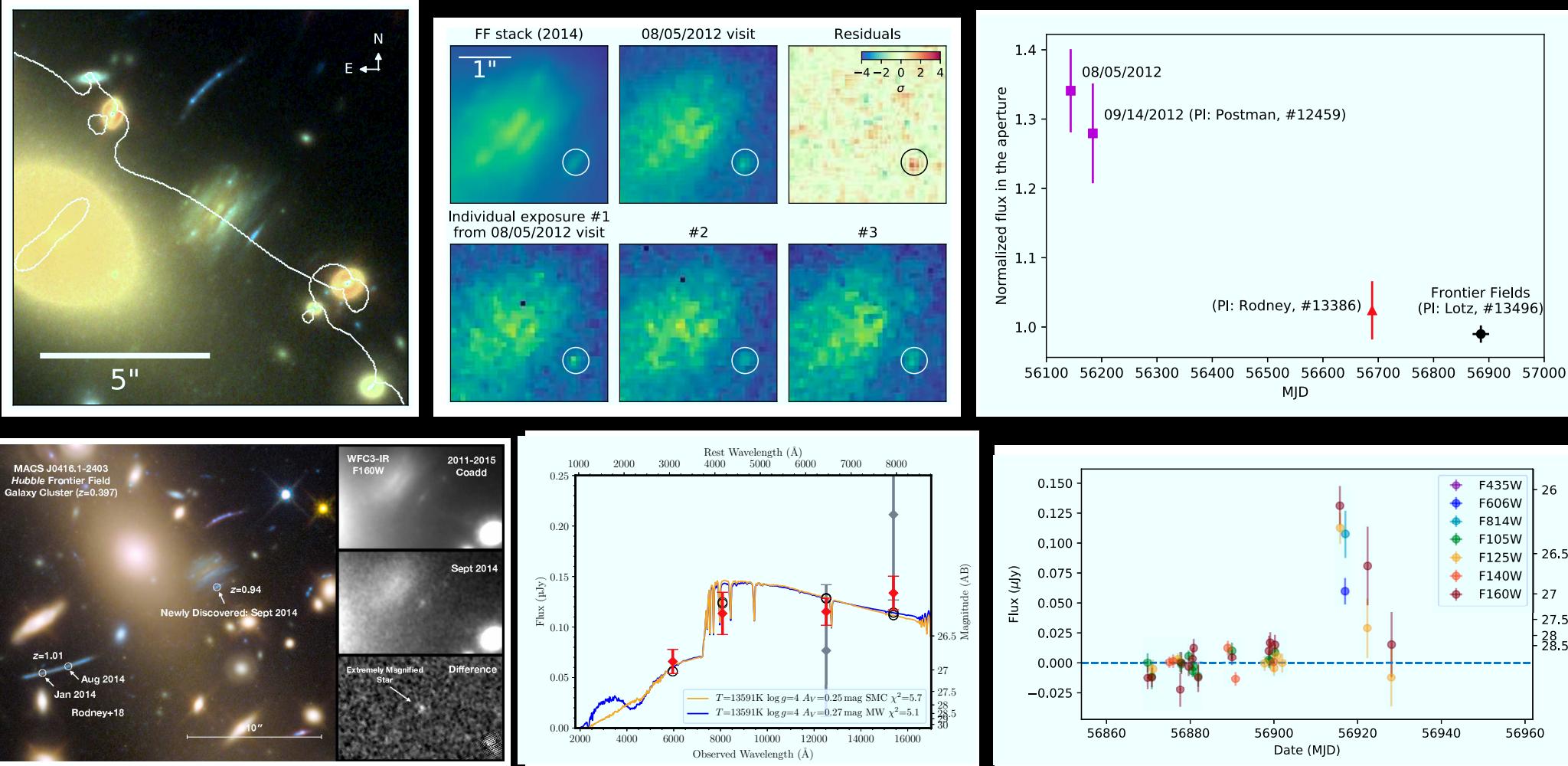


**Fig. 3 |** The SEDs of LS1 measured in 2013–2015 and of the rescaled excess flux density at LS1’s position close to its May 2016 peak. Rescaling the SED of the flux excess (Lev16A; black triangles) to match that of the

Kelley et al. 2018 (Nat. Astr. 2, 334): caustic transit of a B-star at  $z \approx 1.49$ .



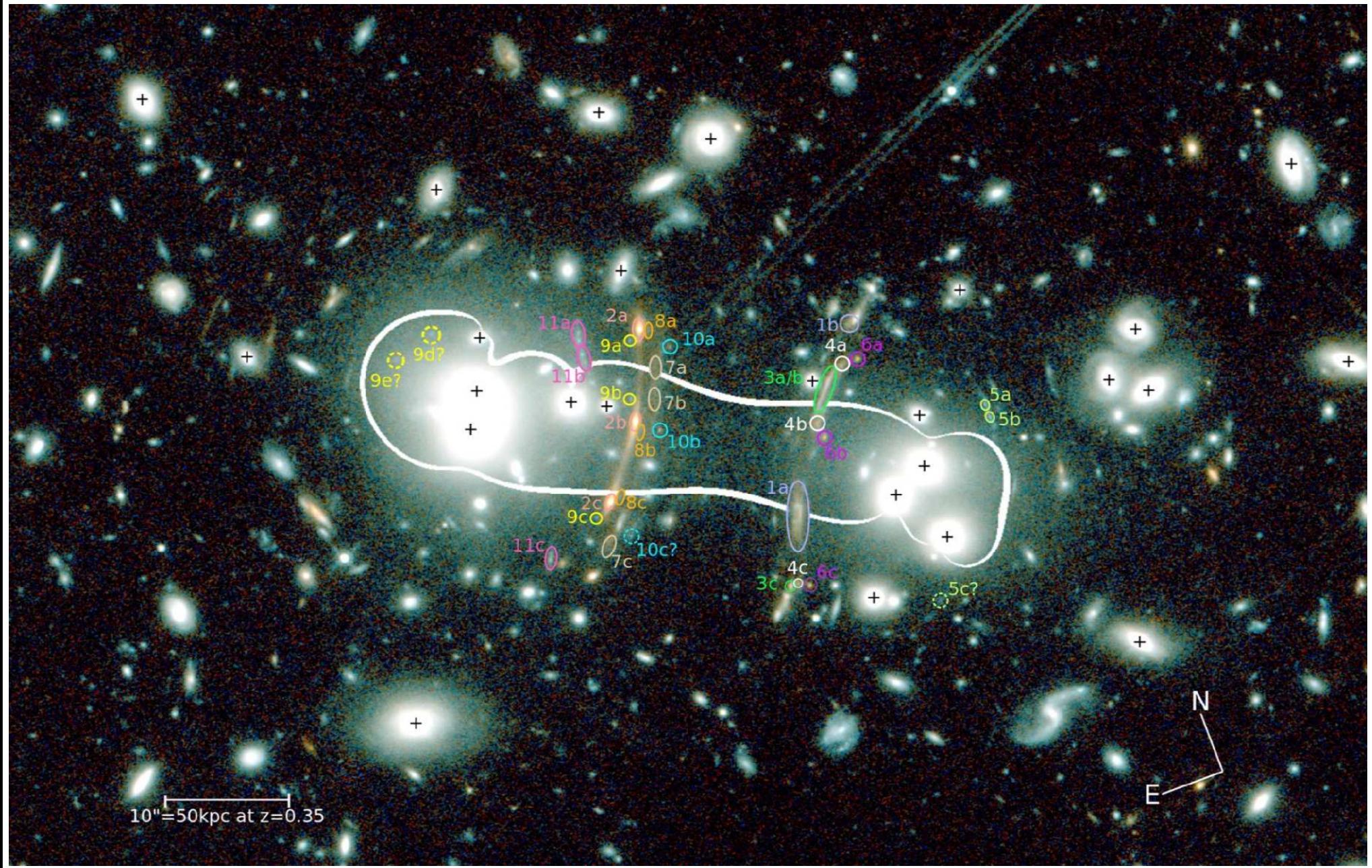
Diego<sup>+</sup> 2018 (ApJ, 857, 25): caustic transits in the presence of microlensing.  
See also Miralda-Escudé (1991), Venumadhav et al. (2017, ApJ, 850, 49).



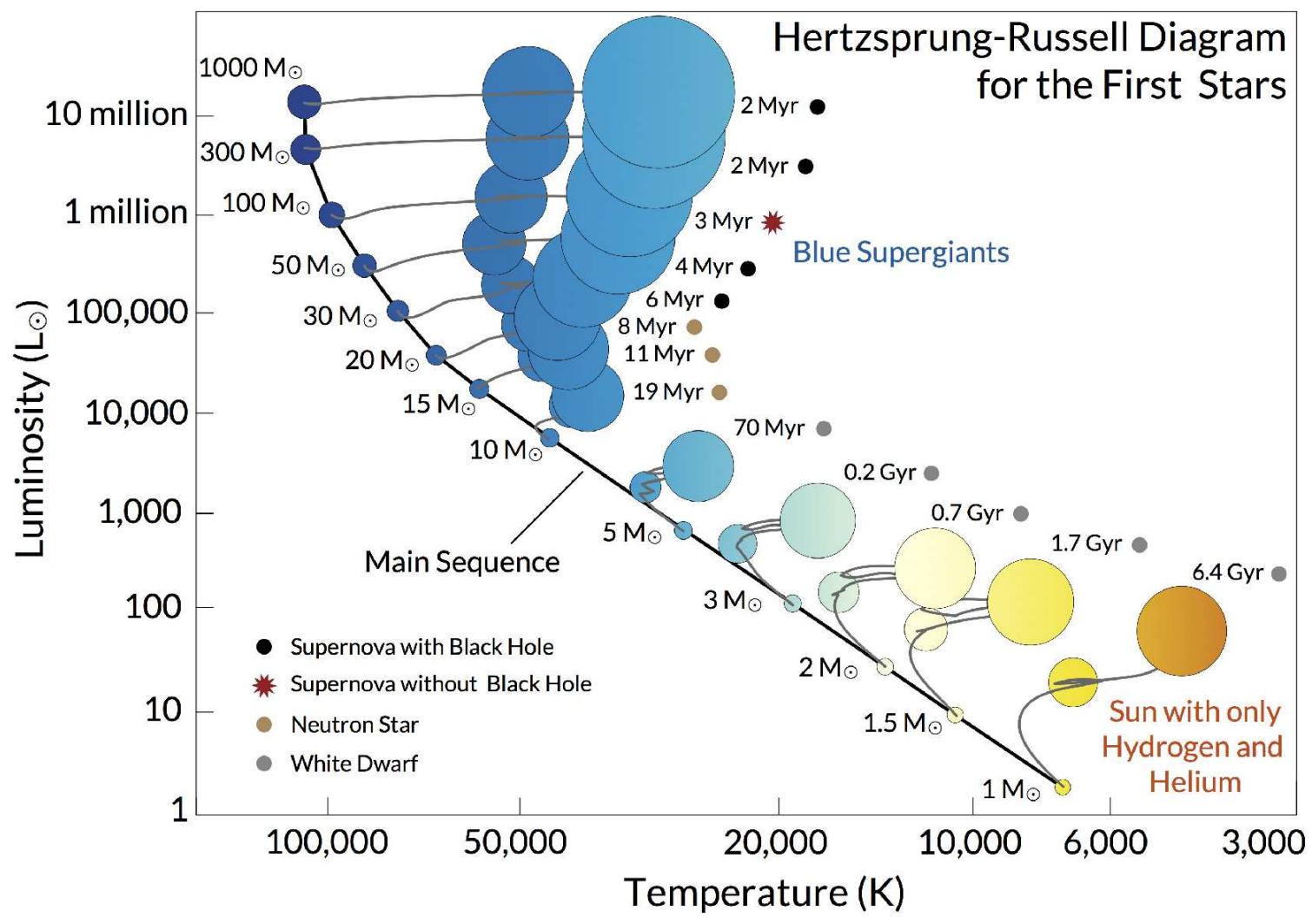
(Top) Caustic Transit at  $z \approx 0.94$  by Kaurov et al. (2019, ApJ, 880, 58)

(Bottom) Caustic Transits at  $z \sim 1$  by Chen et al. (2019, ApJ, 881, 8)

- A  $T \approx 13,500$  K giant at  $z \approx 0.94$  with magnification  $\mu \gtrsim 200-300$ .
- MACS 0416 ICL microlensing complicates analysis (at lower  $z$ 's).



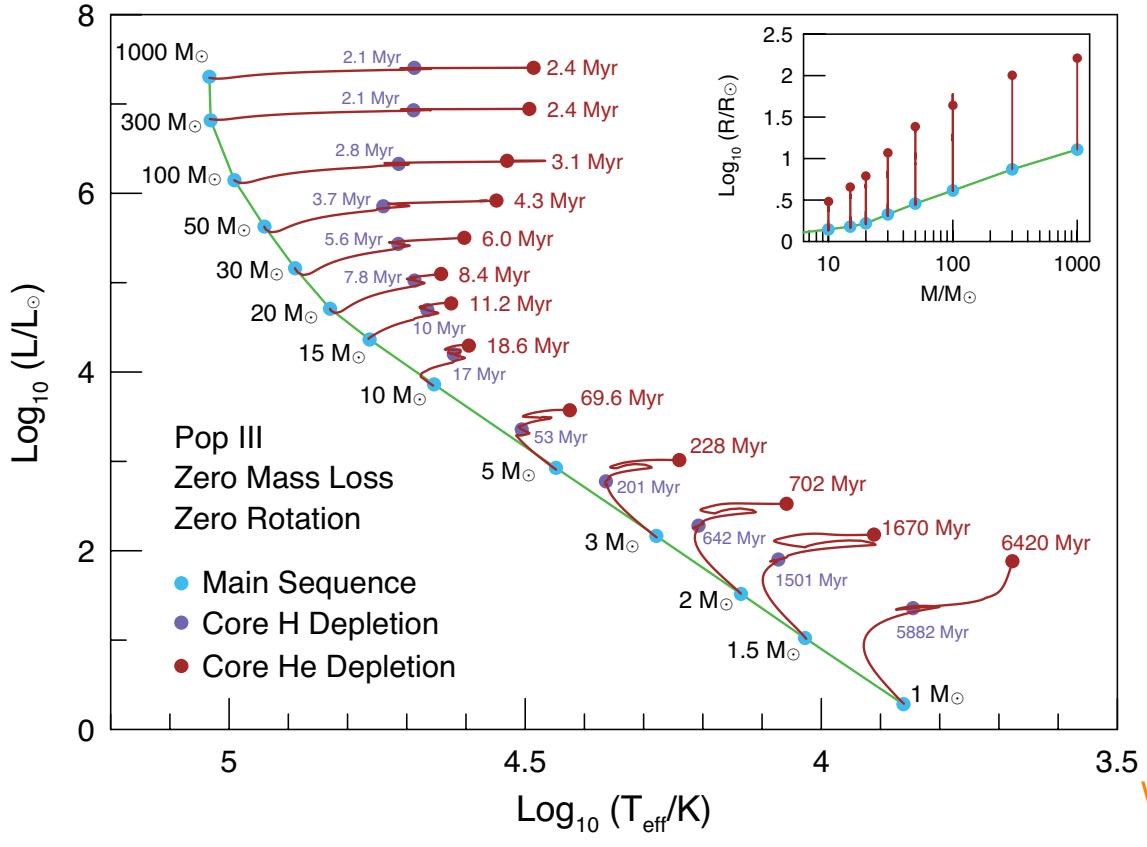
- G165 has two giant lensed arcs at  $z \simeq 2.2$ , and 11 lensed image families.
- Very prominent cluster substructure. Combined with its MMT N ( $z \simeq 0.35$ ), suggests significant transverse velocity needed for caustic transits.



## Pop III star HR-diagram: MESA stellar evolution models for $z=0.0$ $Z_{\odot}$ .

(Windhorst, Timmes, Wyithe et al. 2018, ApJS, 234, 41):  $\mu \gtrsim 10$  mag could make Pop III stars temporarily visible.

- Critical point:  $30\text{--}1000 M_{\odot}$  Pop III stars ( $Z=0.00 Z_{\odot}$ ) live  $\sim 10\times$  shorter than  $2\text{--}5 M_{\odot}$  Pop III stars in their AGB stage.
- Hence,  $2\text{--}5 M_{\odot}$  AGB companion stars can feed the LIGO-mass BHs left over from  $M \gtrsim 30 M_{\odot}$  Pop III stars (assuming binaries in 2nd generation).



Windhorst<sup>+</sup> (2018, ApJS, 234, 41):

- Multicolor accretion-disk models for stellar-mass black holes [RIGHT]: For  $M_{BH} \simeq 5-700 M_{\odot}$ , accretion disk radii and luminosities are similar to those of Pop III AGB stars, when the BH is fed by a Roche lobe-filling lower-mass companion star on the AGB (which live  $\gtrsim 10 \times$  longer!).
- Assumes 2nd generation O-stars have high enough Fe/H ( $\gtrsim 10^{-4} Z_{\odot}$ ) that 2–5  $M_{\odot}$  AGB companion stars exist and feed these LIGO-mass BHs.
- This may make stellar-mass black hole accretion disks at least as likely to be seen via caustic transits as the Pop III stars themselves ( $\mu \gtrsim 10^4$ ).

## Conclusions

Panchromatic X-ray–Radio data accumulating for NEP Time-Domain Field:  
High-z ( $\gtrsim 4$ ) SNe, weak AGN & brown dwarf atmospheric variability.

- We are also getting the best possible (ground-based) data before JWST flies on some of the best lensing clusters.
- $M \gtrsim 30 M_{\odot}$  Pop III ZAMS stars ( $AB \sim 37$ – $42$  mag at  $z \gtrsim 7$ ), with  $\mu \gtrsim 10^4$ – $10^5$  during caustic transits, detectable (for months) to  $AB \lesssim 29$  with JWST.
- Pop III stellar mass black hole ( $M \gtrsim 20 M_{\odot}$ ) accretion disks also be  $\sim 1$  mag brighter *and* live  $\sim 10 \times$  longer than their ZAMS stars.
- JWST could detect *both* Pop III stars and their stellar-mass BH ( $M \gtrsim 20 M_{\odot}$ ) accretion disks at  $AB \lesssim 28$ – $29$  mag via caustic transits for magnifications  $\mu \simeq 10^4$ – $10^5$  (where ICL microlensing doesn't dominate caustics).
- JWST GO community is anticipating this, and planning for it.



Reminder: Your Webb Cycle 2 proposals are fall 2022

You don't want to miss the boat on this ...



Reminder: Your Webb Cycle 2 proposals are due fall 2022

You don't want to miss the boat on this ... Competition will be fierce !

# SPARE CHARTS

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- References and other sources of material shown:

<http://ahah.asu.edu/> [Appreciating Hubble at Hyperspeed]

<http://ahah.asu.edu/download.html> [Download Java–tool]

<http://ahah.asu.edu/clickonHDF/index.html> [Clickable map]

<http://www.jwst.nasa.gov/> & <http://www.stsci.edu/jwst/>

<https://blogs.nasa.gov/webb/>

<http://ircamera.as.arizona.edu/nircam/>

<http://ircamera.as.arizona.edu/MIRI/>

<http://www.stsci.edu/jwst/instruments/nirspec/>

<http://www.stsci.edu/jwst/instruments/fgs>

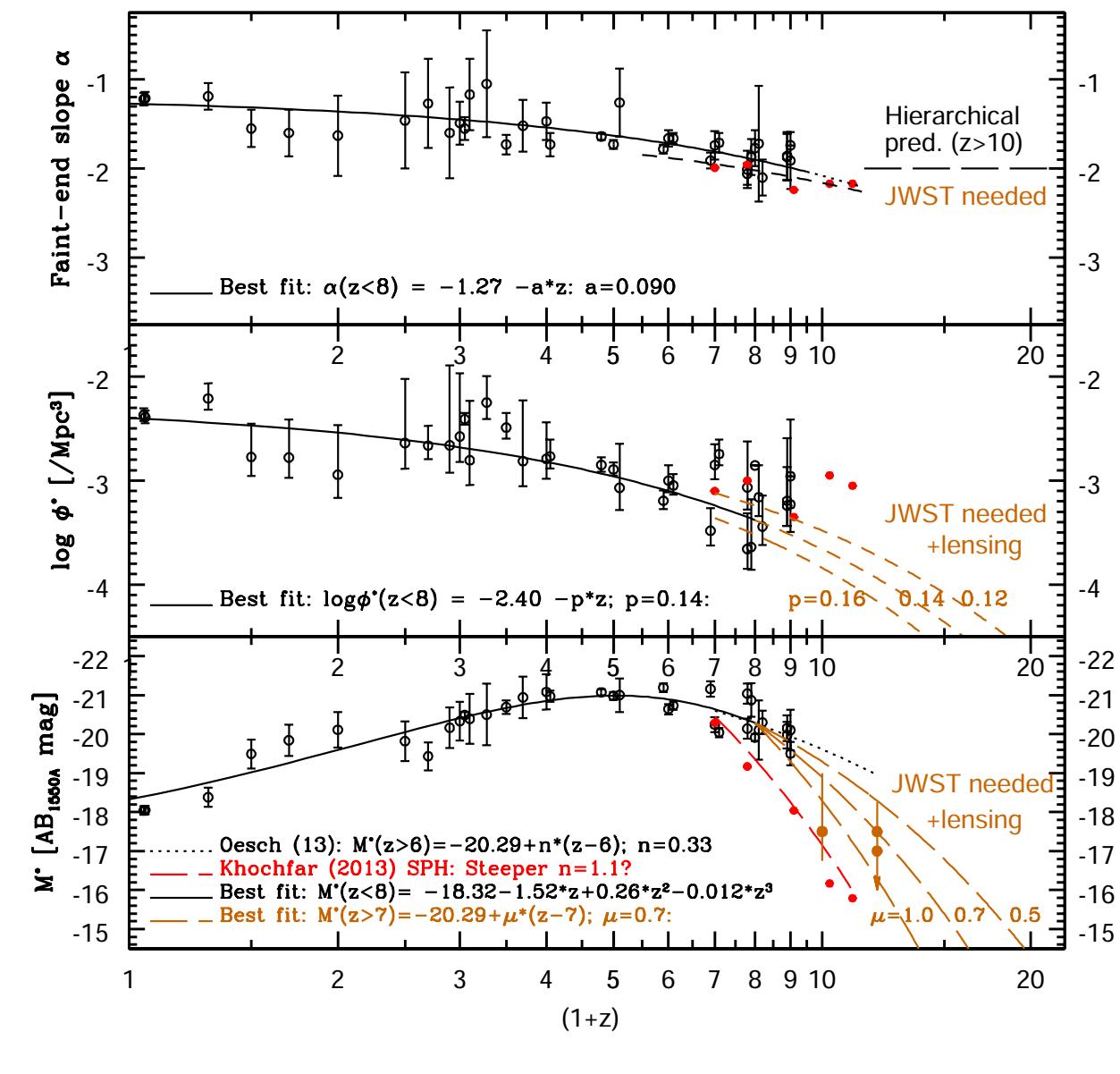
Gardner, J. P., et al. 2006, Space Science Reviews, 123, 485–606

Mather, J., & Stockman, H. 2000, Proc. SPIE Vol. 4013, 2

Windhorst, R., et al. 2008, Advances in Space Research, 41, 1965

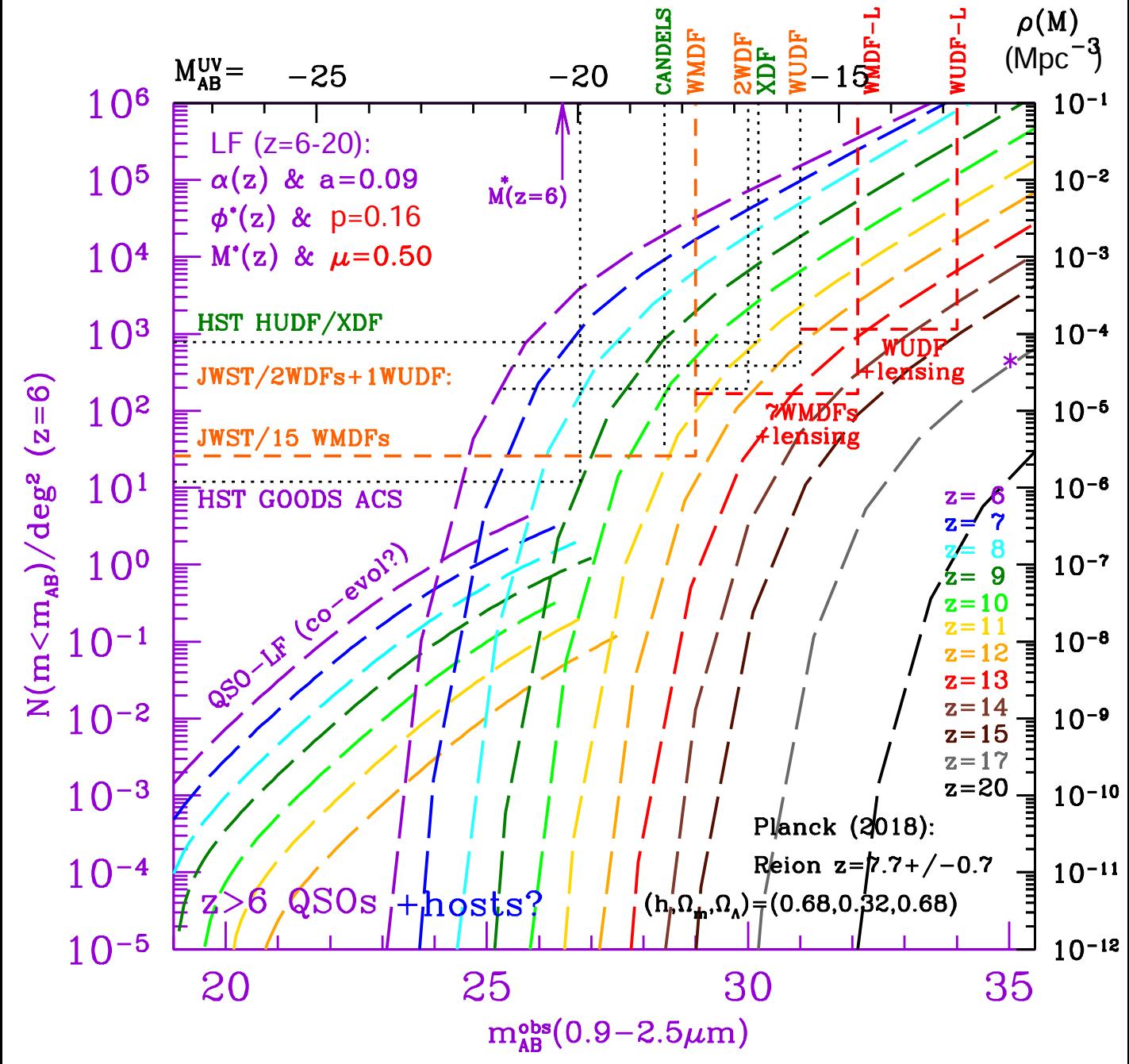
Windhorst, R., et al., 2011, ApJS, 193, 27 (astro-ph/1005.2776).

Windhorst, R., et al., 2018, ApJS, 234, 41 (astro-ph/1801.03584).

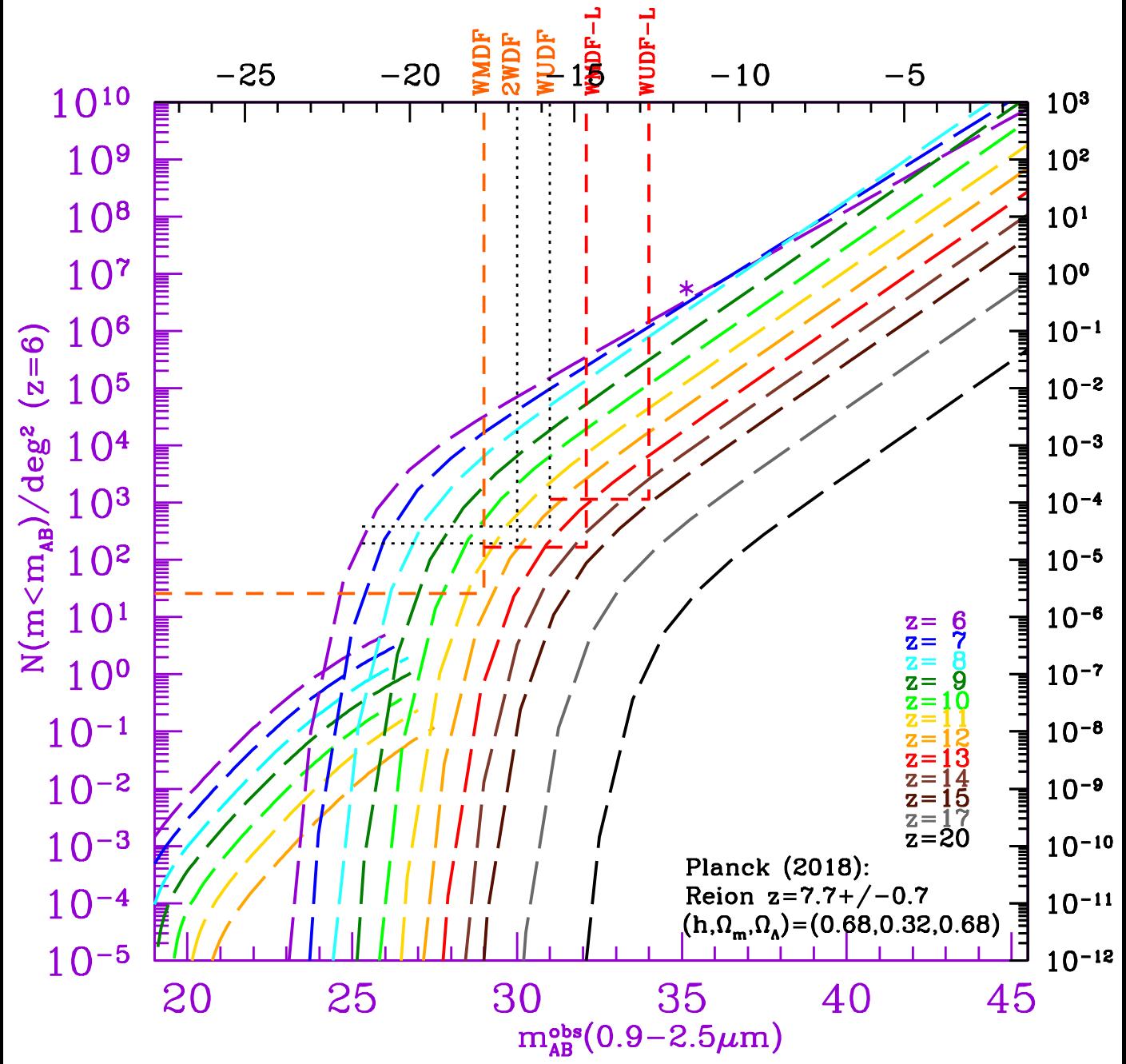


Evolution of Schechter UV-LF: faint-end LF-slope  $\alpha(z)$ ,  $\Phi^*(z)$  &  $M^*(z)$ :

- For JWST  $z \gtrsim 8$ , expect  $\alpha \lesssim -2.0$ ;  $\Phi^* \lesssim 10^{-3}$  ( $\text{Mpc}^{-3.5}$ ) (Oesch+ 11).
  - HUDF: Characteristic  $M^*$  may drop below  $-18$  or  $-17.5$  mag at  $z \gtrsim 10$ .
- ⇒ Has significant consequences for JWST survey strategy.



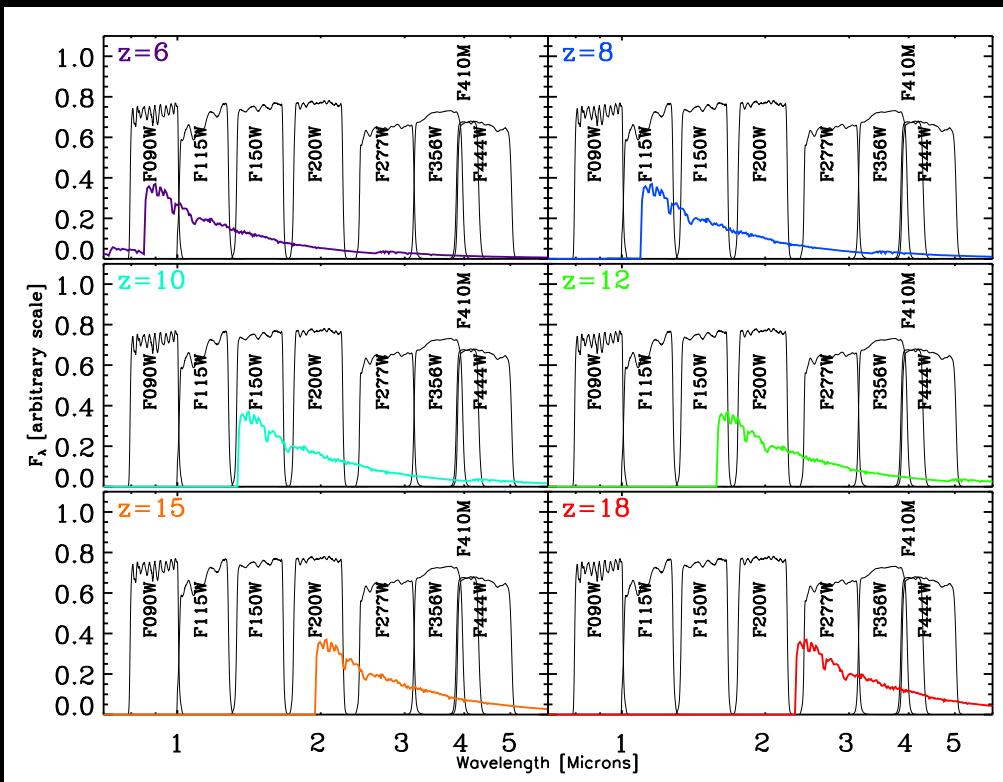
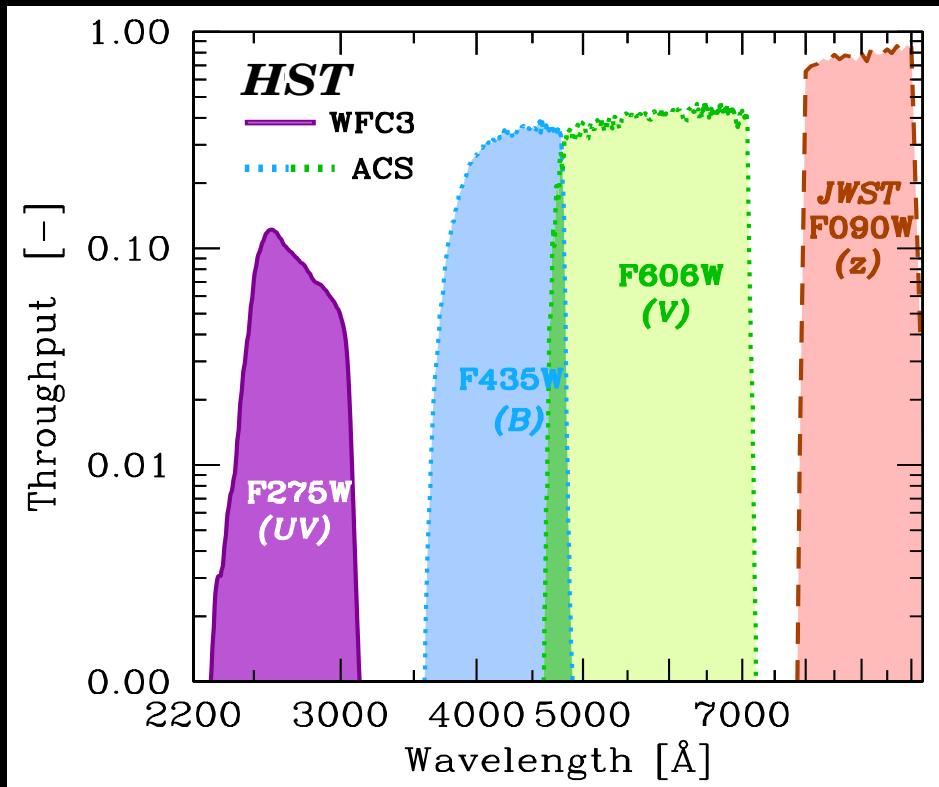
Schechter LF ( $6 \lesssim z \lesssim 20$ ) with best-fit  $\alpha(z)$ ,  $\Phi^*(z)$ ,  $M^*(z)$  &  $\mu=0.50$ .  
 Area/Sensitivity for:  $HUDF/XDF$ , 15  $WMDFs$ , 2  $WDFs$ , & 1  $WUDF$ .  
 • Need lensing targets for  $WMDF-WUDF$  to see  $z \simeq 14-15$  objects.



Schechter LF ( $6 \lesssim z \lesssim 20$ ) with best-fit  $\alpha(z)$ ,  $\Phi^*(z)$ ,  $M^*(z)$  &  $\mu=0.50$ .

Area/Sensitivity for: 15 WMDFs, 2 WDFs, & 1 WUDF.

- At  $M_{AB} \gtrsim -12$  mag, LF dominated by individual Pop III stars ( $\alpha \simeq 2.0$ ?).

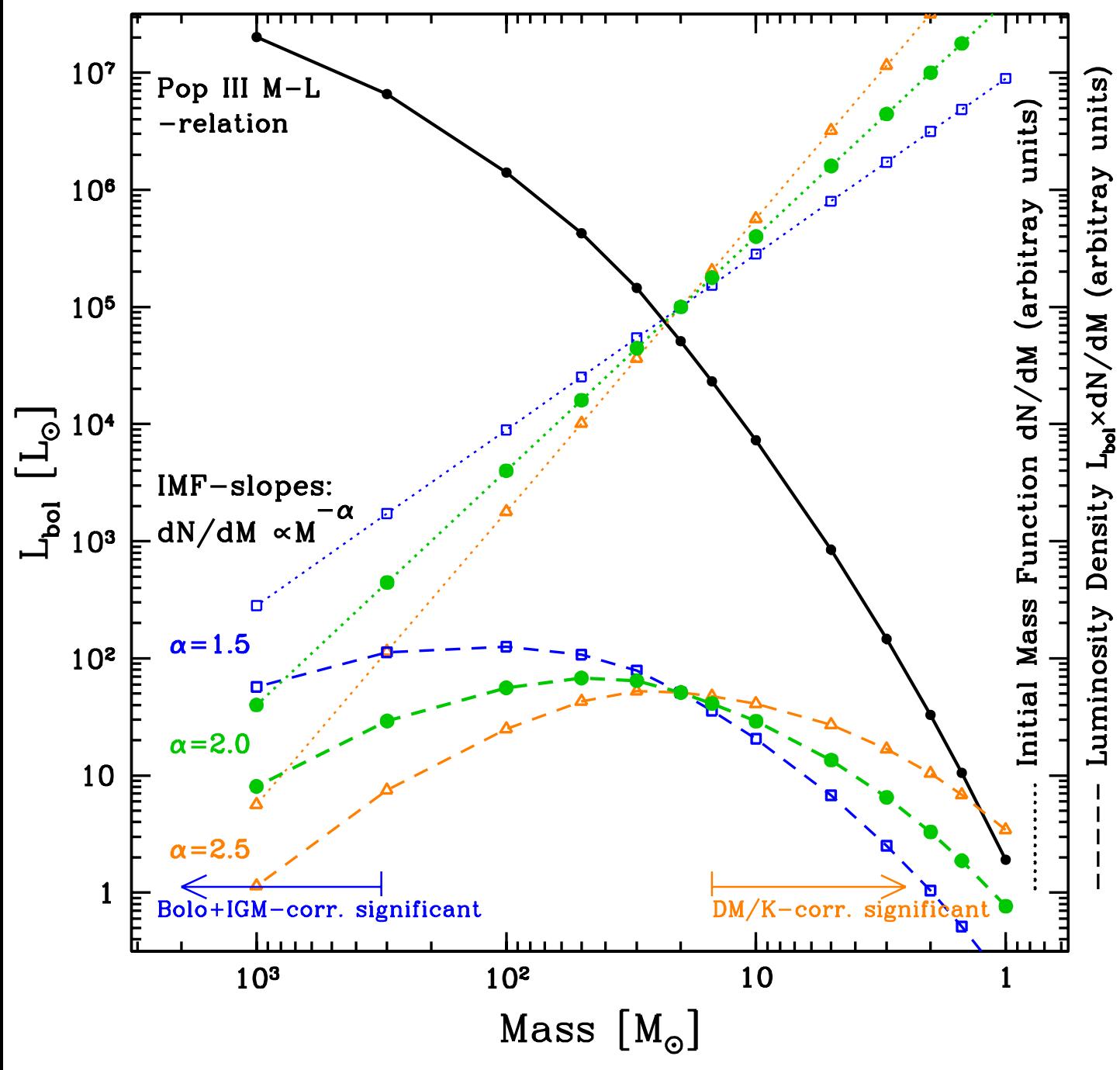


[LEFT] HST UV-vis filters complement the JWST NEP community field:

- HST adds  $\lambda$ 's inaccessible to JWST, or where HST has better PSF.

[RIGHT] Standard 8-band  $0.8\text{--}5 \mu\text{m}$  filter set for JWST NIRCam.

- These are what GTO's will use as standard NIRCam filters.



Mass–Luminosity relation for zero metallicity Pop III MESA models:  
 For range of IMF slopes, most Pop III star sky-SB comes from  $20\text{--}300 M_\odot$ .

**Table 1.** Adopted Pop III Star Physical Parameters from MESA models<sup>a</sup>

Mass ( $M_{\odot}$ )	Age (Myr)	$T_{eff}$	$\log R$	$\log L_{bol}$	$T_{eff}$	$\log R$	$\log L_{bol}$	Age Myr	$T_{eff}$	$\log R$	$\log L_{bol}$	Age Myr	Time <sup>b</sup> (Myr)
		Pre-MS	— at ZAMS —			— at Hydrogen-depletion —			— at Helium-depletion —				AGB-MS
(K)	( $R_{\odot}$ )	( $L_{\odot}$ )	(K)	( $R_{\odot}$ )	( $L_{\odot}$ )	Myr	(K)	( $R_{\odot}$ )	( $L_{\odot}$ )	Myr	(Myr)	(Myr)	
1.0	9.28	7.266e3	-0.0581	0.2825	6.999e3	0.5119	1.3576	5882	— <sup>c</sup>	—	—	6420	538
1.5	6.11	1.065e4	-0.0203	1.0227	1.181e4	0.3292	1.9015	1501	8.149e3	0.7913	2.1804	1670	169
2.0	3.02	1.367e4	0.0108	1.5177	1.611e4	0.2498	2.2815	642	1.145e4	0.6685	2.5249	702	60
3.0	1.38	1.899e4	0.0487	2.1654	2.311e4	0.1843	2.7770	201	1.736e4	0.5510	3.0138	228	27
5.0	0.56	2.805e4	0.0911	2.9274	3.206e4	0.1903	3.3581	53	2.658e4	0.4608	3.5732	70	17
10	0.23	4.508e4	0.1462	3.8618	4.174e4	0.3807	4.1972	17	3.938e4	0.4811	4.2968	19	1.6
15	0.13	5.789e4	0.1803	4.3647	4.624e4	0.5401	4.6937	10	4.215e4	0.6581	4.7691	11	0.8
20	0.09	6.754e4	0.2183	4.7082	4.864e4	0.6612	5.0240	7.8	4.386e4	0.7879	5.0975	8.4	0.6
30	0.05	7.737e4	0.3270	5.1619	5.180e4	0.8120	5.4347	5.6	4.006e4	1.0688	5.5016	6.0	0.5
50	0.03	8.713e4	0.4570	5.6283	5.490e4	0.9722	5.8562	3.7	3.536e4	1.3862	5.9200	4.3	0.5
100	0.02	9.796e4	0.6147	6.1470	5.173e4	1.2610	6.3303	2.8	3.392e4	1.6437	6.3627	3.1	0.3
300	0.02	1.074e5	0.8697	6.8172	4.882e4	1.6111	6.9301	2.1	3.165e4	2.0041	6.9631	2.4	0.3
1000	0.02	1.080e5	1.1090	7.3047	4.807e4	1.8740	7.4288	2.1	3.122e4	2.2119	7.3549	2.4	0.3

Windhorst, Timmes, Wyithe et al. (2018, ApJS, 234, 41):

- 30–1000  $M_{\odot}$  Pop III stars ( $Z=0.00 Z_{\odot}$ ) live  $\sim 10 \times$  shorter than 2–5  $M_{\odot}$  Pop III stars in their AGB stage.
- Hence, 2–5  $M_{\odot}$  AGB companion stars can feed the LIGO-mass BHs left over from  $M \gtrsim 30 M_{\odot}$  Pop III stars (assuming binaries in 2nd generation).

**Table 2.** Implied ZAMS Pop III Star Observational Parameters Relevant to Caustic Transit Calculations

Mass <sup>a</sup>	$T_{\text{eff}}^b$	Radius <sup>c</sup>	$L_{\text{bol}}^d$	$M_{\text{bol}}^e$	Bolo+IGM+K-corr <sup>f</sup>			ZAMS m <sub>UV</sub> <sup>g</sup>			$t_{\text{rise}}^h$	transit <sup>i</sup>
ZAMS ( $M_{\odot}$ )	— at ZAMS —	—	—	—	z=7	z=12	z=17	z=7	z=12	z=17	caust	rate
	(K)	( $R_{\odot}$ )	( $L_{\odot}$ )	(AB)	(AB-mag)			(AB-mag)			(hr)	(/cl/yr)
1.0	7.266e3	0.87	1.92	+4.03	+4.44	+3.13	+2.61	57.71	57.74	58.07	0.17	$8 \times 10^5$
1.5	1.065e4	0.95	10.5	+2.18	+1.45	+0.42	-0.06	52.87	53.18	53.55	0.18	$1.1 \times 10^4$
2.0	1.367e4	1.03	32.9	+0.95	+0.30	-0.59	-1.06	50.49	50.93	51.31	0.20	$1.5 \times 10^3$
3.0	1.899e4	1.12	146.	-0.67	-0.51	-1.26	-1.72	48.06	48.64	49.03	0.22	182.
5.0	2.805e4	1.23	846.	-2.58	-0.70	-1.35	-1.80	45.96	46.65	47.04	0.24	29.1
10	4.508e4	1.40	7.28e3	-4.91	-0.22	-0.79	-1.23	44.10	44.88	45.27	0.27	5.70
15	5.789e4	1.51	2.32e4	-6.17	+0.23	-0.30	-0.75	43.30	44.10	44.50	0.29	2.78
20	6.754e4	1.65	5.11e4	-7.03	+0.56	+0.04	-0.40	42.77	43.59	43.99	0.32	1.74
30	7.737e4	2.12	1.45e5	-8.16	+0.88	+0.36	-0.08	41.95	42.78	43.17	0.41?	0.82?
50	8.713e4	2.86	4.25e5	-9.33	+1.17	+0.66	+0.22	41.08	41.91	42.31	0.55*	0.37*
100	9.796e4	4.12	1.40e6	-10.63	+1.47	+0.96	+0.52	40.08	40.91	41.31	0.80*	0.15*
300	1.074e5	7.41	6.56e6	-12.30	+1.71	+1.21	+0.77	38.64	39.48	39.88	1.43*	0.039*
1000	1.080e5	12.9	2.02e7	-13.52	+1.72	+1.22	+0.78	37.44	38.28	38.68	2.48*	0.013*

- If  $M \gtrsim 30 M_{\odot}$  Pop III ZAMS stars have  $\mu \gtrsim 10^4 - 10^5$  during caustic transits, they could be detectable for months to AB  $\lesssim 29$  mag with JWST.
- Expect  $\lesssim 1$  caustic transit/yr at  $z \gtrsim 7$  when JWST monitors  $\gtrsim 3$  clusters.

**Table 3.** Implied Red Giant Branch Pop III Star Observational Parameters Relevant to Caustic Transit Calculations

Mass <sup>a</sup> GB ( $M_{\odot}$ )	$T_{\text{eff}}^b$ — at Hydrogen-depletion (K)	Radius <sup>c</sup> ( $R_{\odot}$ )	$L_{\text{bol}}^d$ ( $L_{\odot}$ )	$M_{\text{bol}}^e$ (AB)	Bolo+IGM+K-corr <sup>f</sup> z=7 z=12 z=17 (AB-mag)			Giant Branch muv <sup>g</sup> z=7 z=12 z=17 (AB-mag)			$t_{\text{rise}}^h$ caust (hr)	transit <sup>i</sup> rate (/cl/yr)
1.0	6.999e3	3.25	22.8	+1.35	+4.83	+3.48	+2.96	55.42	55.41	55.73	0.63	$9 \times 10^4$
1.5	1.181e4	2.13	79.7	-0.01	+0.91	-0.06	-0.53	50.13	50.51	50.88	0.41	$1.0 \times 10^3$
2.0	1.611e4	1.78	191.	-0.96	-0.19	-1.01	-1.47	48.08	48.60	48.99	0.34	175.
3.0	2.311e4	1.53	598.	-2.20	-0.69	-1.39	-1.84	46.35	46.99	47.38	0.30	39.8
5.0	3.206e4	1.55	2.28e3	-3.66	-0.63	-1.25	-1.70	44.95	45.67	46.07	0.30	11.8
10	4.174e4	2.40	1.57e4	-5.75	-0.34	-0.92	-1.36	43.15	43.91	44.31	0.46	2.33
15	4.624e4	3.47	4.94e4	-6.99	-0.18	-0.74	-1.19	42.06	42.84	43.24	0.67?	0.87?
20	4.864e4	4.58	1.06e5	-7.82	-0.10	-0.65	-1.09	41.32	42.11	42.51	0.88*	0.44*
30	5.180e4	6.49	2.72e5	-8.85	+0.02	-0.53	-0.97	40.41	41.20	41.60	1.25*	0.19*
50	5.490e4	9.38	7.18e5	-9.90	+0.13	-0.42	-0.86	39.47	40.26	40.66	1.81*	0.081*
100	5.173e4	18.2	2.14e6	-11.09	+0.02	-0.53	-0.98	38.17	38.96	39.36	3.52*	0.024*
300	4.882e4	40.8	8.51e6	-12.59	-0.09	-0.65	-1.09	36.57	37.35	37.75	7.88*	0.006*
1000	4.807e4	74.8	2.68e7	-13.83	-0.12	-0.67	-1.12	35.29	36.07	36.47	14.44*	0.002*

- If  $M \gtrsim 20 M_{\odot}$  Pop III RGB stars have  $\mu \gtrsim 10^4$ – $10^5$  during caustic transits, they could be detectable for a few months to AB $\lesssim 29$  mag with JWST.
- Note the combined Bolometric+IGM+K-corrections are more advantageous for Pop III RGB stars.

**Table 4.** Implied AGB Pop III Star Observational Parameters Relevant to Caustic Transit Calculations

Mass <sup>a</sup>	$T_{\text{eff}}^b$	Radius <sup>c</sup>	$L_{\text{bol}}^d$	$M_{\text{bol}}^e$	Bolo+IGM+K-corr <sup>f</sup>	AGB m <sub>UV</sub> <sup>g</sup>			$t_{\text{rise}}^h$	transit <sup>i</sup>		
AGB	— at Helium-depletion —				z=7	z=12	z=17	z=7	z=12	z=17	caust	rate
( $M_{\odot}$ )	(K)	( $R_{\odot}$ )	( $L_{\odot}$ )	(AB)	(AB-mag)			(AB-mag)			(hr)	(/cl/yr)
1.0	6.312e3 <sup>j</sup>	5.23 <sup>j</sup>	39.8 <sup>j</sup>	+0.74	+6.01	+4.57	+4.03	55.99	55.89	56.19	1.01	$1.4 \times 10^5$
1.5	8.149e3	6.18	151.	-0.71	+3.36	+2.14	+1.64	51.89	52.01	52.35	1.19	$4.0 \times 10^3$
2.0	1.145e4	4.66	335.	-1.57	+1.06	+0.07	-0.40	48.73	49.08	49.45	0.90	273.
3.0	1.736e4	3.56	1.03e3	-2.79	-0.36	-1.15	-1.60	46.09	46.64	47.03	0.69	28.9
5.0	2.658e4	2.89	3.74e3	-4.19	-0.72	-1.38	-1.82	44.33	45.01	45.41	0.56	6.43
10	3.938e4	3.03	1.98e4	-6.00	-0.42	-1.00	-1.45	42.82	43.57	43.97	0.58	1.71
15	4.215e4	4.55	5.88e4	-7.18	-0.33	-0.90	-1.34	41.73	42.50	42.89	0.88?	0.64?
20	4.386e4	6.14	1.25e5	-8.00	-0.27	-0.84	-1.28	40.97	41.74	42.14	1.19*	0.32*
30	4.006e4	11.7	3.17e5	-9.01	-0.40	-0.98	-1.42	39.83	40.59	40.98	2.26*	0.11*
50	3.536e4	24.3	8.32e5	-10.06	-0.55	-1.15	-1.59	38.63	39.37	39.77	4.70*	0.036*
100	3.392e4	44.0	2.31e6	-11.17	-0.59	-1.19	-1.64	37.49	38.22	38.61	8.50*	0.012*
300	3.165e4	101.	9.19e6	-12.67	-0.64	-1.26	-1.71	35.93	36.65	37.04	19.49*	0.003*
1000	3.122e4	163.	2.26e7	-13.65	-0.65	-1.28	-1.72	34.94	35.66	36.05	31.45*	0.001*

- If  $M \gtrsim 20 M_{\odot}$  Pop III AGB stars have  $\mu \gtrsim 10^4 - 10^5$  during caustic transits, they could be detectable for a few months to AB  $\lesssim 29$  mag with JWST.
- Note the combined Bolometric+IGM+K-corrections are far more advantageous for Pop III AGB stars (especially at  $z \gtrsim 12$ )!

**Table 5.** Pop III Stellar Mass Black Hole Accretion Disk Parameters Adopted for Caustic Transit Calculations

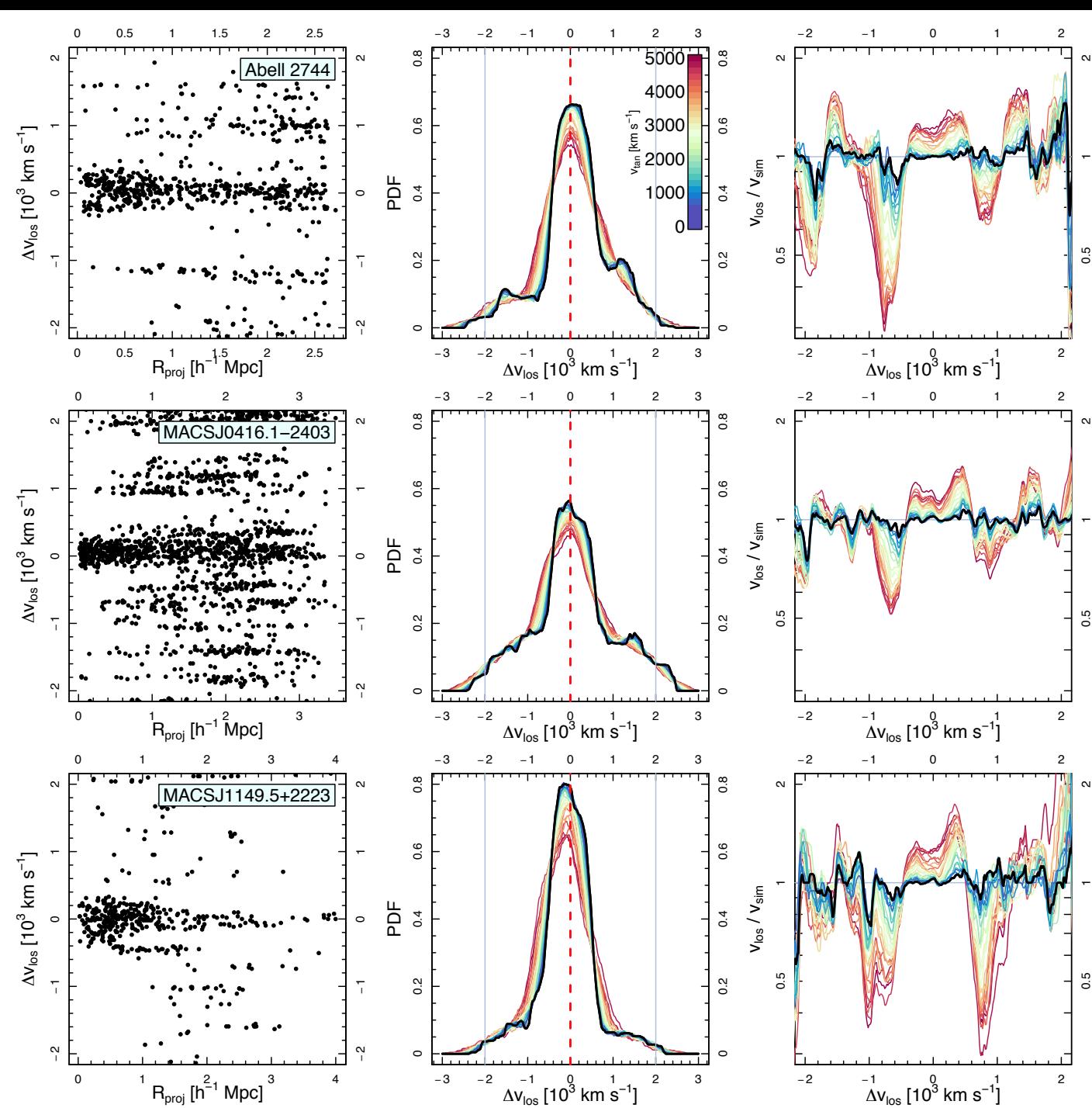
Mass <sup>a</sup>	M <sub>compact</sub> <sup>b</sup>	R <sub>s</sub> <sup>c</sup>	Radius <sup>d</sup>	L <sub>bol</sub> <sup>e</sup>	M <sub>bol</sub> <sup>f</sup>	bolo+IGM+K-corr <sup>g</sup>	m <sub>AB</sub> -limits at <sup>h</sup>	t <sub>rise</sub> <sup>i</sup>	Transit <sup>j</sup>
ZAMS		BH	— of the UV accretion disk —	z=7	z=12	z=17	z=7	z=12	(z=12)
(M <sub>⊙</sub> )	(M <sub>⊙</sub> )	(km)	(R <sub>⊙</sub> )	(L <sub>⊙</sub> )	AB-mag	(AB-mag)	(AB-mag)	(hr)	(/cl/yr)
BH accretion-disk bolometric luminosities and UV half-light radii scaling from microlensed quasars (Blackburne et al. 2011)									
30	~5.0 BH	15	1.4	≤4.2×10 <sup>4</sup>	≥−6.8	−0.6	−1.4	−1.7	0.27?
50	~24 BH	72	3.0	≤2.0×10 <sup>5</sup>	≥−8.5	−0.4	−1.2	−1.5	0.58*
100	~65 BH	195	4.9	≤5.4×10 <sup>5</sup>	≥−9.6	−0.2	−0.9	−1.3	0.95*
300	~230 BH	690	9.2	≤1.9×10 <sup>6</sup>	≥−11.0	−0.2	−1.0	−1.3	1.8*
1000	~720 BH	2160	16.3	≤6.0×10 <sup>6</sup>	≥−12.2	−0.2	−0.9	−1.3	3.2*
BH accretion-disk bolometric luminosities and UV half-light radii estimated from multi-color thin-disk model									
30	~5.0 BH	15	1.9	≤3.1×10 <sup>4</sup>	≥−6.5	−0.6	−1.4	−1.7	0.37?
50	~24 BH	72	4.5	≤1.8×10 <sup>5</sup>	≥−8.4	−0.4	−1.2	−1.5	0.87*
100	~65 BH	195	7.8	≤5.9×10 <sup>5</sup>	≥−9.7	−0.2	−0.9	−1.3	1.51*
300	~230 BH	690	15.8	≤2.0×10 <sup>6</sup>	≥−11.0	−0.2	−1.0	−1.3	3.1*
1000	~720 BH	2160	29.8	≤6.6×10 <sup>6</sup>	≥−12.3	−0.2	−0.9	−1.3	5.8*

- If M ≥ 20 M<sub>⊙</sub> Pop III stellar mass black hole accretion disks have μ ≥ 10<sup>4</sup>–10<sup>5</sup> during caustic transits, they could be detectable for a few months to AB ≤ 29 mag with JWST. Rise times ~hours–1 day; Decay times ≤ 0.4 yr.
- Note the combined Bolometric+IGM+K-corrections are also more advantageous for Pop III stellar-mass black hole accretion disks.

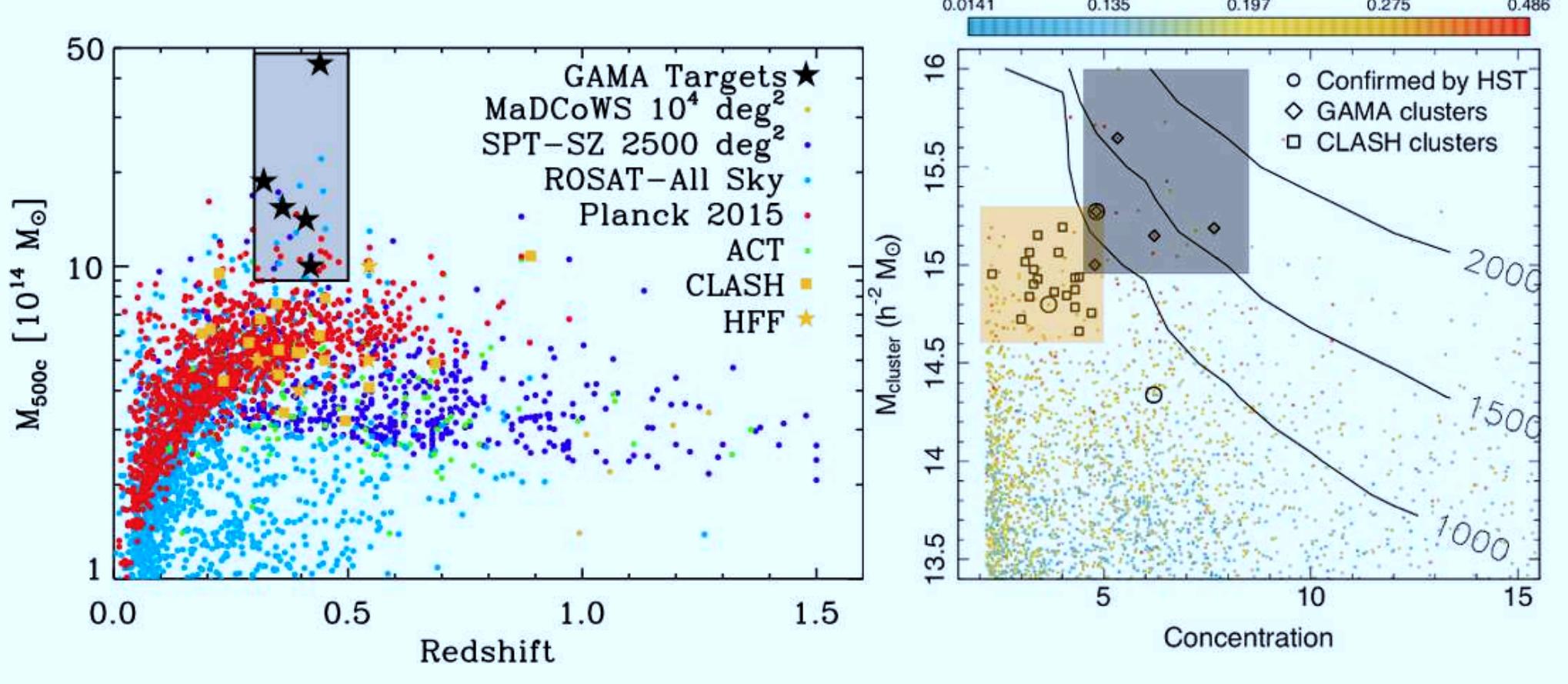
Multi-λ model: T ∝ r<sup>−3/4</sup>; T<sub>max</sub> ≈ 10(M<sub>BH</sub>/100)<sup>−3/8</sup> keV; r<sub>hl</sub> ∝ M<sub>BH</sub><sup>1/2</sup>.

Trumpet diagrams for JWST lensing clusters from ground-based spectroscopic  $N(z)$  (Windhorst<sup>+</sup> 2018):

- 1) Add random space velocity  $v_{sp}$  to clusters.
- 2) Projected  $v_T$  must be  $\lesssim 1000 \text{ km/s}$  for  $v_{sp}$  not to unduly disturb radial  $N(z)$ .
- 3) Best clusters (Bullet) for caustic transits can have  $v_T \lesssim 2700 \text{ km s}^{-1}$ .



- JWST should monitor such clusters during its lifetime for caustic transits.



What are the best lensing clusters for JWST to see First Light objects?:

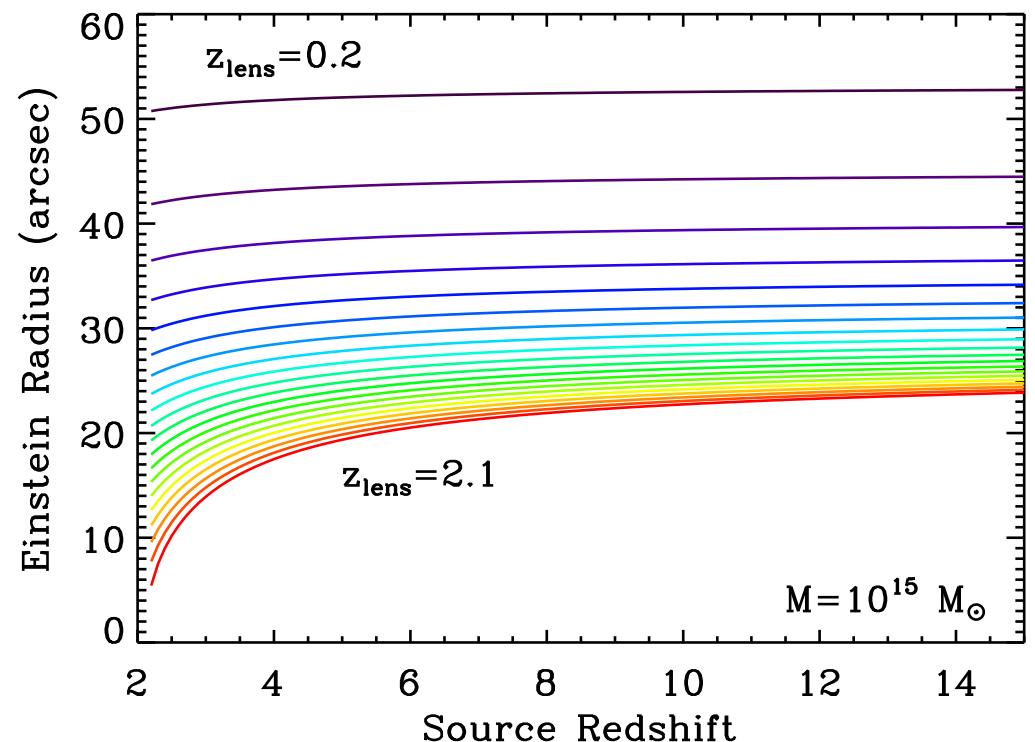
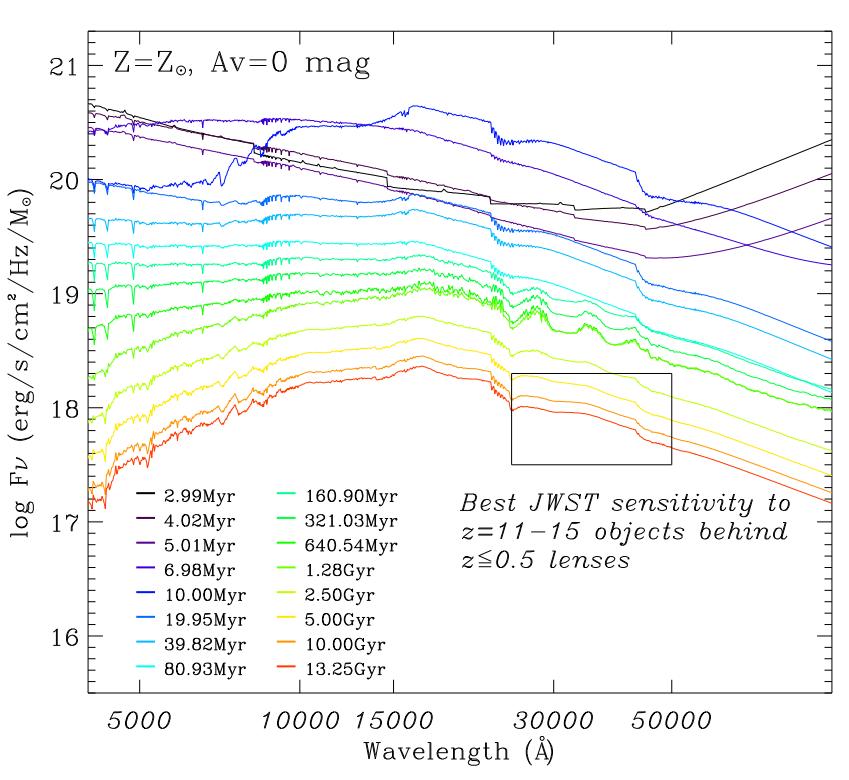
[LEFT] Best lensing clusters vs. ROSAT, Planck, SPT, MaDCoWS.

[RIGHT] Best lensing clusters compared to CLASH clusters.

(Contours: Number of lensed JWST sources at  $z \approx 1-15$  to  $AB \lesssim 31$  mag).

- Resulting sweet spot for JWST lensing of First Light Objects ( $z \gtrsim 10$ ):

Redshift:  $0.3 \lesssim z \lesssim 0.5$ ; Mass:  $10^{15-15.6} M_\odot$ ; Concentration:  $4.5 \lesssim C \lesssim 8.5$



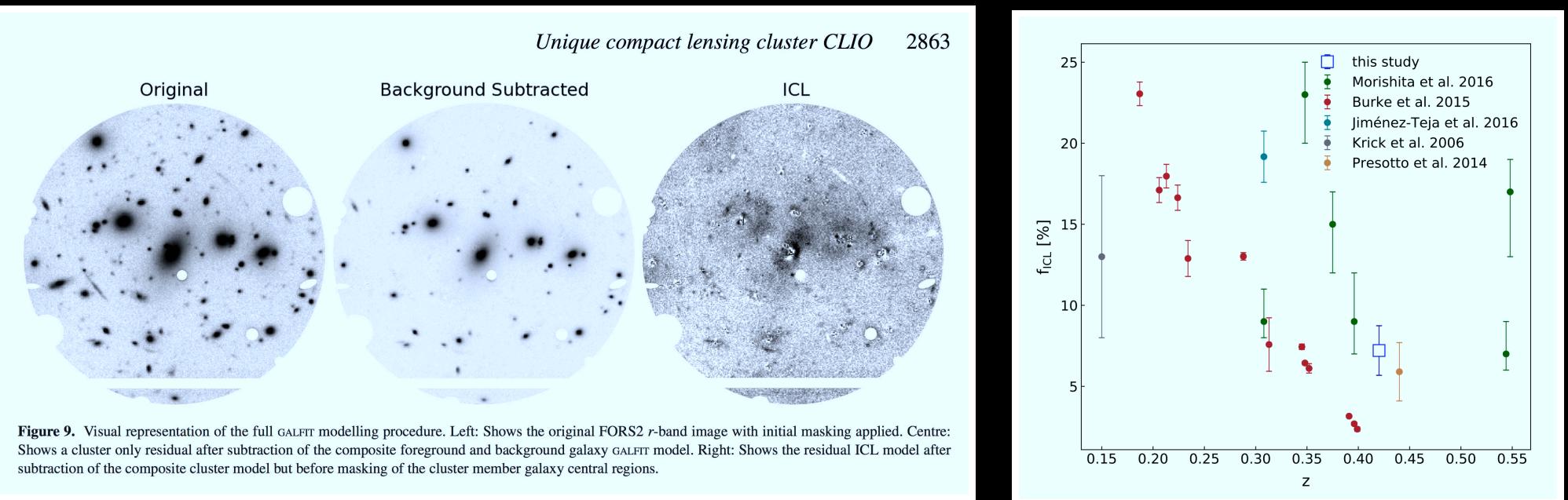
Galaxy SEDs for different ages: peak at  $\lambda_{rest} \approx 1.6 \mu\text{m}$  (Kim et al. 2017).

JWST-NIRCam peaks in sensitivity for  $\lambda = 3-5 \mu\text{m}$ , where Zodi is lowest.

Sweet spot for lensing cluster  $z \lesssim 0.5$ : Zodi-gain mitigates  $(1 + z)^4$ -dimming.

- Minimizes effects from near-IR K-correction and ambient ICL.
- Lower redshift clusters also have higher (virialized) masses and much larger Einstein radii.
- This is critical for optimizing caustic transit detections away from ICL.

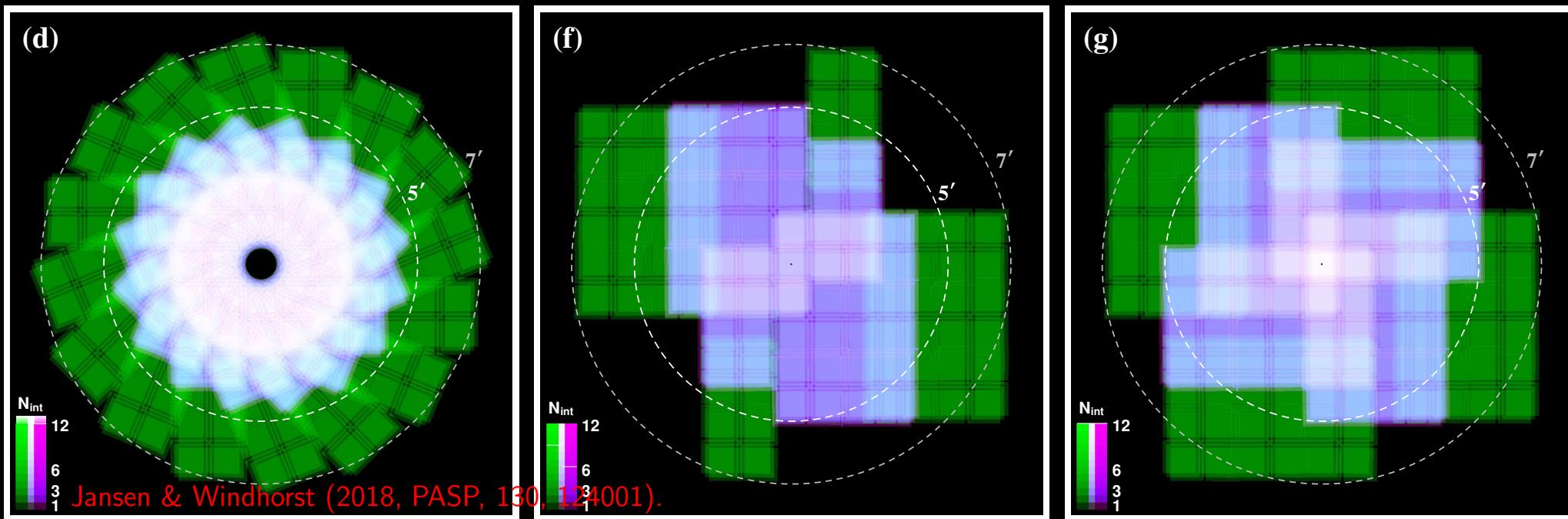
### (3) What are the best lensing clusters to monitor caustic transits?



**Figure 9.** Visual representation of the full GALFIT modelling procedure. Left: Shows the original FORS2  $r$ -band image with initial masking applied. Centre: Shows a cluster only residual after subtraction of the composite foreground and background galaxy GALFIT model. Right: Shows the residual ICL model after subtraction of the composite cluster model but before masking of the cluster member galaxy central regions.

Griffiths et al. (2018 MNRAS, 475, 2853): GAMA cluster at  $z \approx 0.42$  found through mass-concentration selection. Has 89 VLT MUSE members:

- Cluster has minimal ICL near the critical curves, optimal for caustic transit studies. Can see several arcs clearly in ground-based images.
- JWST should monitor clusters with minimal ICL near the critical curves to minimize microlensing and maximize caustic transit magnifications.



[LEFT]: Example of 16-epoch extension. Alternatively:

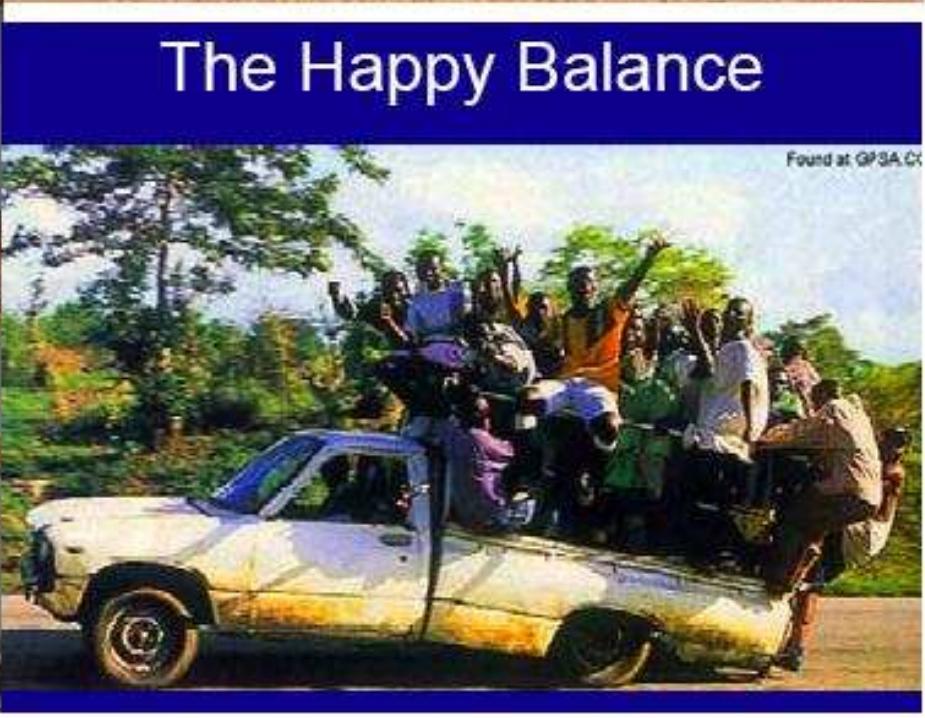
[MIDDLE]: 4-epoch filled NIRCam + NIRISS Windmill mosaic.

[RIGHT]: 4-epoch extended NIRCam + NIRISS Windmill mosaic.

- GO's can repeat NIRCam primaries + NIRISS parallels as often as needed during JWST's 5–14 year lifetime at *any* PA — no ORIENT restrictions!
- NEP yields time-domain imaging to AB $\lesssim$ 29 mag.
- NEP provides robust multi-ORIENT grism spectra to AB $\lesssim$ 28 mag.

What the Scientists See:

What the Project Manager Sees:



## The Happy Balance

Found at GFSACX

Any (space) mission is a balance between what science demands, what technology can do, and what budget & schedule allows ... (courtesy Prof. R. Ellis).

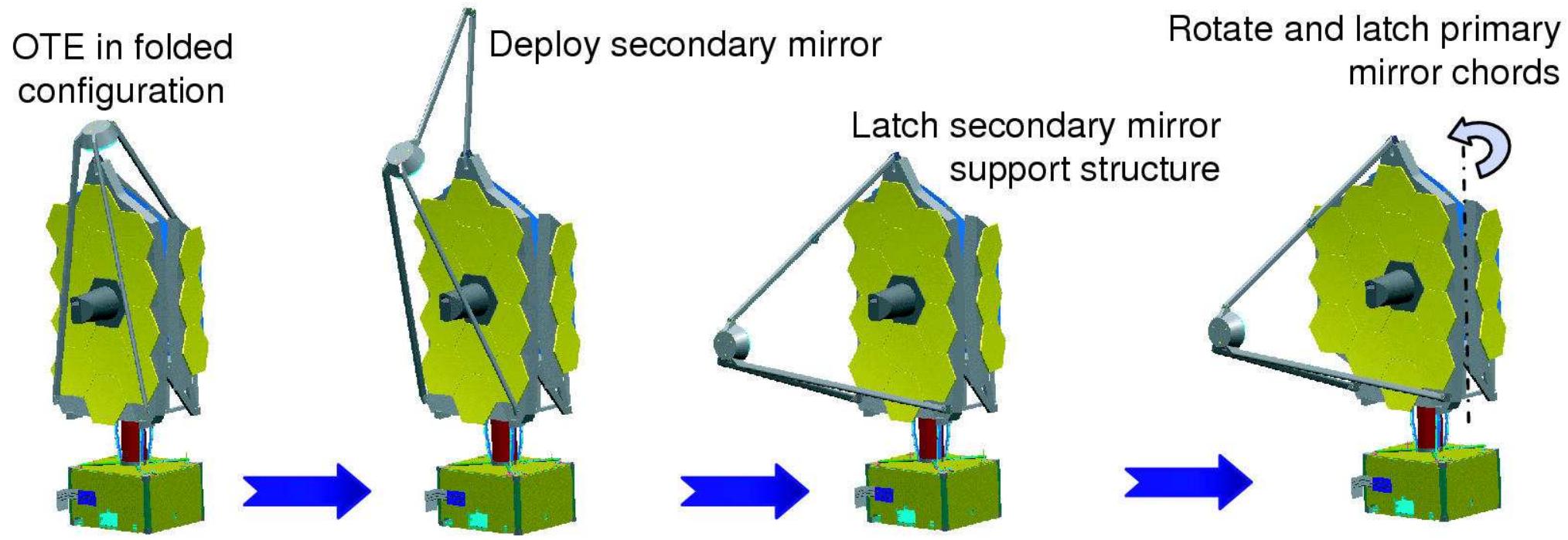
- (6) Update of JWST programmaticas as of 2021

## Northrop Grumman Expertise in Space Deployable Systems

- Over 45 years experience in the design, manufacture, integration, verification and flight operation of spacecraft deployables
- 100% mission success rate, comprising over 640 deployable systems with over 2000 elements

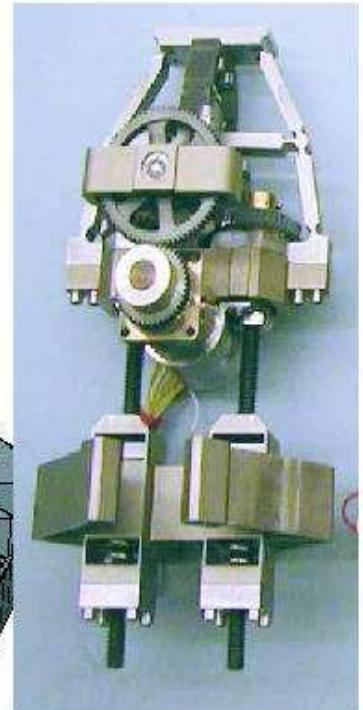
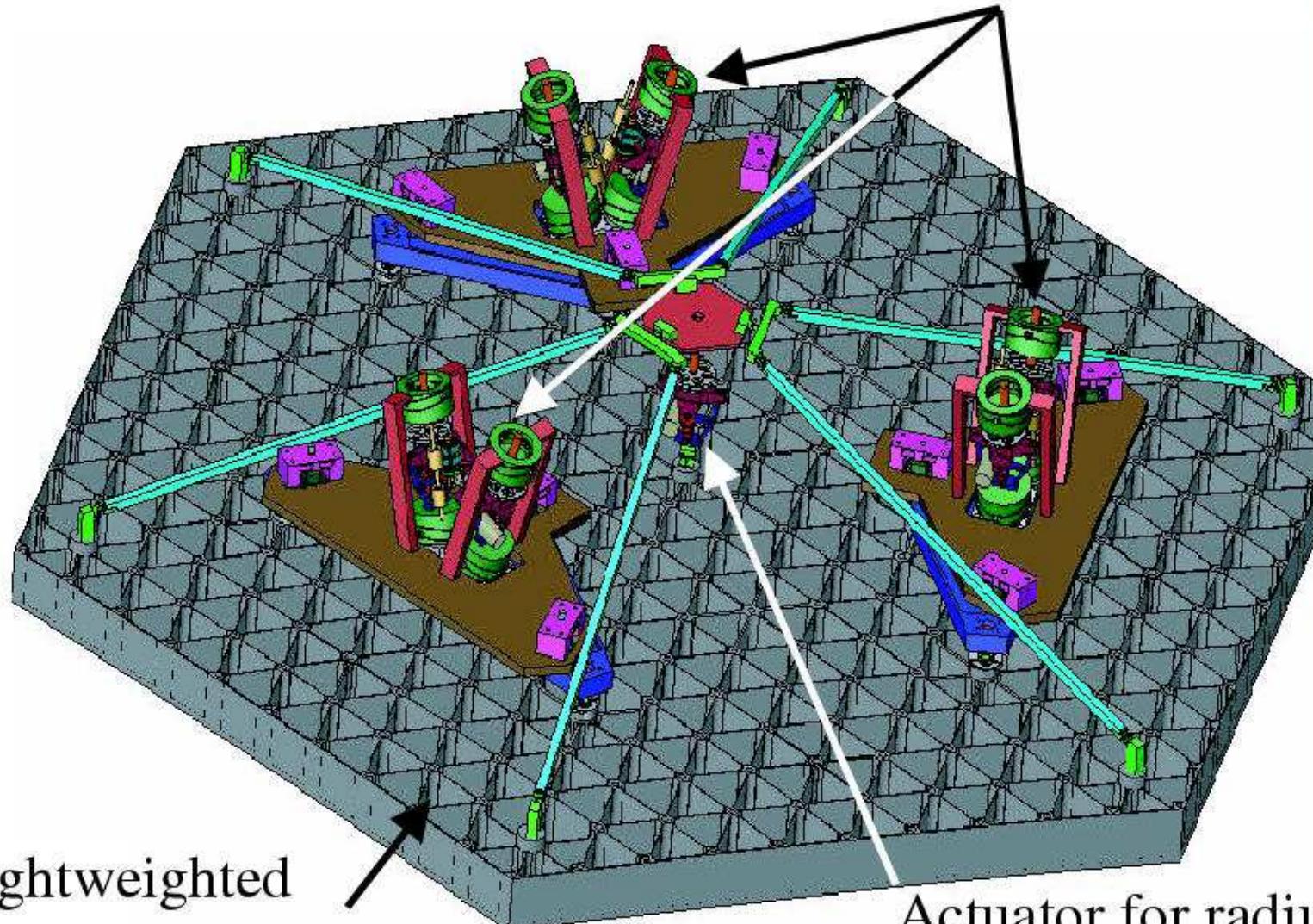


- (1b) How will JWST be automatically deployed?



- During its two month journey to L2, JWST will be automatically deployed, its instruments will be cooled, and be inserted into an L2 orbit.
- The entire JWST deployment sequence is tested several times in 1-G from 2014–2019 at GSFC (MD), Northrop (CA), and JSC (Houston).
- All 18 flight mirrors completely done, and meet the 40K specifications.

## Actuators for 6 degrees of freedom rigid body motion



Actuator  
development  
unit

Lightweighted  
Beryllium Mirror

Actuator for radius  
of curvature adjustment

Active mirror segment support through “hexapods”, similar to Keck.

Redundant & doubly-redundant mechanisms, quite forgiving against failures.



### Baseline "Cup Down" Tower Configuration at JSC (Before)

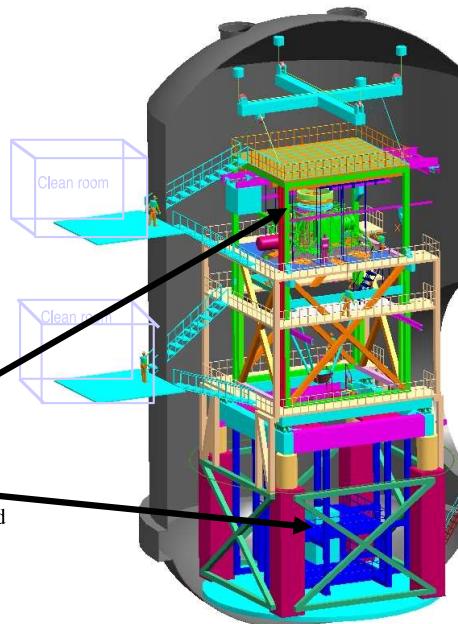
Most recent Tower Design shows an Inner Optical Tower supported by an Outer structure with Vibration Isolation at the midplane. Everything shown is in the 20K region (helium connections, etc. not shown) except clean room and lift fixture.

Current plan calls for 33KW cooldown capability, 12 KW steady state, 300-500mW N2 cooling

JSC currently has 7 KW He capability

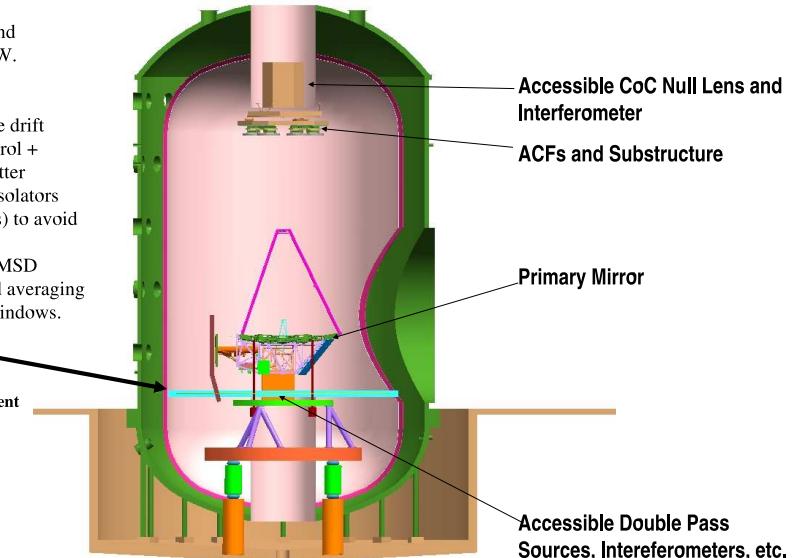
Current plan includes 10 trucks of LN2/day during cooldown

Interferometers, Sources, Null Lens and Alignment Equipment Are in Upper and Lower Pressure Tight Enclosure Inside of Shroud



### JSC "Cup Up" Test Configuration (New Proposal)

No Metrology Tower and Associated Cooling H/W. External Metrology  
Two basic test options:  
1. Use isolators, remove drift through fast active control + freeze test equipment jitter  
2. Eliminate vibration isolators (but use soft dampeners) to avoid drift, freeze out jitter  
Builds on successful AMSD heritage of freezing and averaging jitter, testing through windows.



Drawing care of ITT

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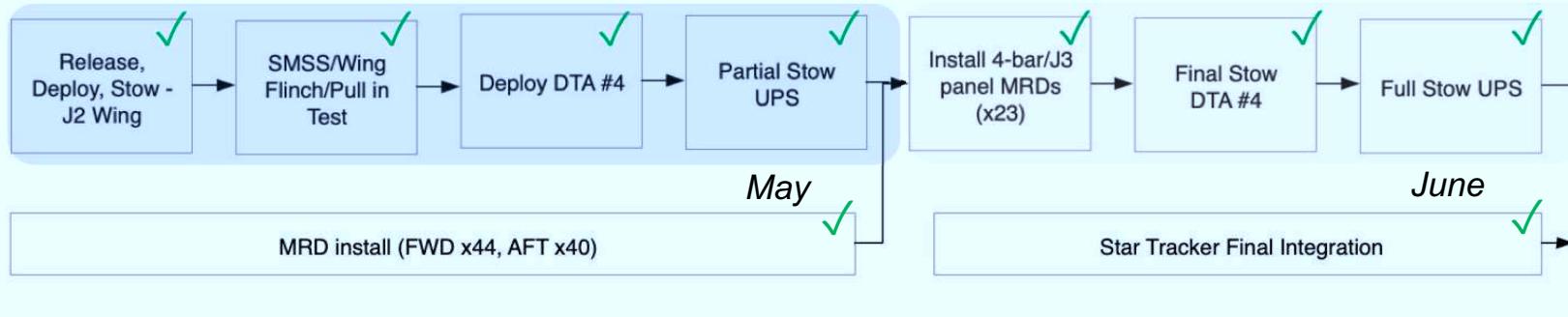
JWST underwent several significant replans and risk-reduction schemes:

- $\lesssim$ 2003: Reduction from 8.0 to 7.0 to 6.5 meter. Ariane-V launch vehicle.
- 2005: Eliminate costly 0.7-1.0  $\mu\text{m}$  performance specs (kept 2.0  $\mu\text{m}$ ).
- 2005: Simplification of thermal vacuum tests: cup-up, not cup-down.
- 2006: All critical technology at Technical Readiness Level 6 (TRL-6).
- 2008: Passes Mission Preliminary Design & Non-advocate Reviews.
- 2010, 2011: Passes Mission Critical Design Review: Replan Int. & Testing.
- 2017–2018: Replan final Integration & Testing  $\Rightarrow$  Dec. 2021 launch.

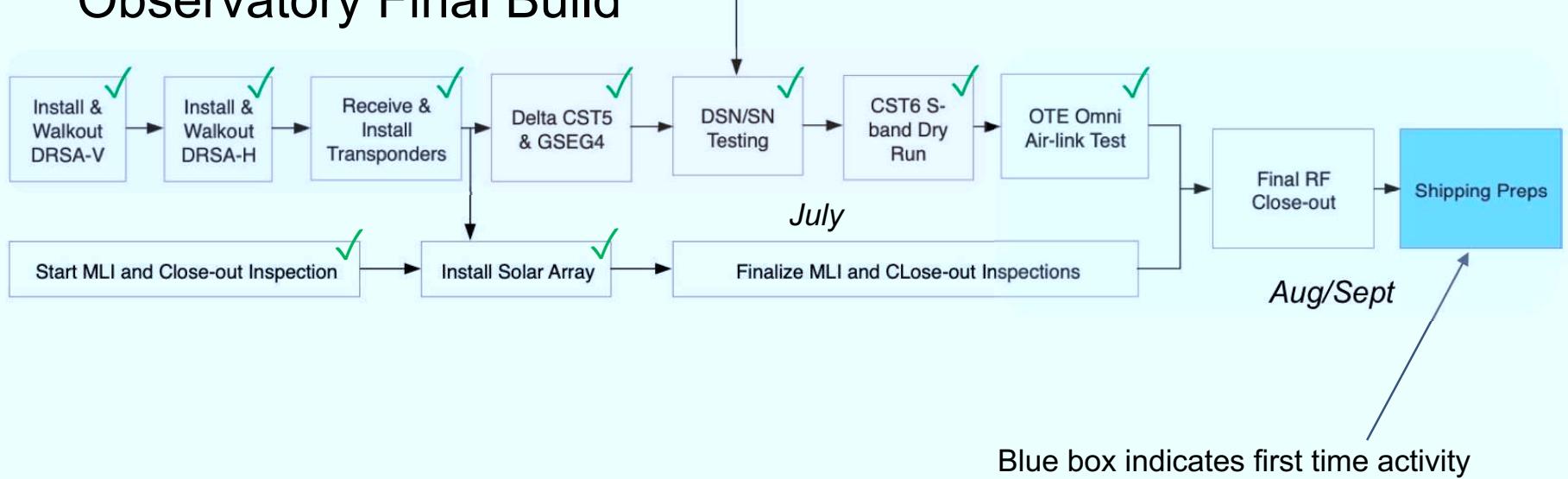


# Remaining I&T Steps

## Observatory Deployments



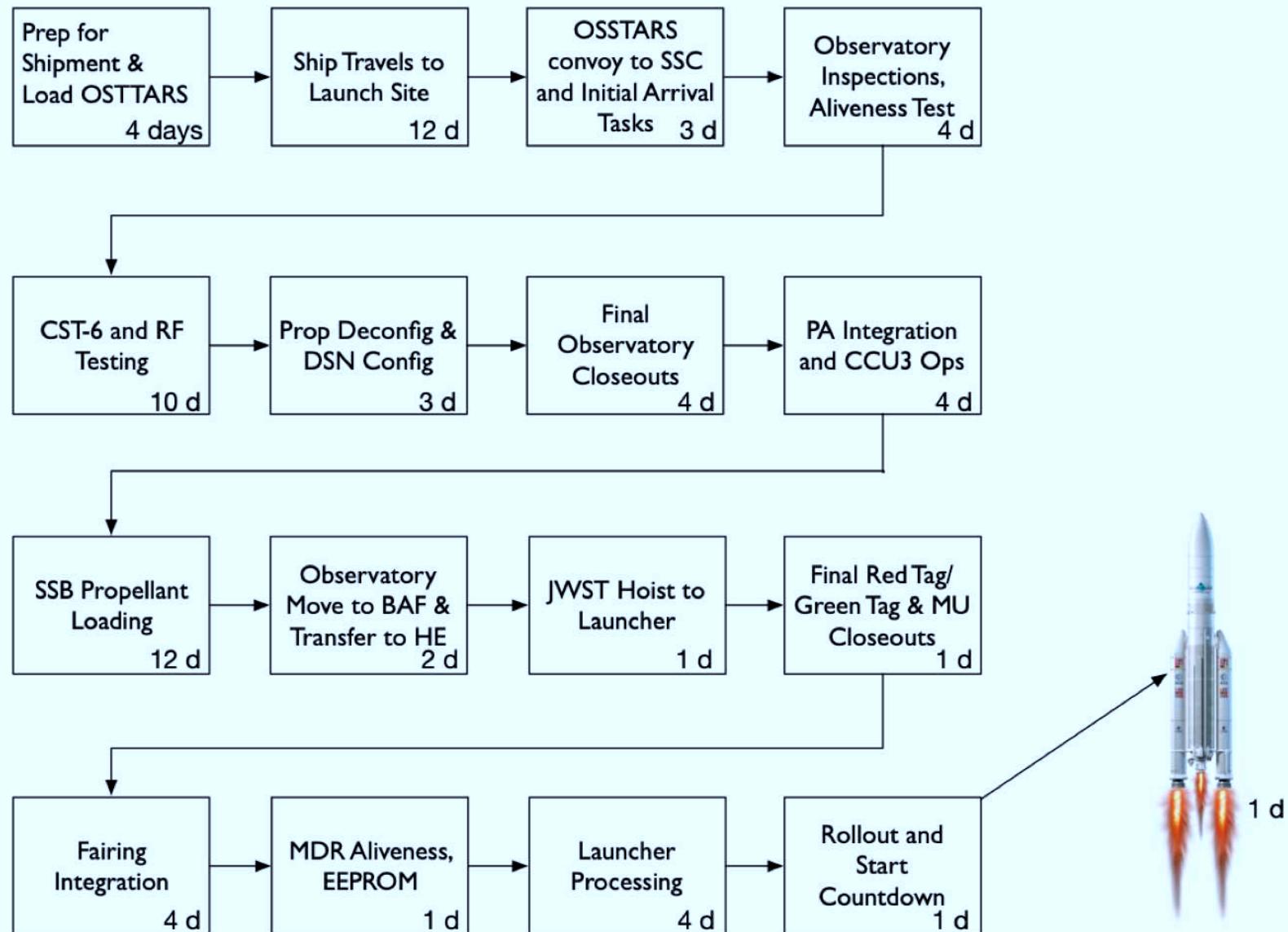
## Observatory Final Build



Flowchart of Project tasks for FY21.

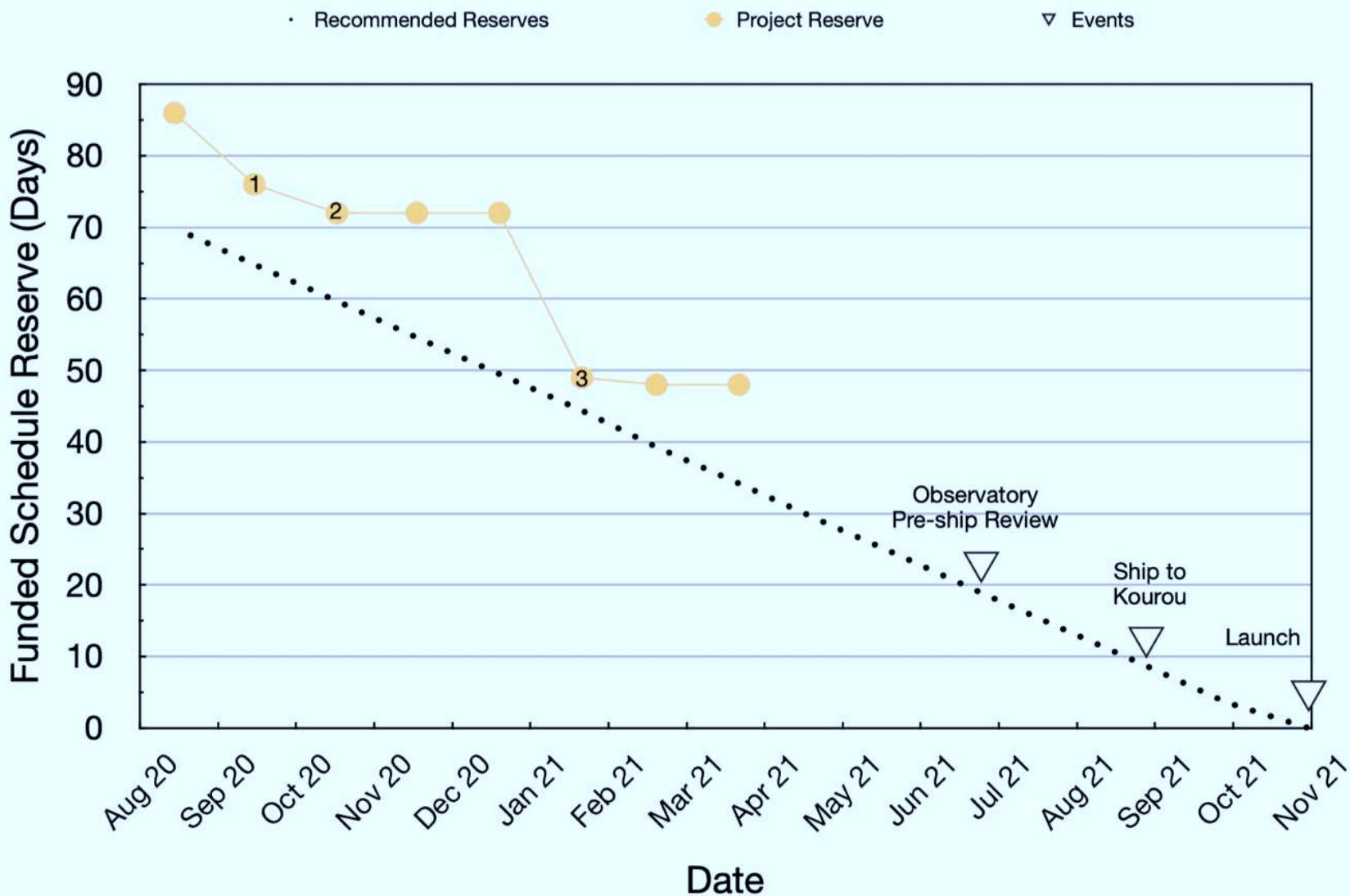
Blue = First-time operation (all others done before at sub-system level).

# Kourou Activities



Flowchart of ESA and Project tasks at Kourou (French Guyana).

# Current Funded Schedule Reserve



Reserve uses: (1) ~~Bldg M4 issues, additional Z-axis vibe run,~~ (2) Ka-band measurements, APCO adapter (3)  
Planned sunshield repairs and patching

Project reserves in Spring 2021 for launch in late 2021.

# Fiscal Year 2021 JWST HQ Milestones

Month	Milestone	Comment
Oct-20	1 Complete Observatory Environmental Testing	Completed 10/2/20
Nov-20		
Dec-20	2 Complete Post Environmental Testing Spacecraft Bus Deployments	<u>Completed 11/12/20</u>
Jan-21	3 Complete Post Environmental Testing Sunshield Deployments	<u>Completed 12/16/20</u>
Feb-21	4 Complete Comprehensive System Test #5	Completed 2/13/21
Mar-21	5 Complete Cycle 1 General Observer Proposal Reviews	<u>Completed 3/30/21</u>
	6 Sunshield Fold Complete	<u>Completed 4/6/21</u>
	7 Launch Readiness Exercise #2	Completed 3/8/21
Apr-21		
May-21	8 Final Deployable Tower deployment	<u>Completed 6/8/21</u>
Jun-21		
Jul-21	9 Final Observatory Stow Complete	Completed 7/15/21
	10 Observatory Pre-Ship Review	Completed 7/29/21
	11 Launch Readiness Exercise #4	<u>Completed 6/22/21</u>
Aug-21	12 Operational Readiness Review	
	13 Ship Observatory to Launch Site	
Sep-21		

Blue font(underline) denotes milestones accomplished ahead of schedule; orange font denotes milestones accomplished late.

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Milestones left to go as of Summer 2021.

Operational Readiness Review passed in Aug. 2021, Launch Readiness in Nov. 2021

# Milestone Performance

- Since the September 2011 replan JWST reports high-level milestones monthly to numerous stakeholders

	Total Milestones	Total Milestones Completed	Number Completed Early	Number Completed Late	Deferred to Next Year	Deferred more than one quarter
FY2011	21	21	6	3	0	0
FY2012	37	34	16	2	3	3
FY2013	41	38	20	5	3	2
FY2014♦	36	23	10	8	11	10
FY2015	48	44	22	12	4	3
FY2016	45	39	25	7	6	2
FY2017	38	32	12	13	8	5
FY2018	31	18	7	2	13	13
FY2019	25	19	8	9	2	1

♦ Milestone accounting in FY2014 was complicated by the government shutdown and multicomponent milestones

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FY14: 8 milestones late by 1 mo due to Oct 2013 Government shutdown.

FY15: Most “Lates” not on critical path.

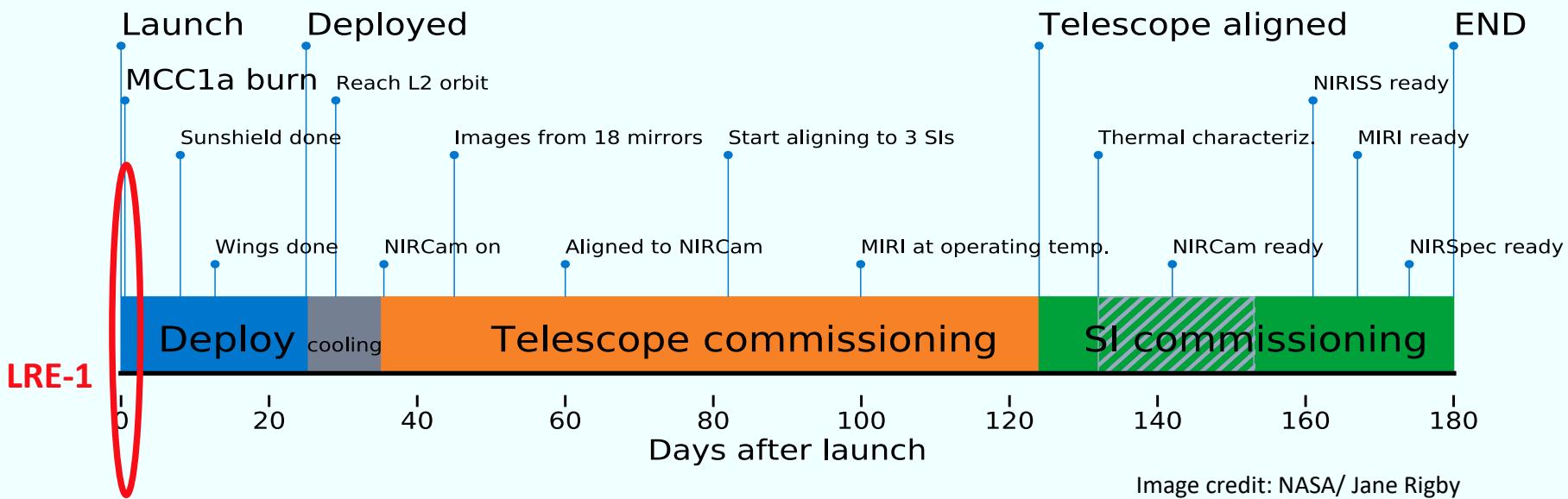
FY17: Lates started to outnumber Early's ⇒ Replan Integration & Testing.

# Commissioning At A Glance

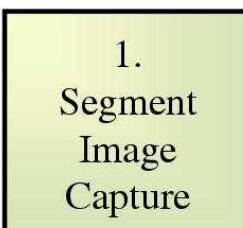
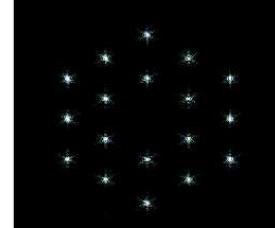
Commissioning begins at launch and is ~180 days long, including the following key events:

1. Launch and Ascent – power positive, safe attitude, and communications established
  2. Mid Course Correction – MCC1 (a and b) corrects launcher dispersions for proper L2 trajectory
  3. Deployments
  4. Cool-Down/Cryo-Cooler Activation
  5. Mirror segment deploy and wave-front control
  6. Science Instrument calibrations and checkout
- Launch and Deploy Phase

Cool-Down/OTIS Phase



JWST Commissioning Plan after launch from Kourou in Dec. 22, 2021.

<i>First light NIRCam</i>	<i>After Step 1</i>	<i>Initial Capture</i>	<i>Final Condition</i>
		18 individual 1.6-m diameter aberrated sub-telescope images PM segments: < 1 mm, < 2 arcmin tilt SM: < 3 mm, < 5 arcmin tilt	PM segments: < 100 $\mu\text{m}$ , < 2 arcsec tilt SM: < 3 mm, < 5 arcmin tilt
<b>2. Coarse Alignment</b> Secondary mirror aligned Primary RoC adjusted		Primary Mirror segments: < 1 mm, < 10 arcsec tilt Secondary Mirror : < 3 mm, < 5 arcmin tilt	WFE < 200 $\mu\text{m}$ (rms)
<b>3. Coarse Phasing - Fine Guiding (PMSA piston)</b>		WFE: < 250 $\mu\text{m}$ rms	WFE < 1 $\mu\text{m}$ (rms)
<b>4. Fine Phasing</b>		WFE: < 5 $\mu\text{m}$ (rms)	WFE < 110 nm (rms)
<b>5. Image-Based Wavefront Monitoring</b>		WFE: < 150 nm (rms)	WFE < 110 nm (rms)

JWST's Wave Front Sensing and Control is similar to the Keck telescope.

In L2, need WFS updates every 10 days depending on scheduling/illumination.