2020 Update of JWST Hardware and Science: Faint Object Time-Domain & Population III Caustic Transits

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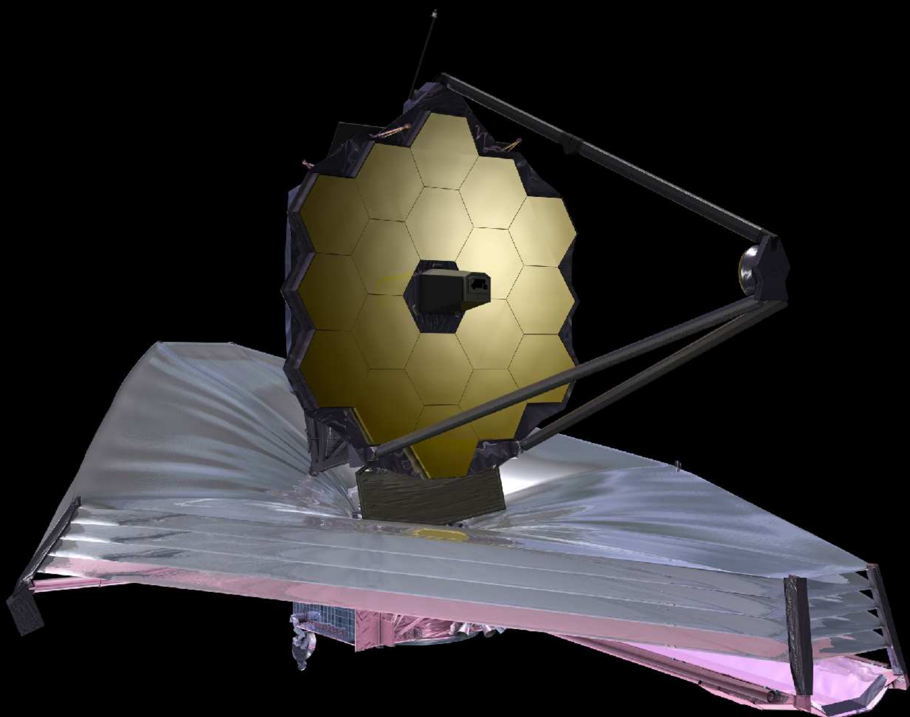


- Today, the JWST science remains as compelling as it was ∼20 years ago.

- In fact, the JWST science is far more exciting today than we could have imagined or planned for ∼20 years ago.

Talk at the JWST Workshop, U. Santiago, Santiago, Chile; Oct. 6, 2020

Talk is on: `http://www.asu.edu/clas/hst/www/jwst/jwsttalks/almasantiago20_jwst.pdf`

Outline & Conclusions

(1) Update on the James Webb Space Telescope (JWST), 2020.

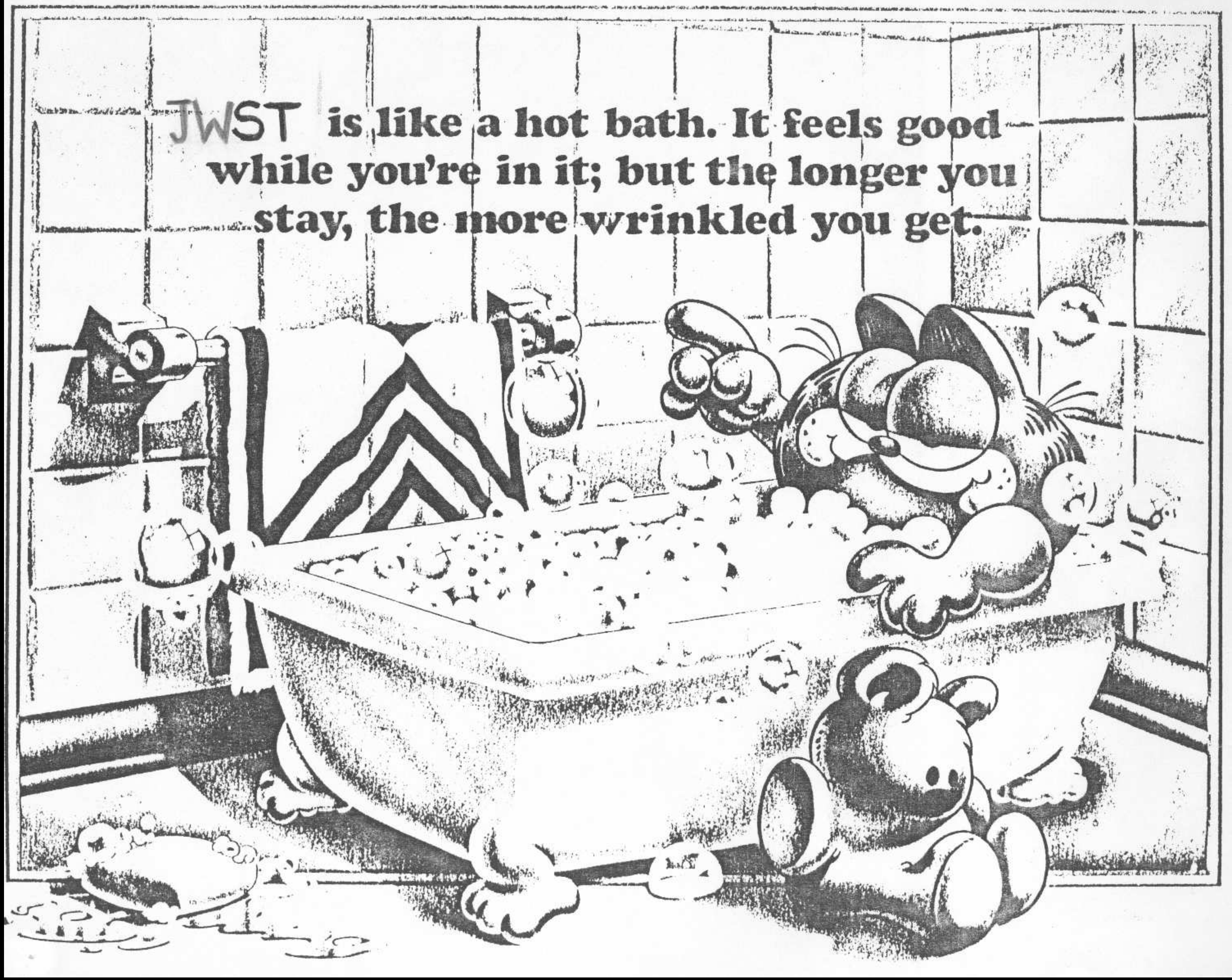
(2) JWST Time-Domain Field in the NEP Continuous Viewing Zone:

- 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.

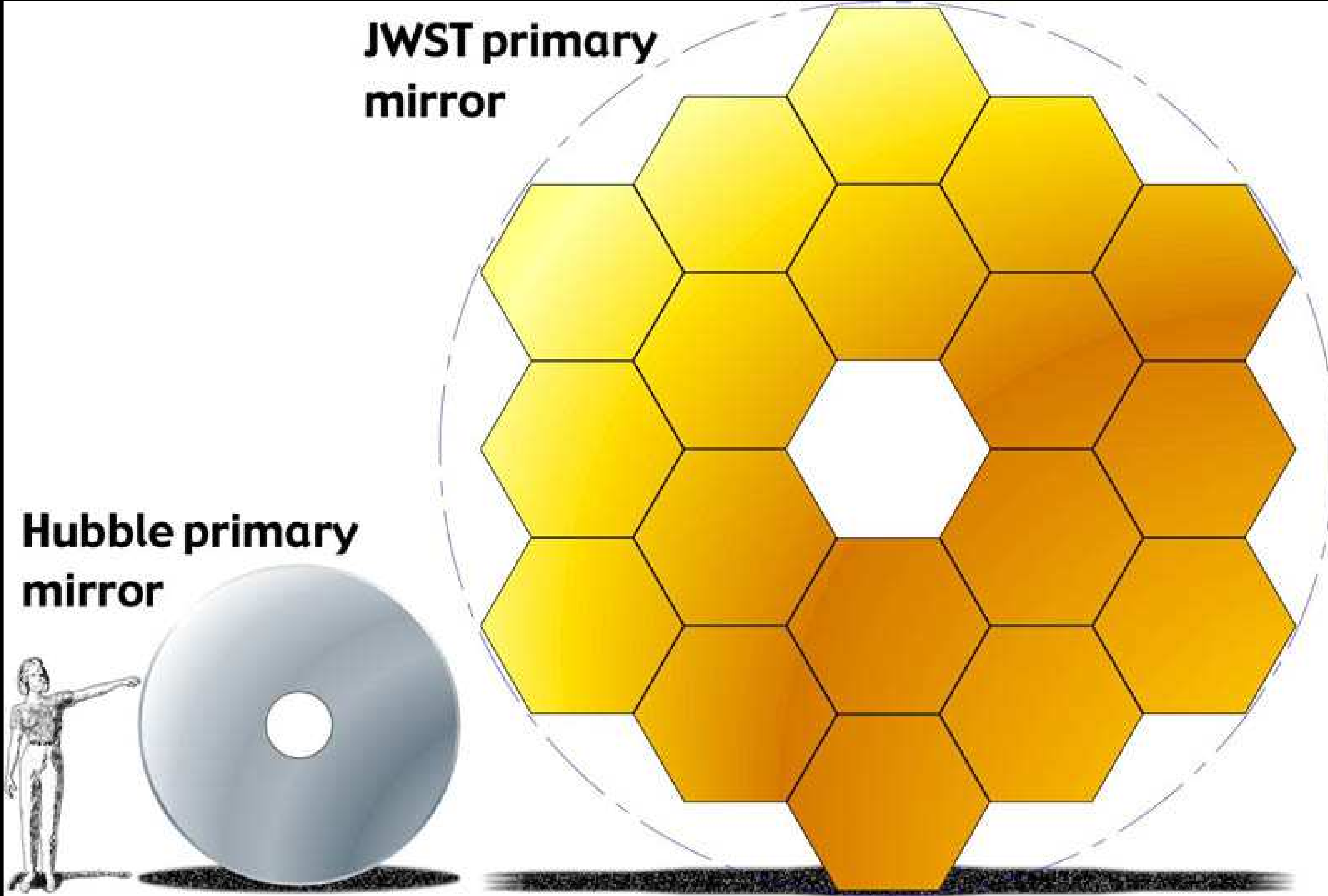
(3) Monitor the best lensing clusters for possible JWST caustic transits of Pop III stars and their stellar-mass black hole accretion disks at z$\gtrsim$7.

- Limits to the SKY-SB from First Stars & Stellar-Mass Black Holes $\Longrightarrow$
- JWST may detect Pop III objects directly monitoring $\gtrsim$3 lensing clusters.



WARNING: Both Hubble and James Webb are 30–40$^+$ year projects:

You will feel wrinkled before you know it ... :)



JWST ≃2.5× larger than Hubble, so at ∼2.5× larger wavelengths:

JWST has the same resolution in the near-IR as Hubble in the optical.

The James Webb Space Telescope

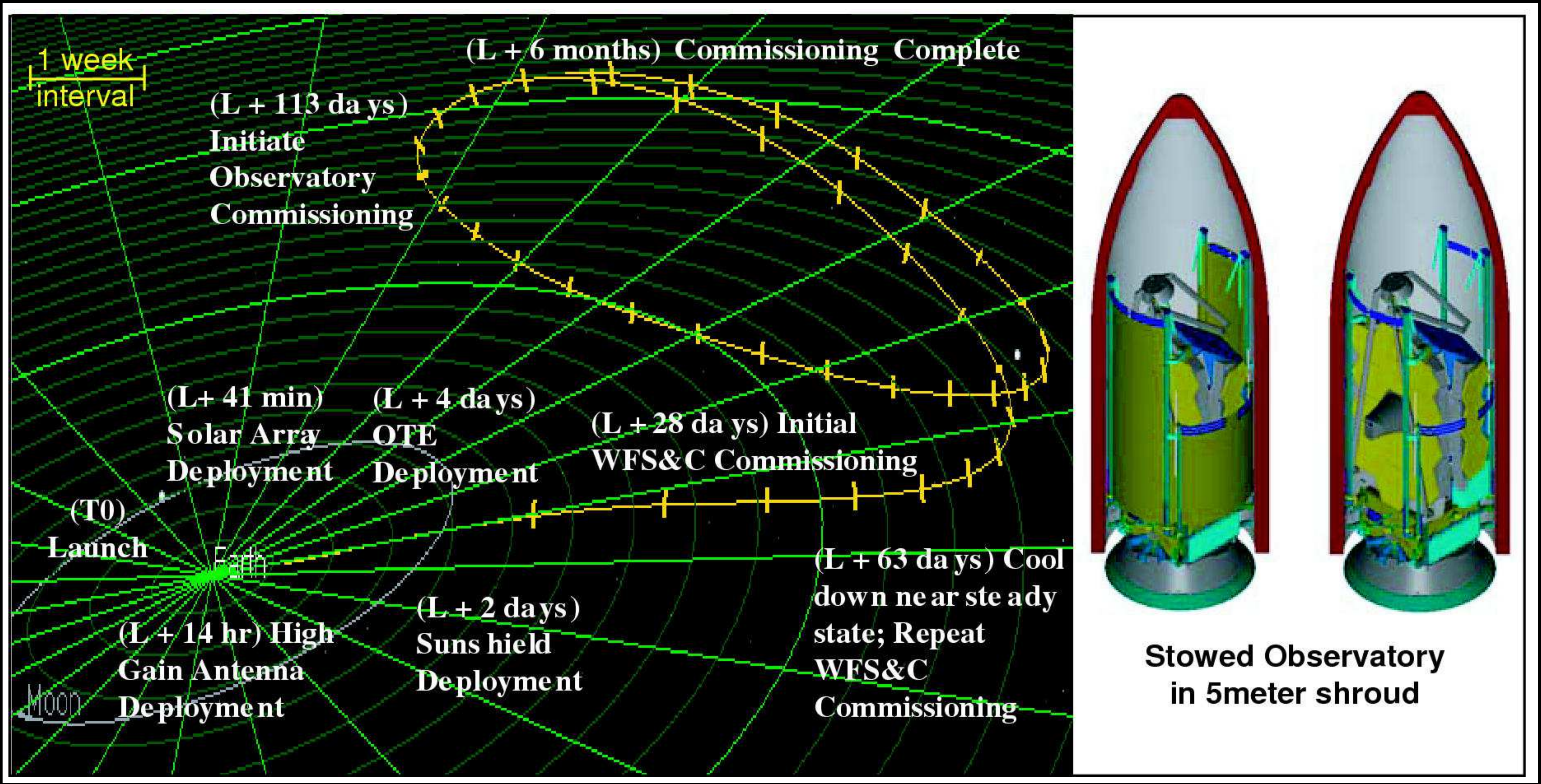
JWST Launch

- 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

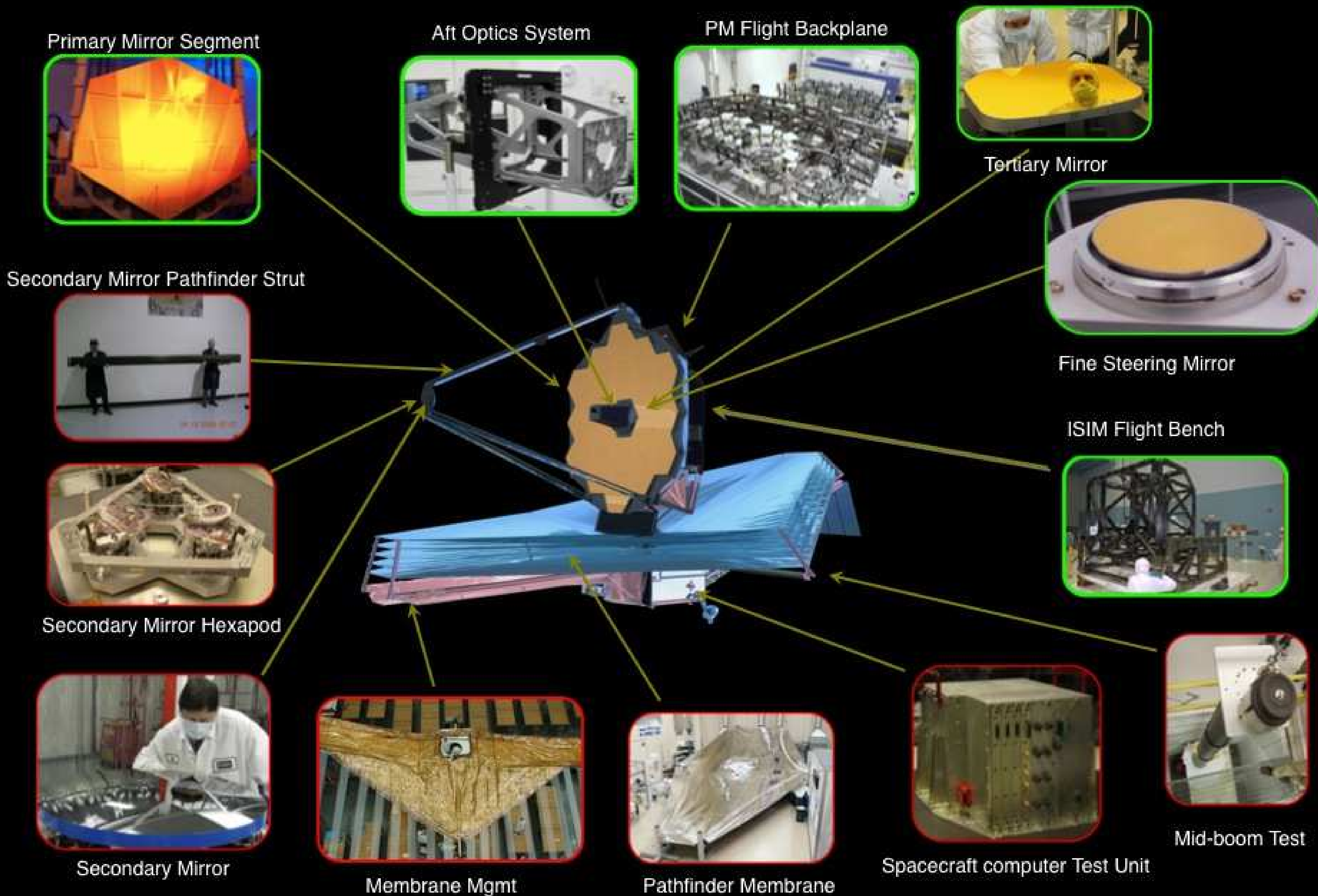
• The JWST launch weight will be $\lesssim$6500 kg, and it will be launched to L2 with an ESA Ariane-V launch vehicle from Kourou in French Guiana.

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



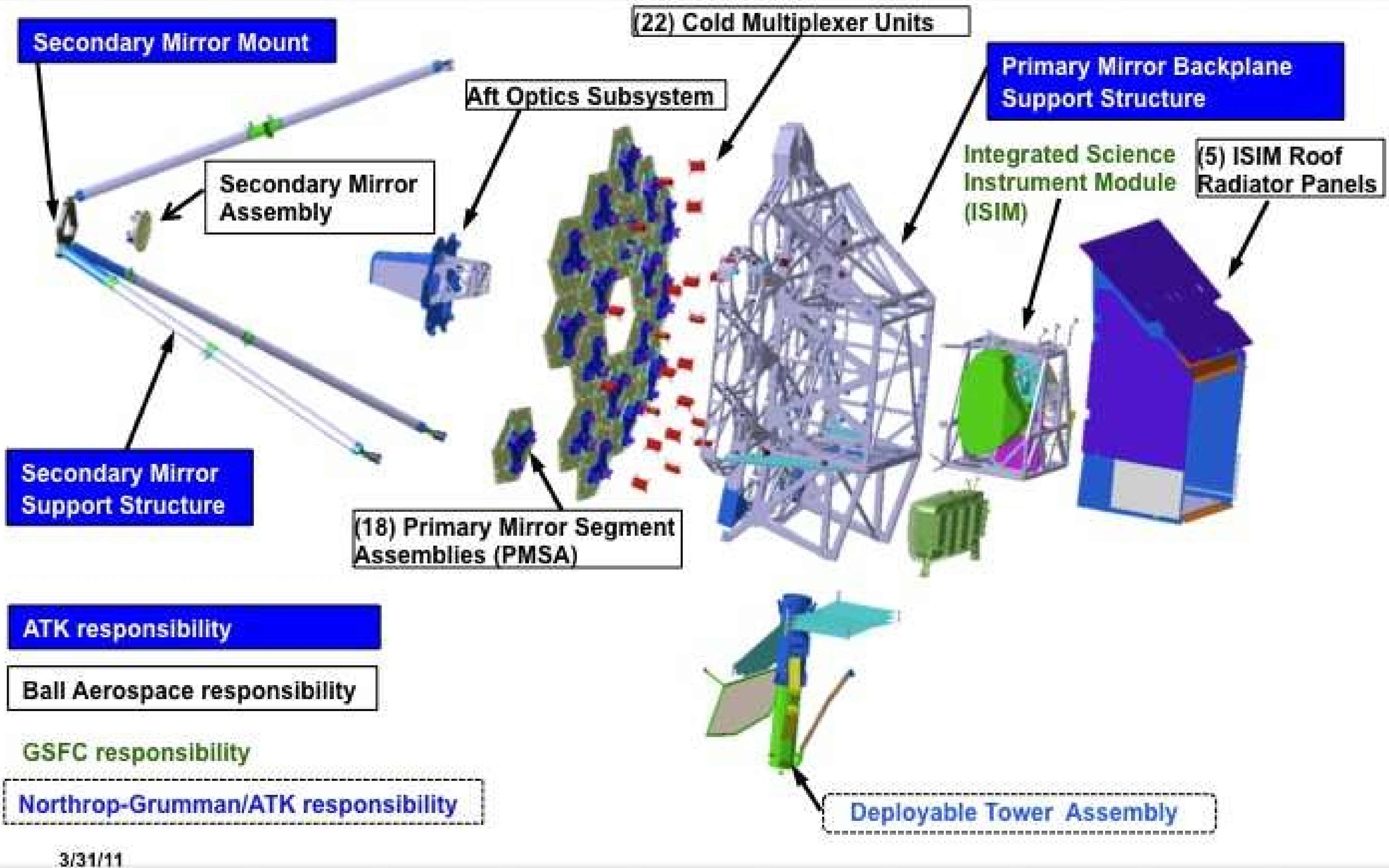
- After launch in Oct. 2021 with an ESA Ariane-V, JWST will orbit around the Earth–Sun Lagrange point L2, 1.5 million km from Earth.
- JWST can cover the whole sky in segments that move along with the Earth, observe $\gtrsim$70% of the time, and send data back to Earth every day.

JWST Hardware Status



Fall 2020: 100% of launch mass designed and built ($\gtrsim$99% weighed).

TELESCOPE ARCHITECTURE

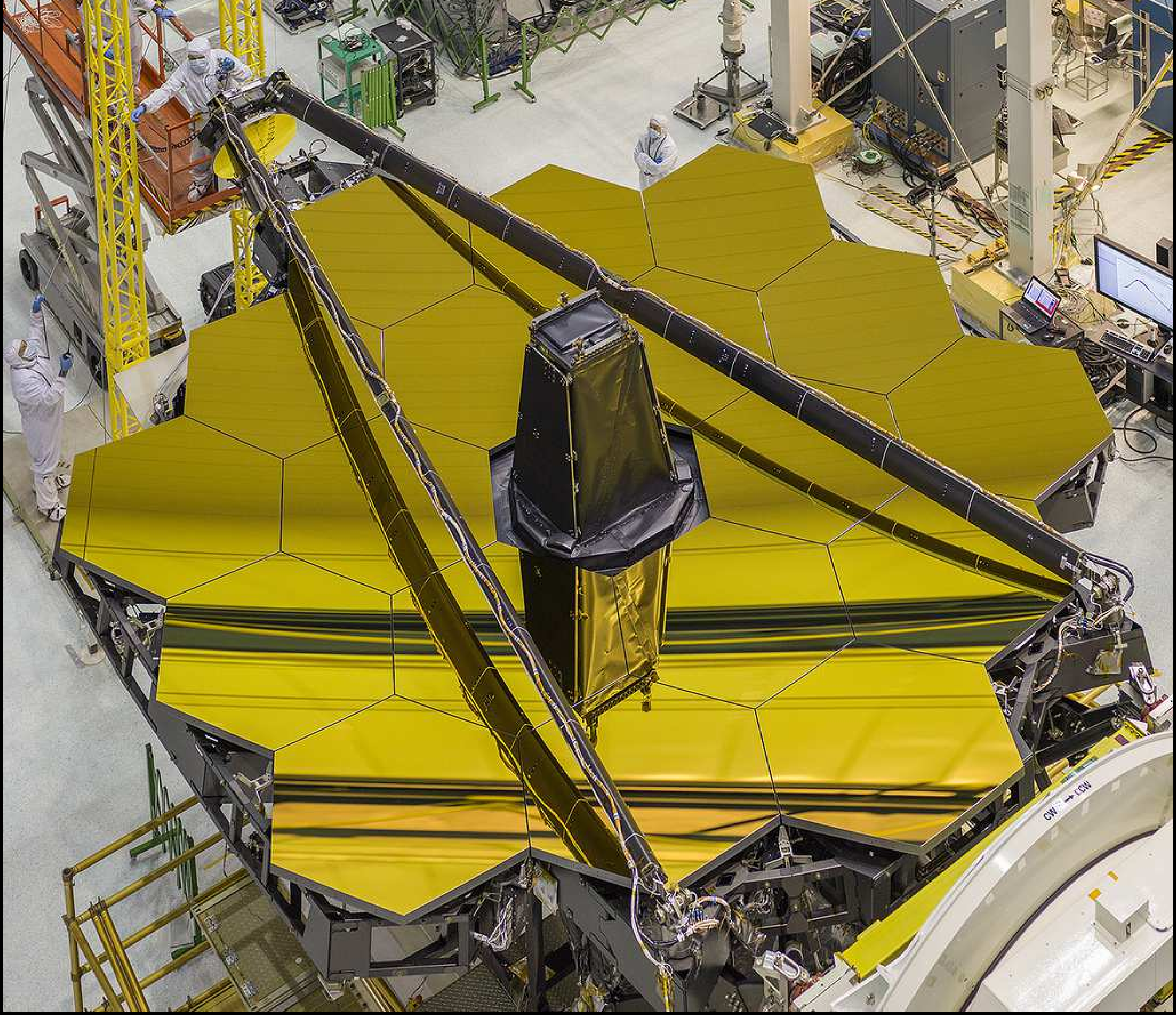


2014–2019: Complete system integration at GSFC and Northrop.

NASA team-work to take JWST mirror covers off!

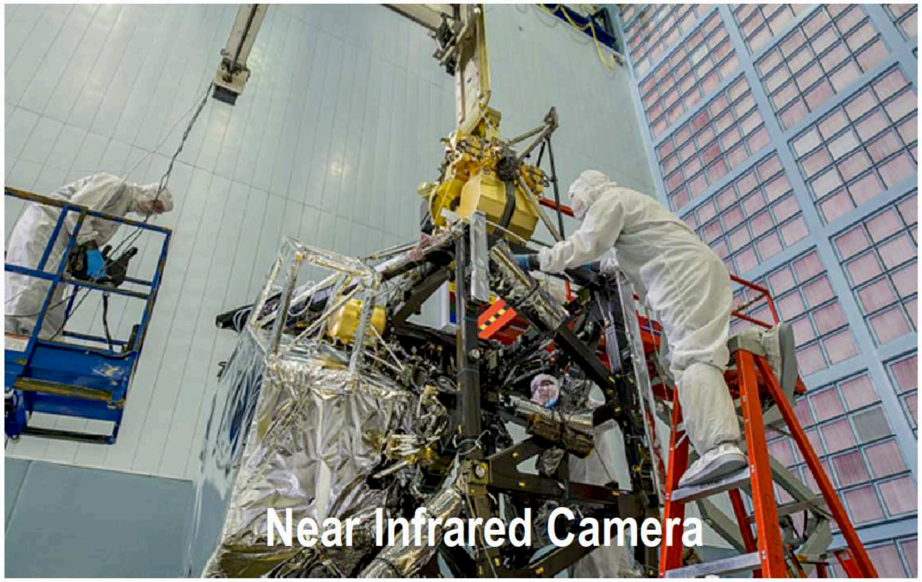
JWST being tilted into the right position

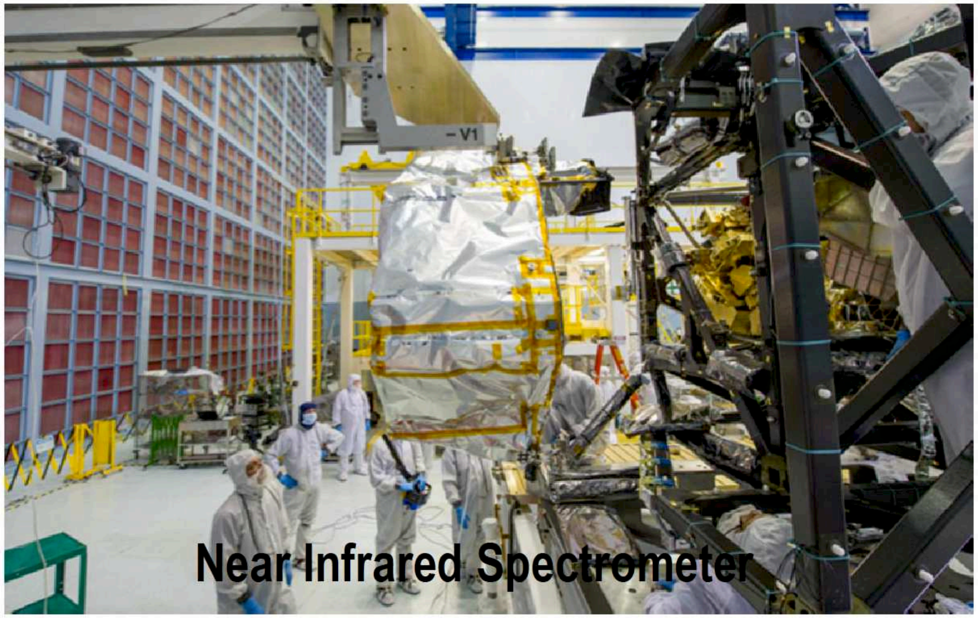
Webb mirrors finally mounted and ready!

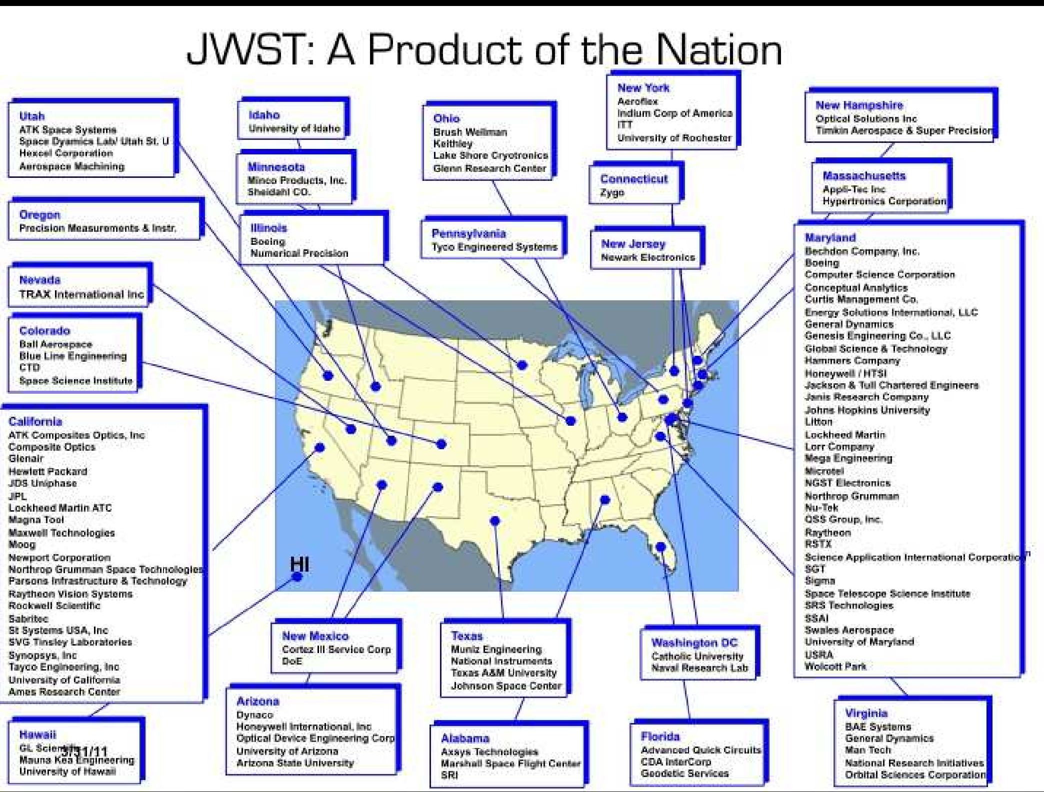


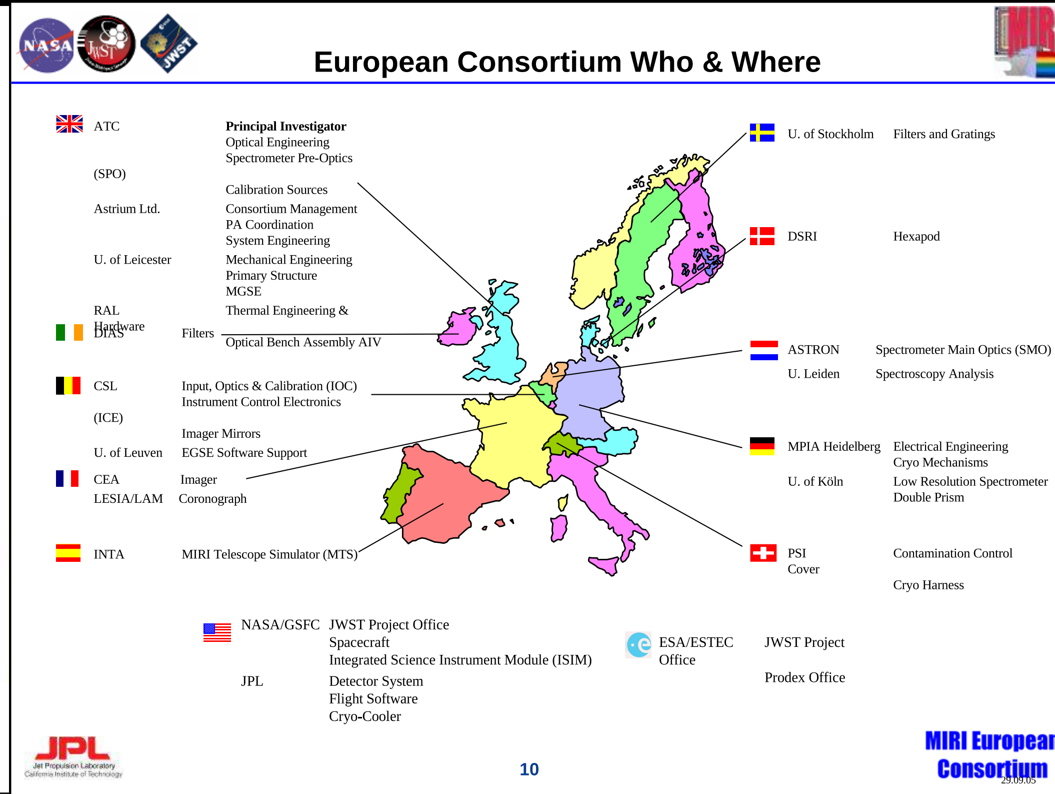
JWST stowed for final instrument mounting

All Instruments Integrated









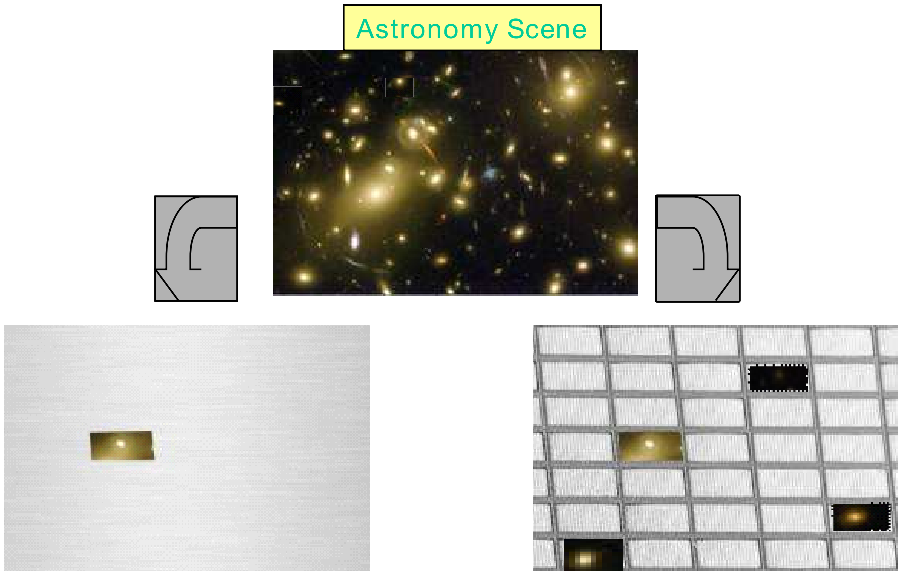
- JWST hardware made in 27 US States: 100% of launch-mass finished.

- Ariane V Launch & NIRSpec provided by ESA; & MIRI by ESA & JPL.

- JWST Fine Guider Sensor + NIRISS provided by Canadian Space Agency.

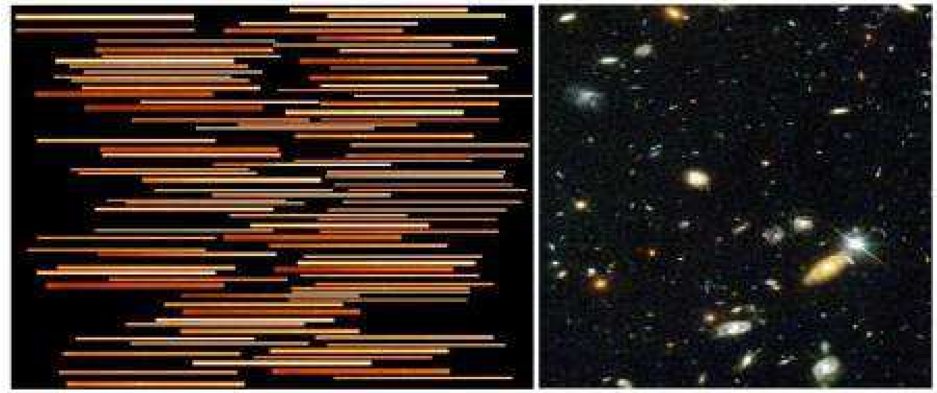
- JWST NIRCam made by UofA and Lockheed.

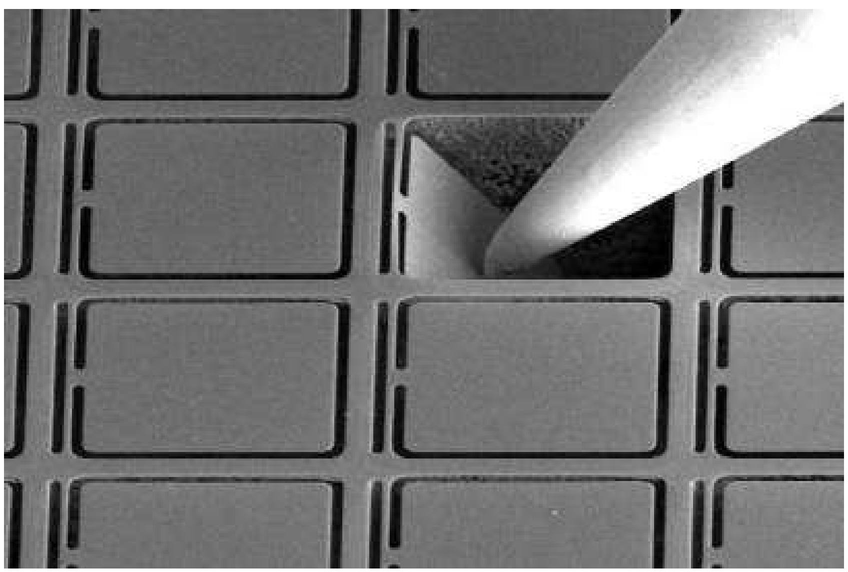
Micro Shutters



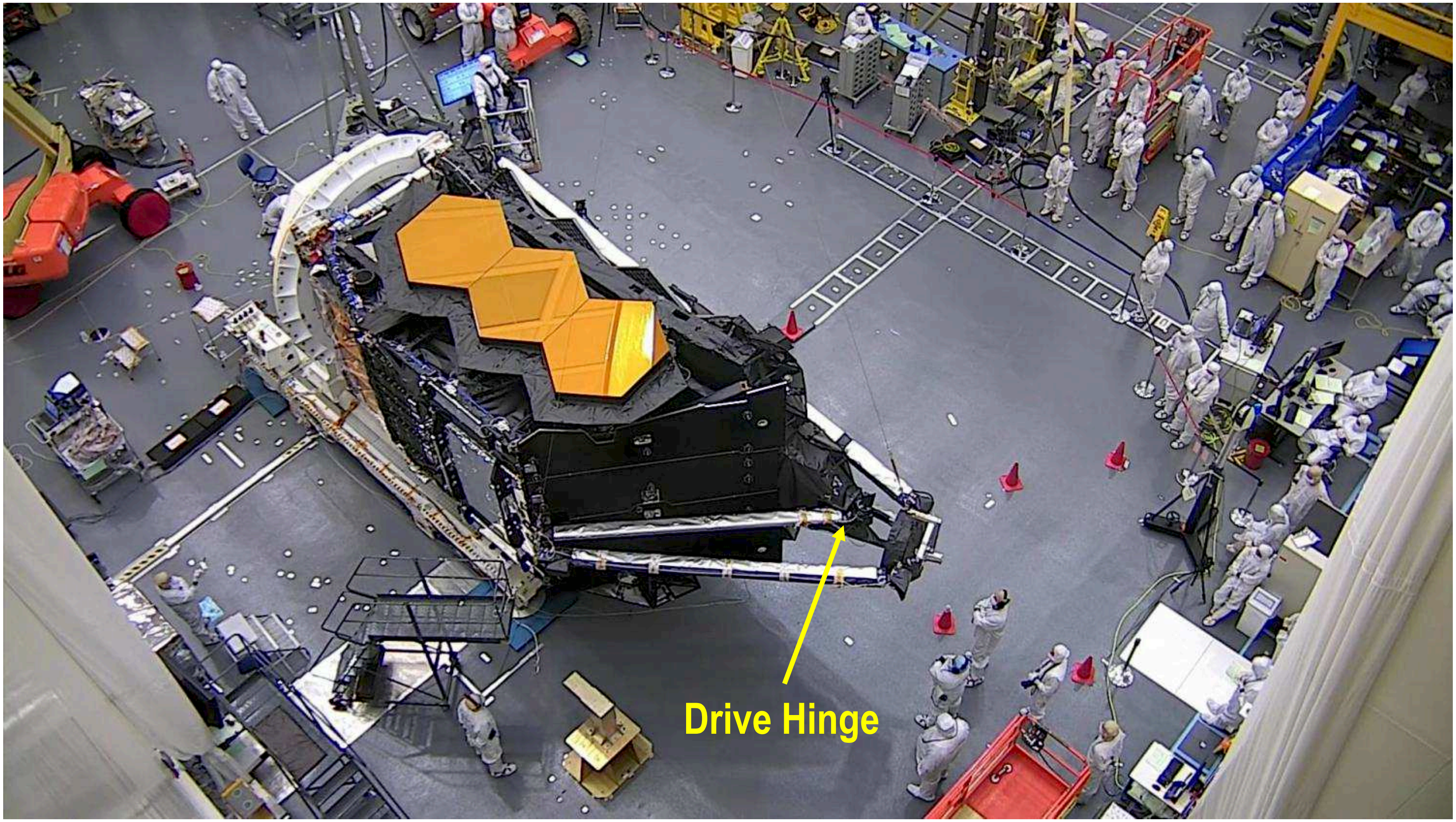
Metal Mask/Fixed Slit

Shutter Mask



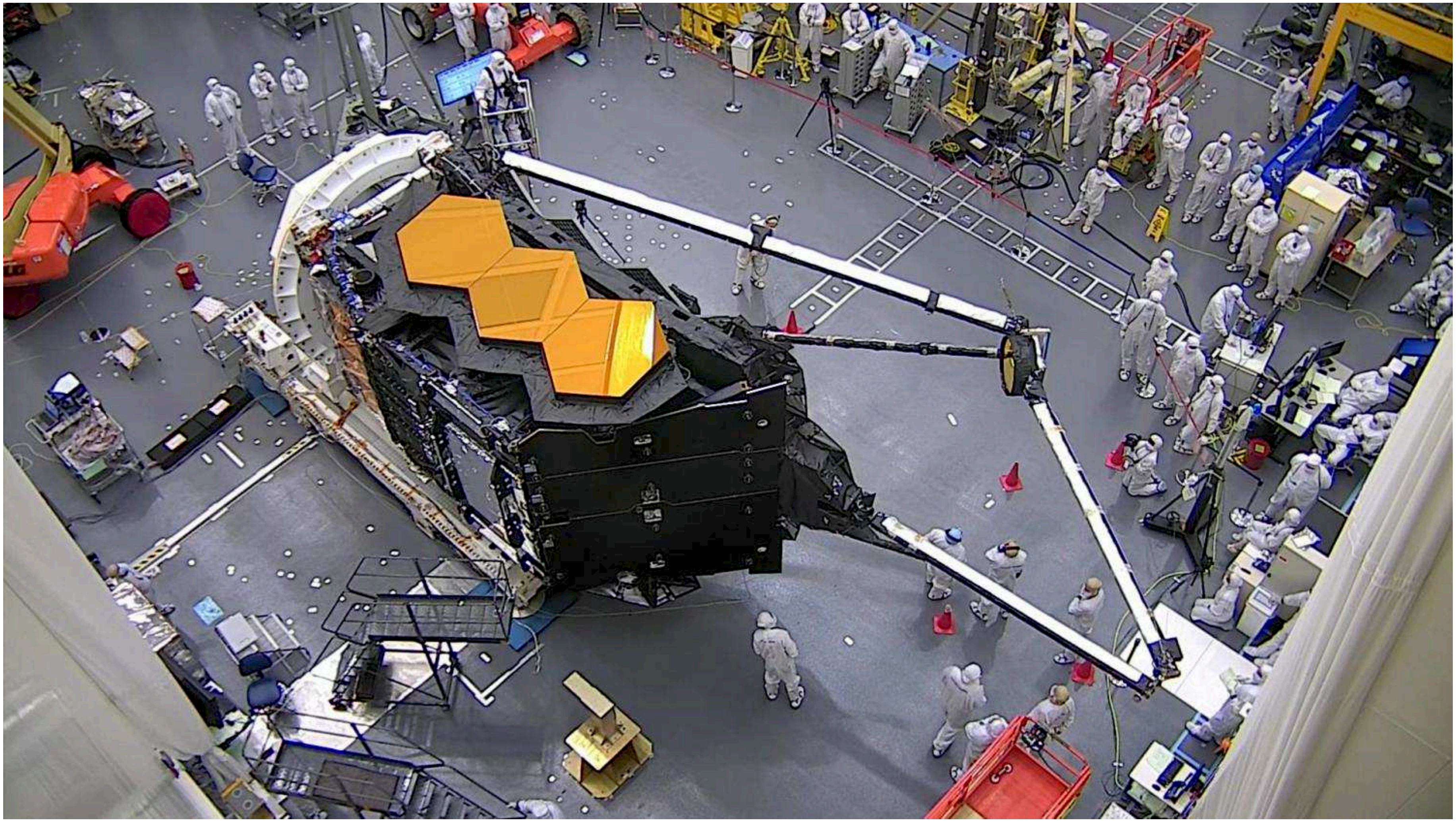


SMSS Deployment Sequence (1)



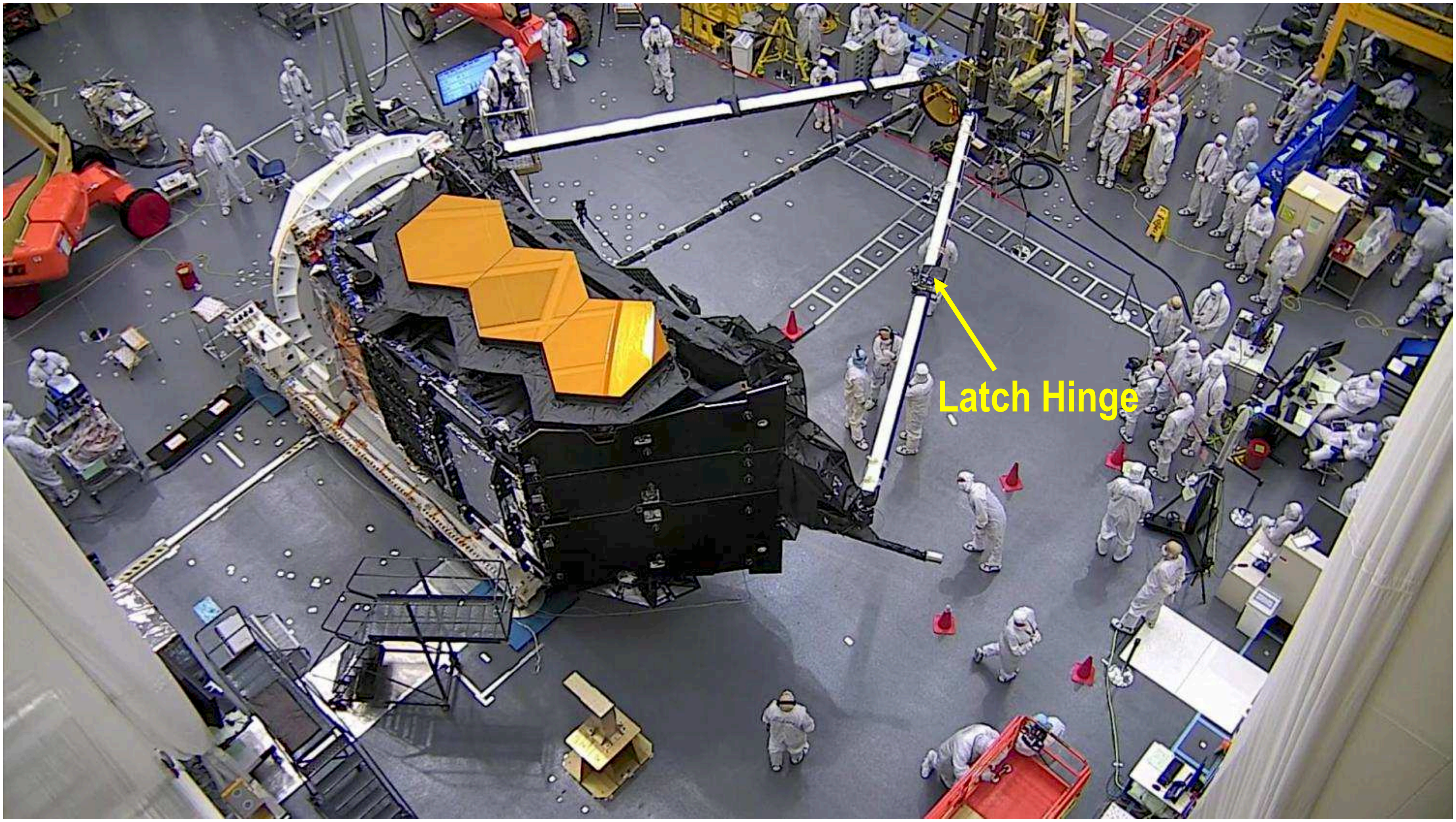
July 2019: Full 1-G deployment of JWST secondary mirror (SM) .

SMSS Deployment Sequence (2)



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

SMSS Deployment Sequence (3)



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

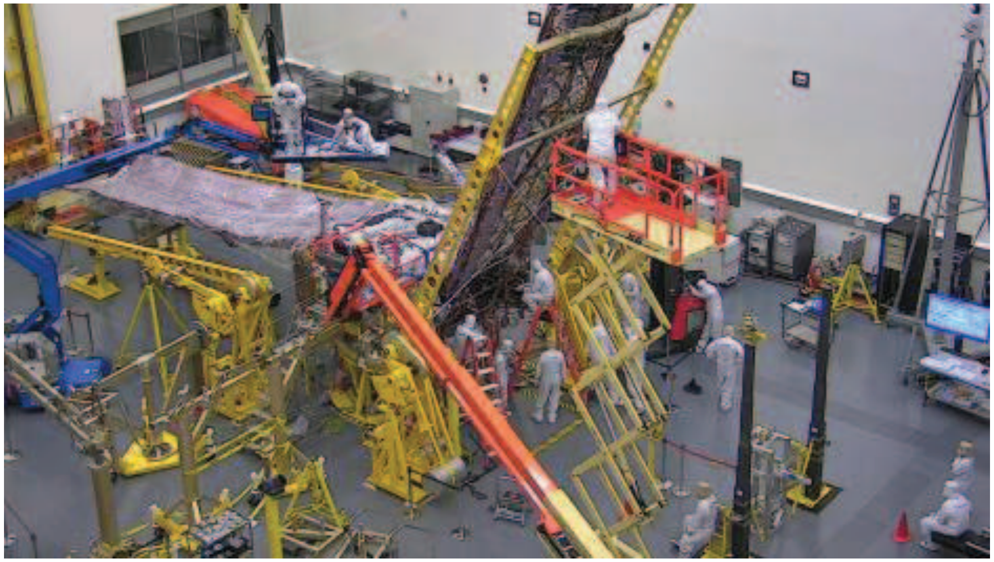
JWST in enclosure at Johnson Space Center in Houston.

Program Update: OTIS

NORTHROP GRUMMAN

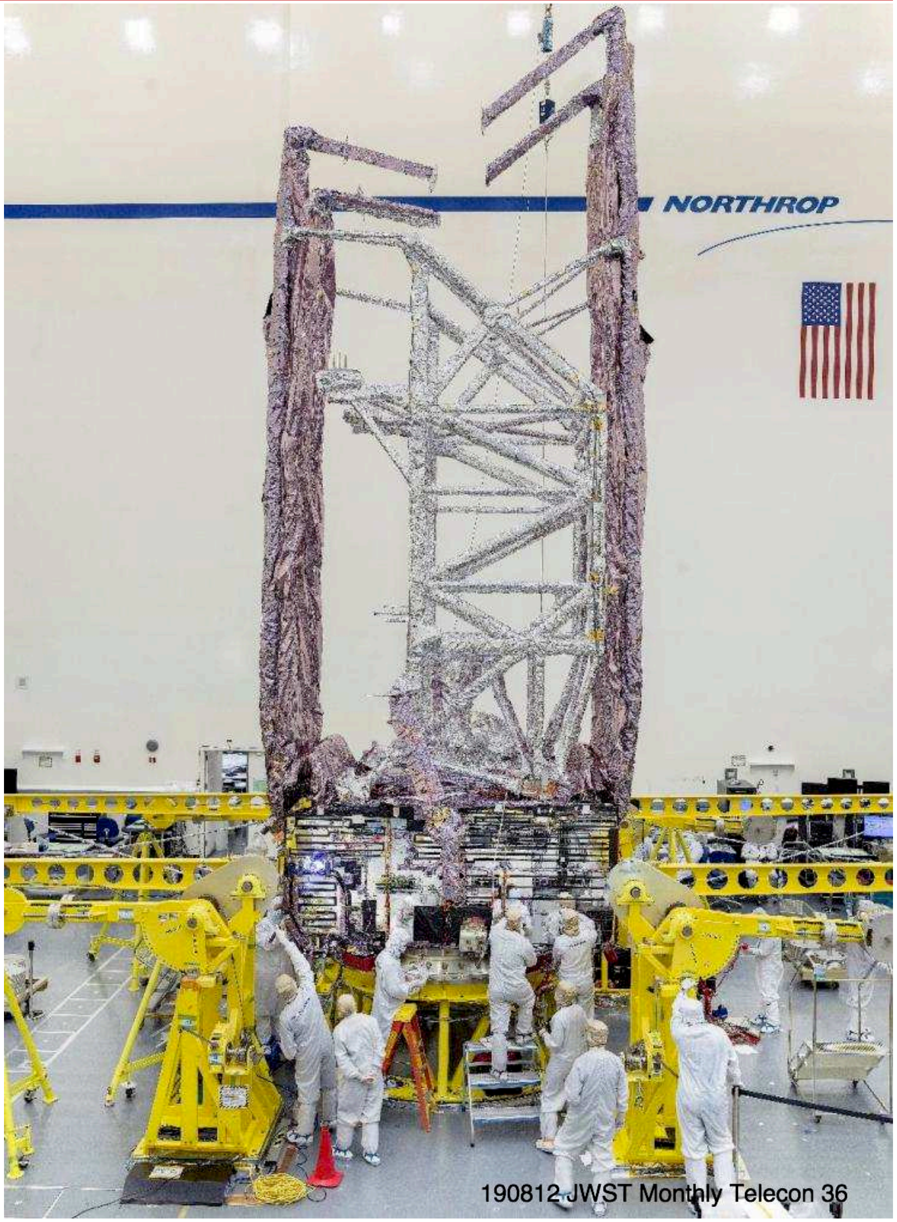
JWST going into Chamber A at Johnson Space Center in Houston.

Program Updates: Spacecraft and Sunshield



JWST Flight Sunshield assembled and tested at Northrop.

SCE to Elephant Stand

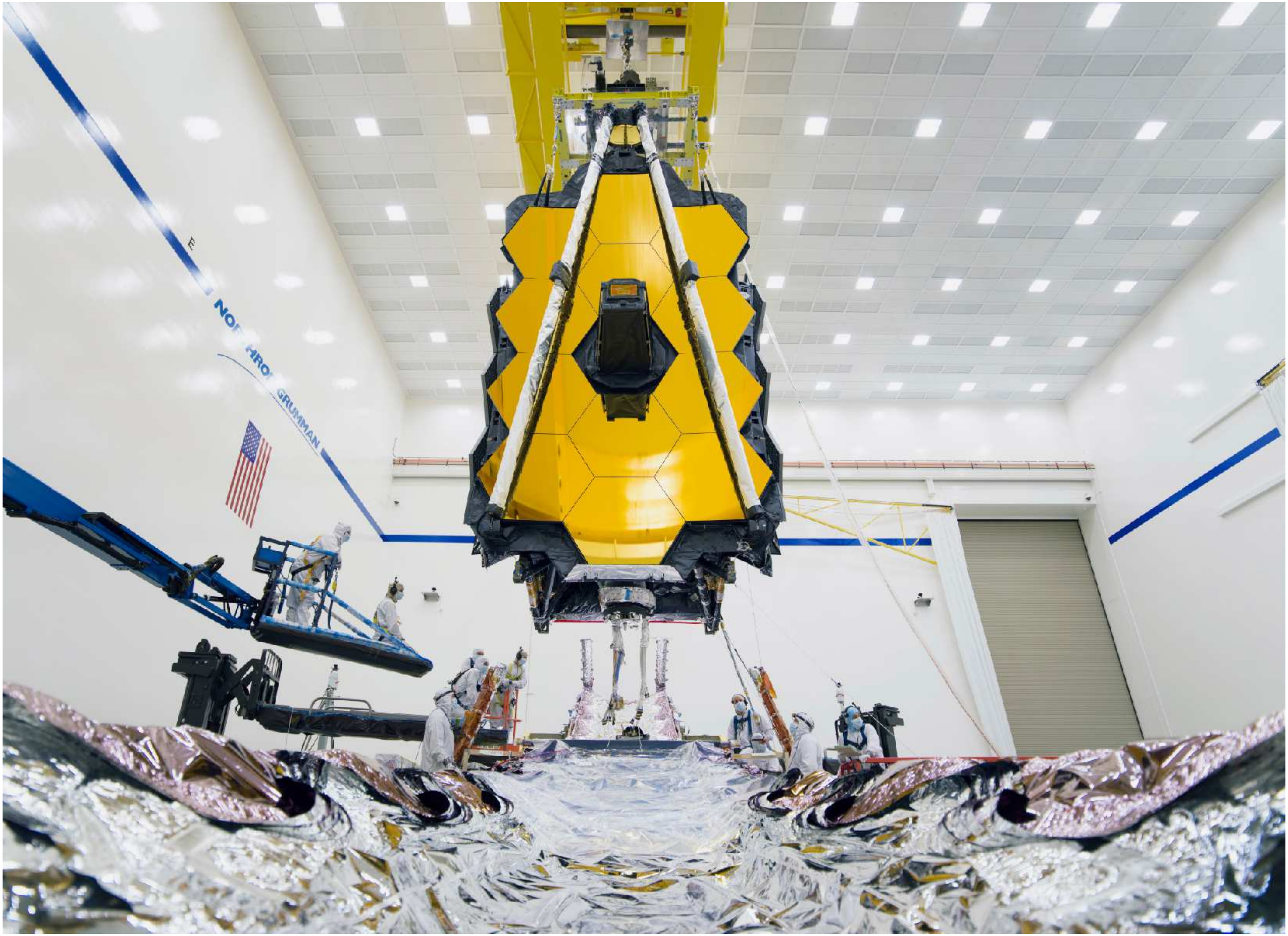


Aug. 2019: Stowed flight sunshield before integration with JWST OTE.

SMSS Deployment

NORTHROP GRUMMAN

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

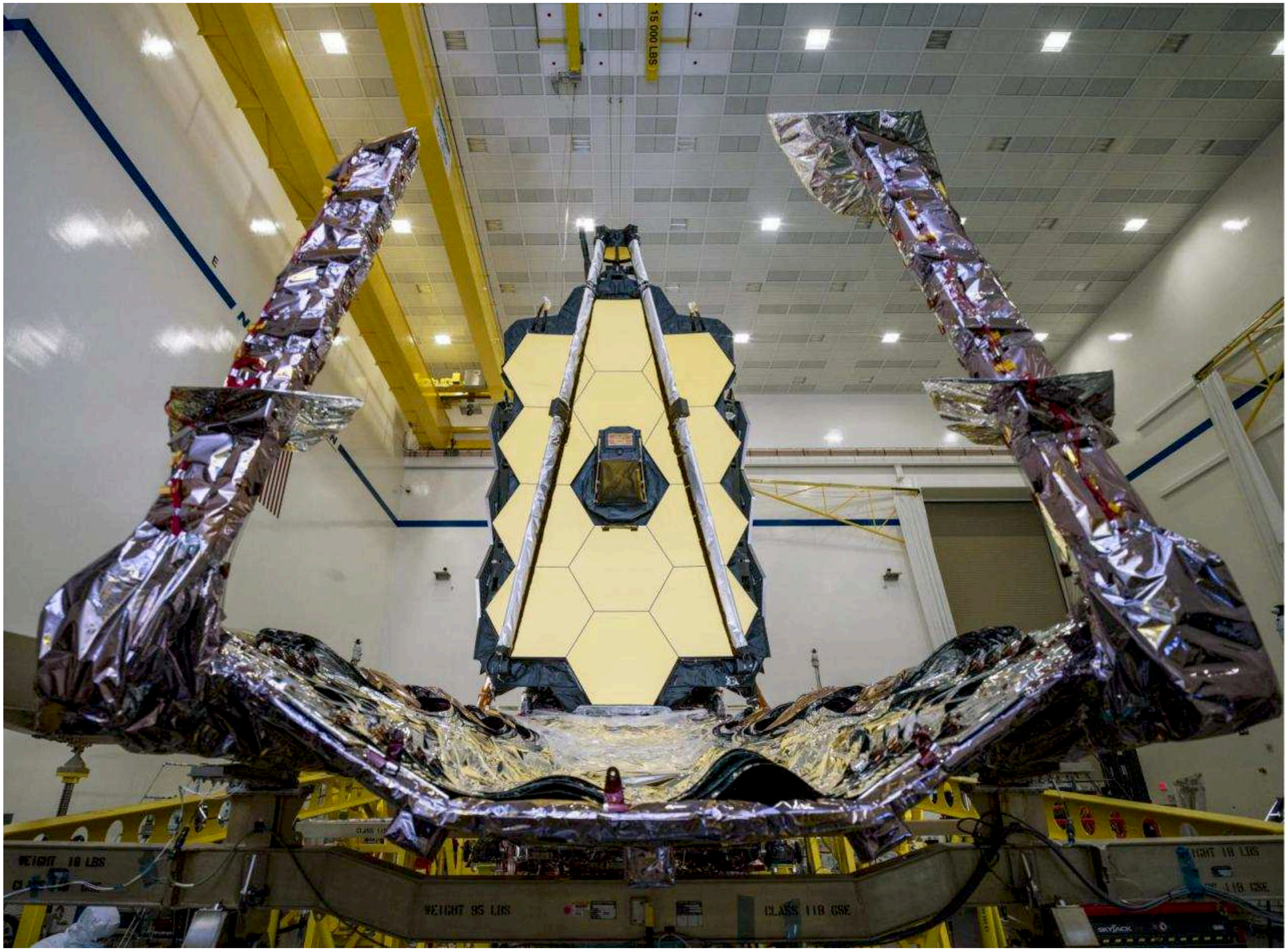


August 2019: JWST OTE+ISIM lowered into Sunshield+Spacecraft

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

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

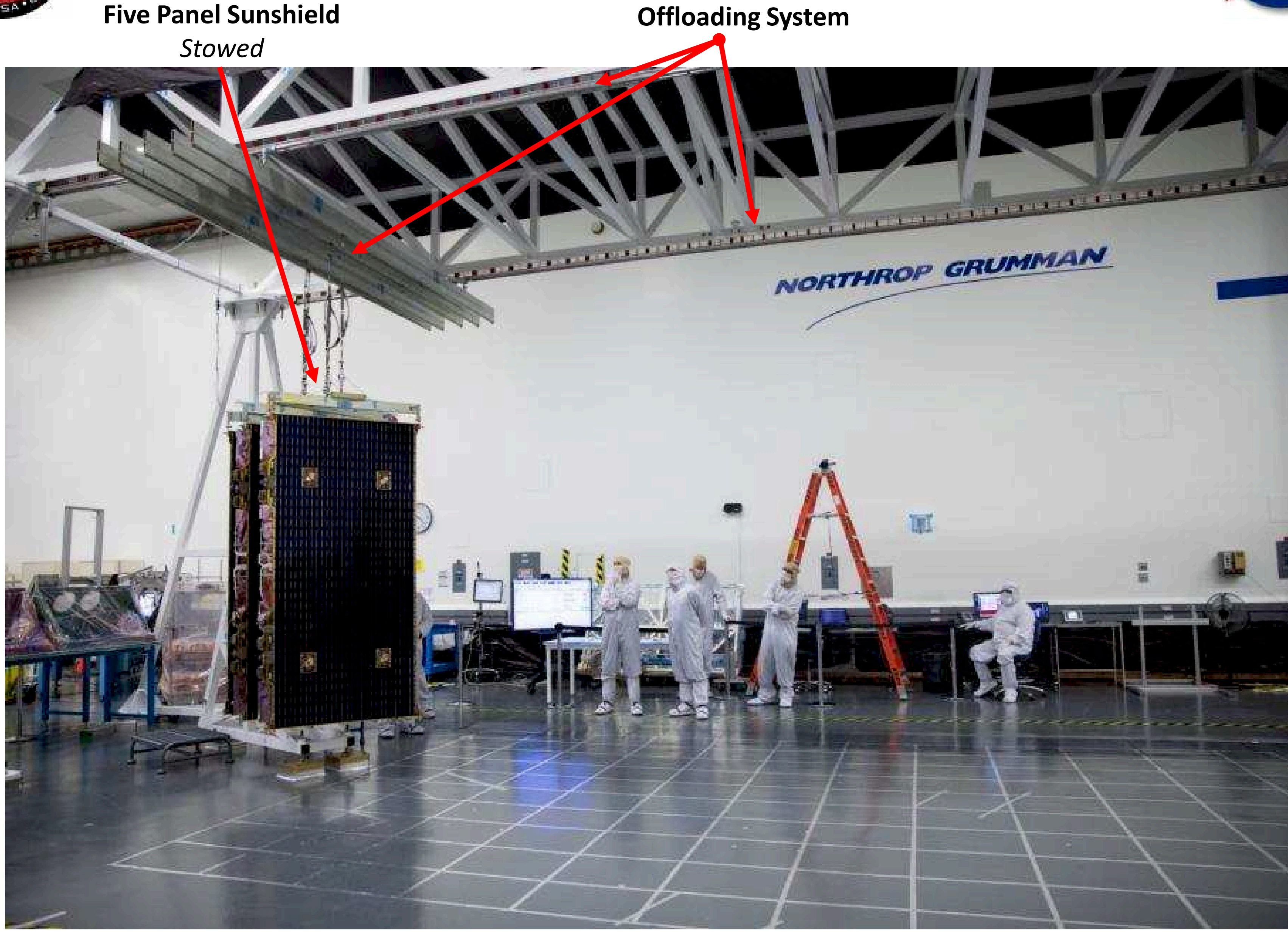
Meet the JWST Observatory 1



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

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

Solar Array Deployment 1



May 2020: Ready for Solar Array deployment test

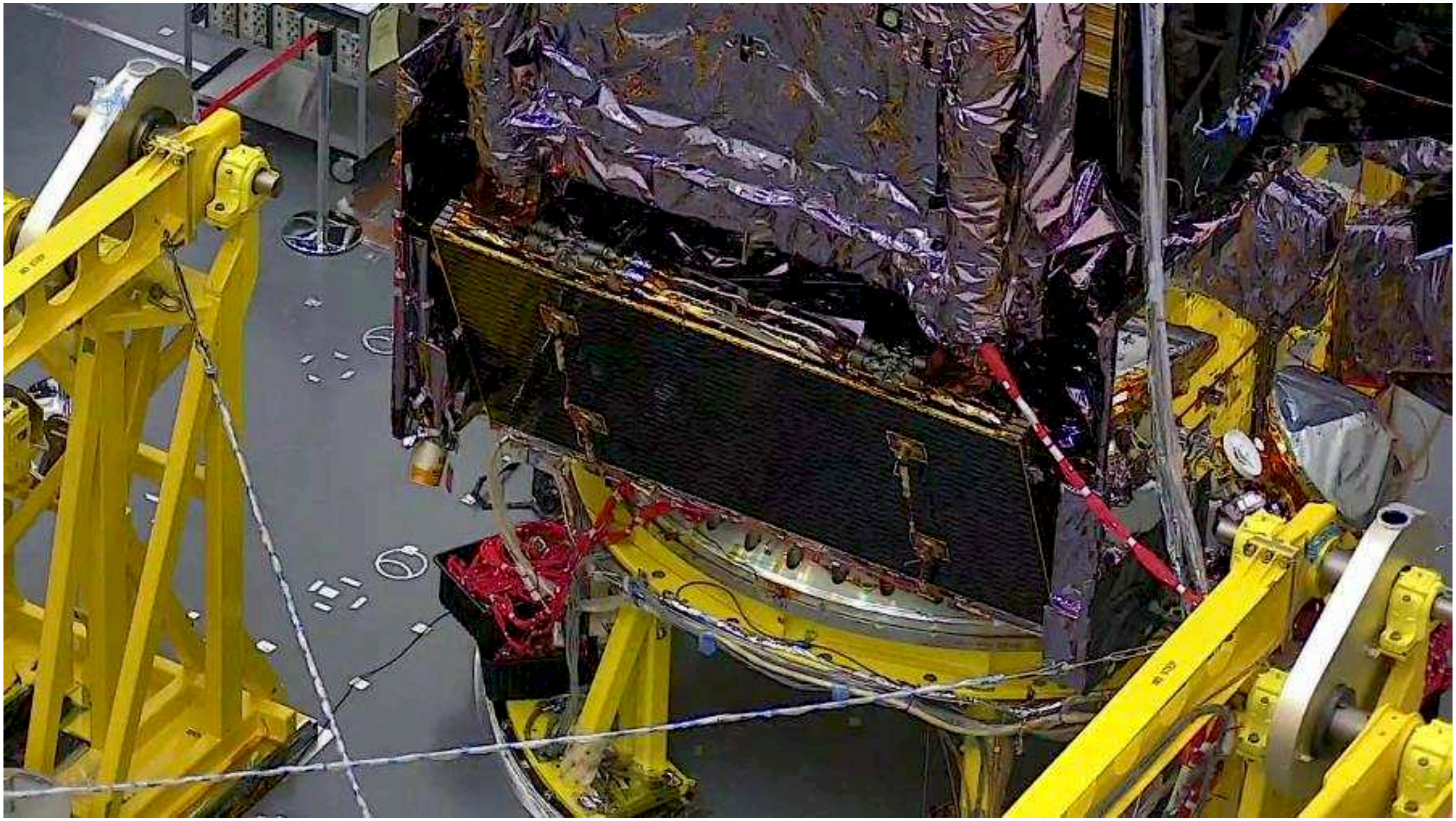
Solar Array Deployment 2

May 2020: Solar Array deployment with gravity off-loading

Solar Array Deployment 3

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

7/26/20: Solar Array Installed for Environments

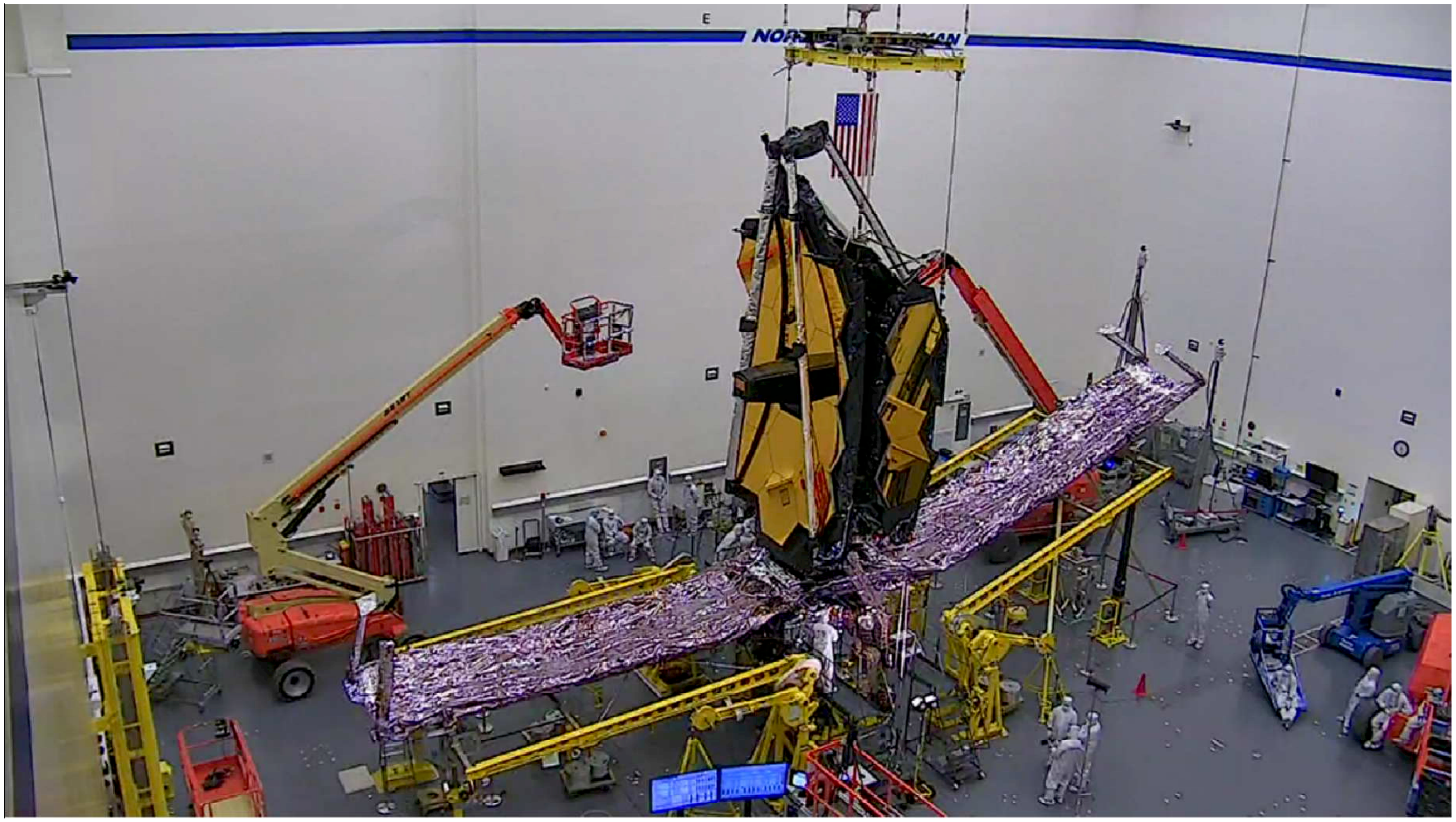


May 2020: Solar Array as installed on JWST Observatory

5/28/20: DTA Deployment

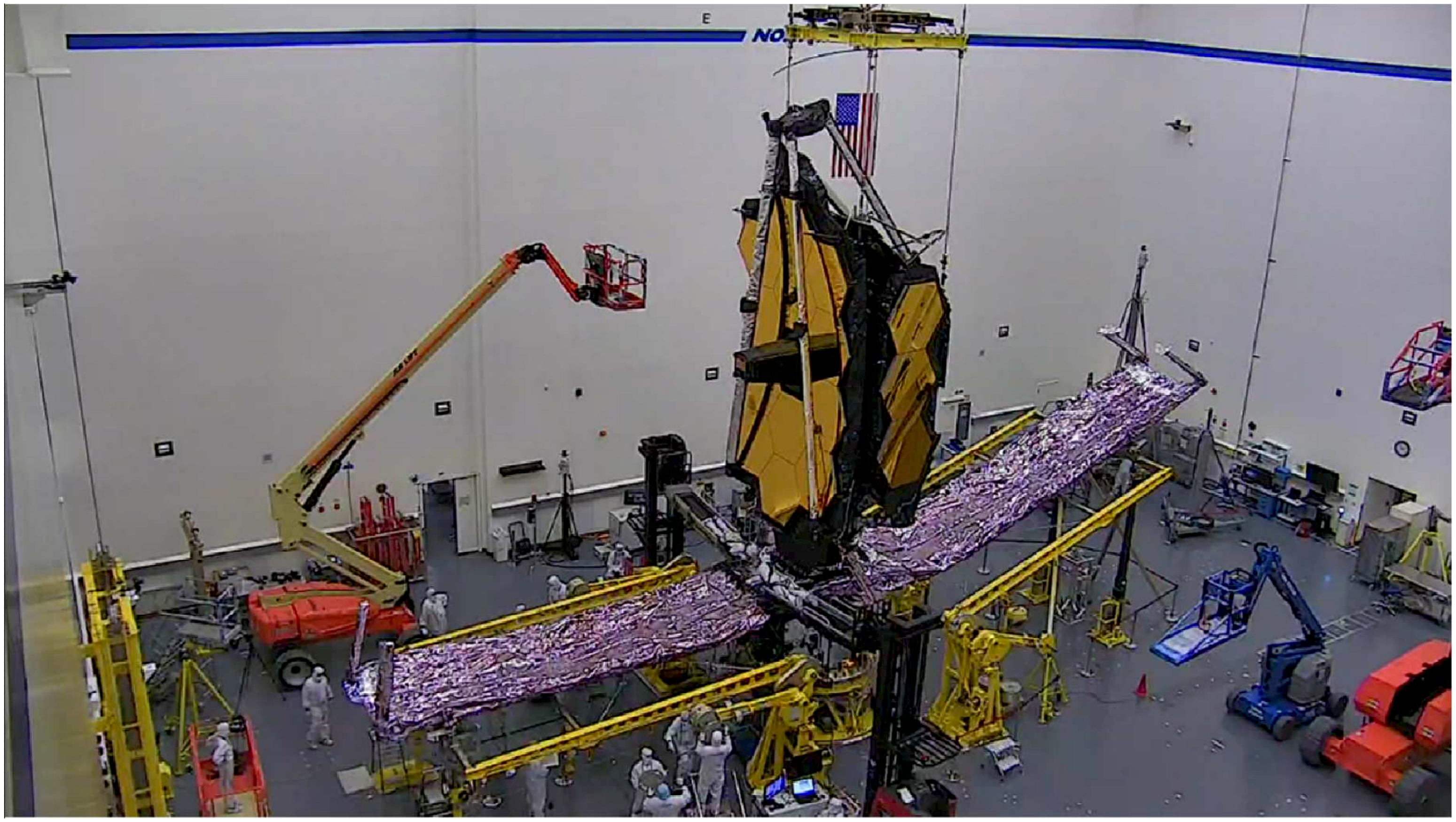
June 2020: Deployable Tower Assembly test

5/28/20: DTA Deployment



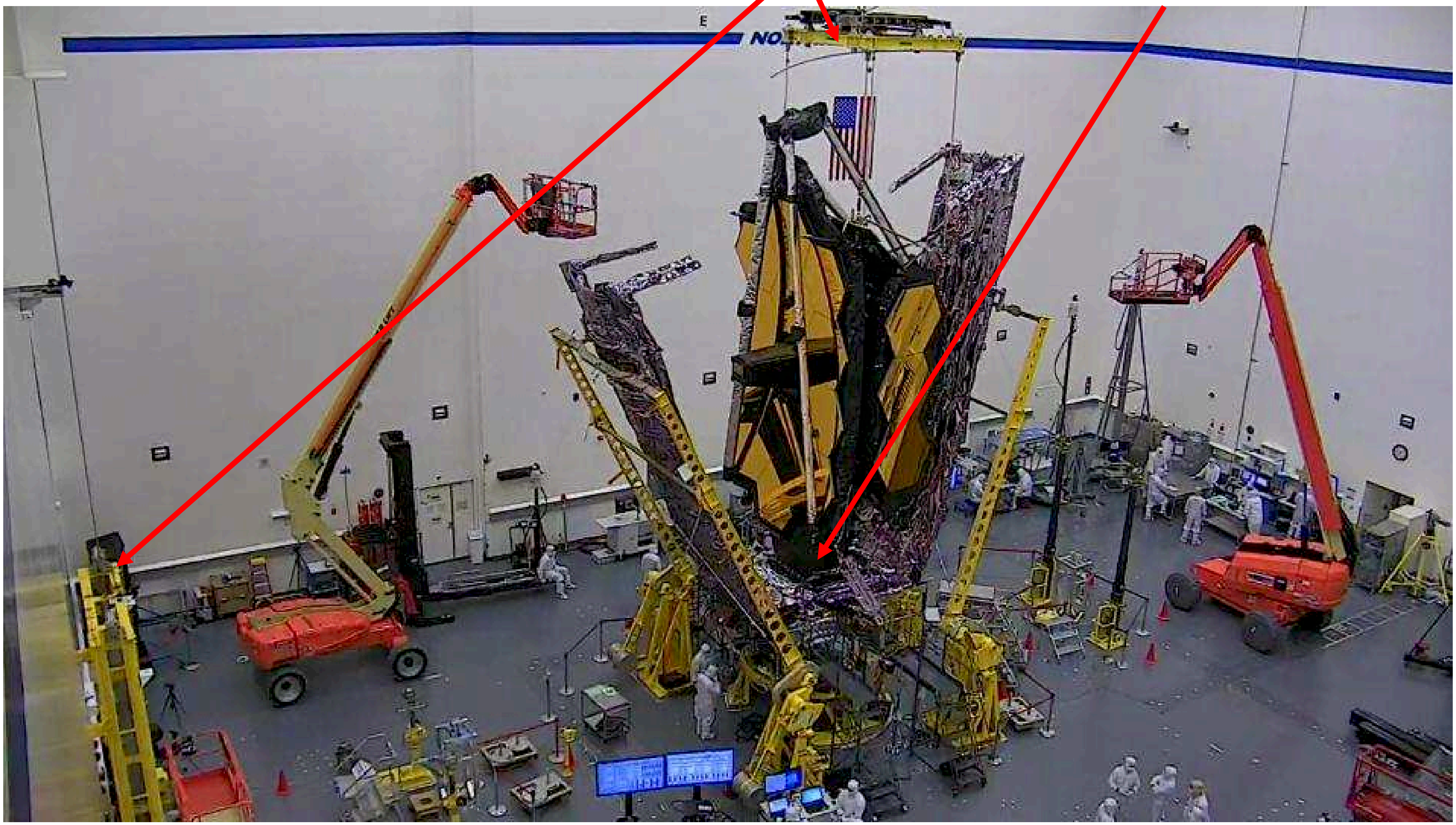
June 2020: Deployable Tower Assembly test with gravity off-loading.

5/29/20: DTA Deployment



June 2020: Deployable Tower Assembly motor tested in 1G

DTA Stow 1



July 2020: Deployable Tower Assembly stow for launch

DTA Stow 2

July 2020: Deployable Tower Assembly stowed for launch

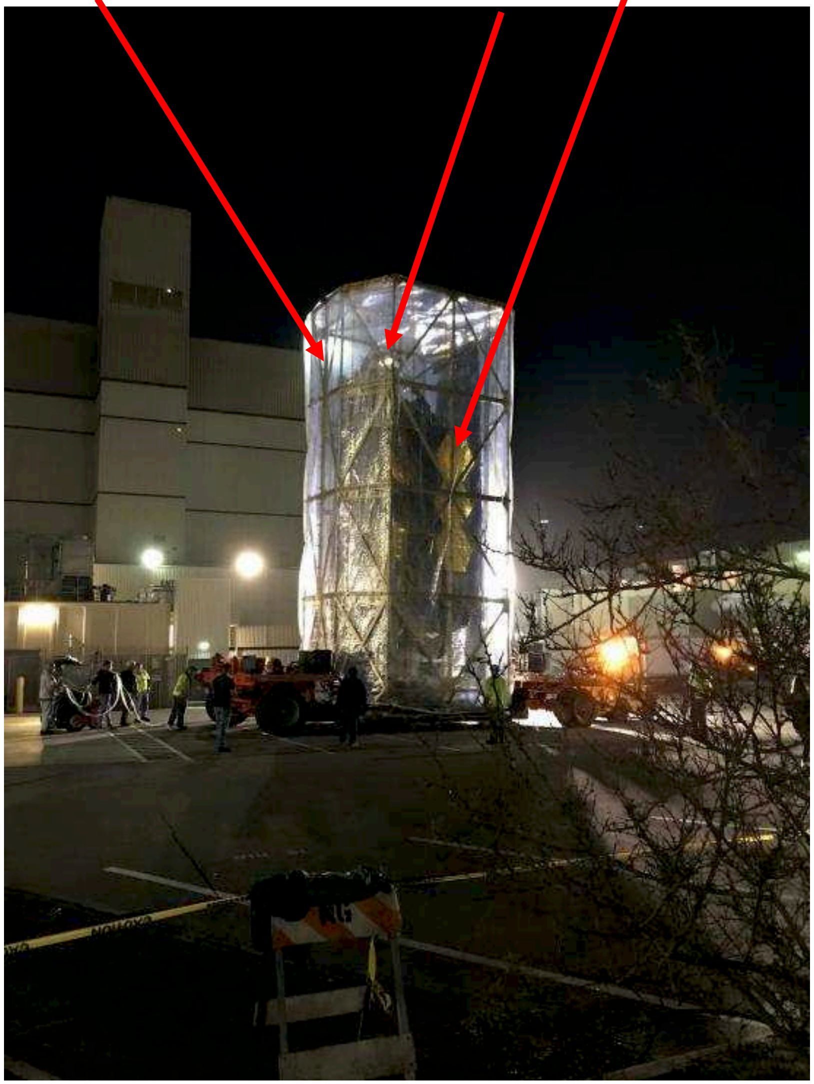
Aft UPS Stow 1

July 2020: Aft UPS stow for launch

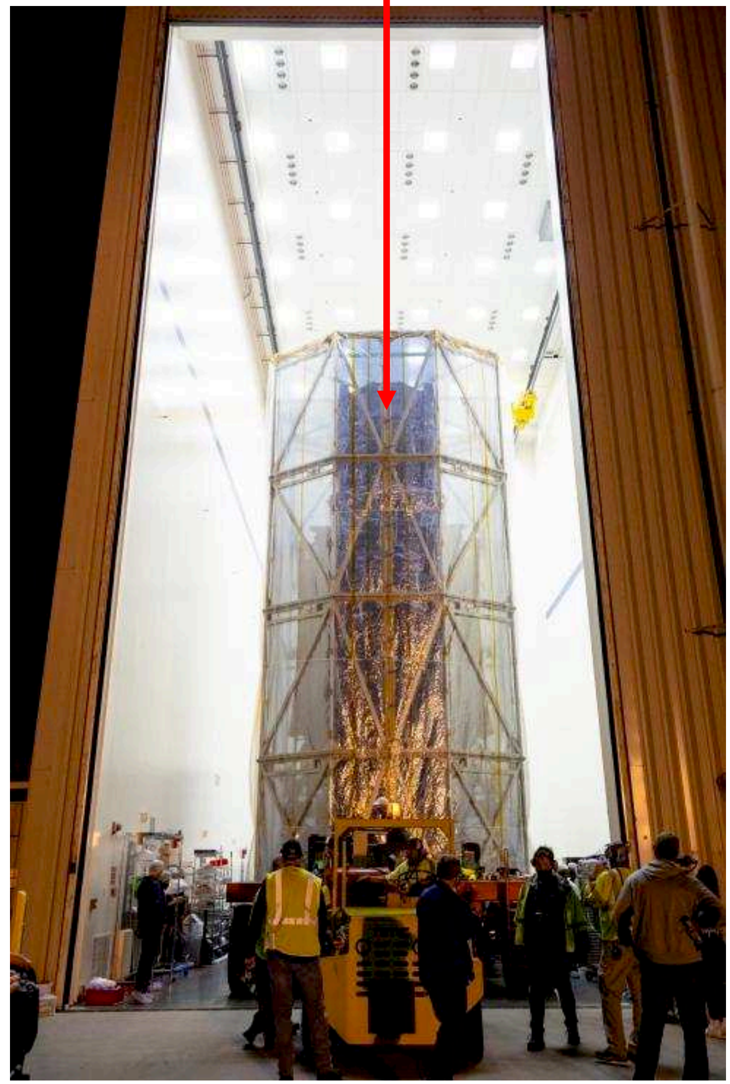
Aft UPS Stow 2

Fall 2020: Aft UPS stowed for launch

Transport to the Large Acoustic Test Facility



En route through the Space Park, Credit: NGSS

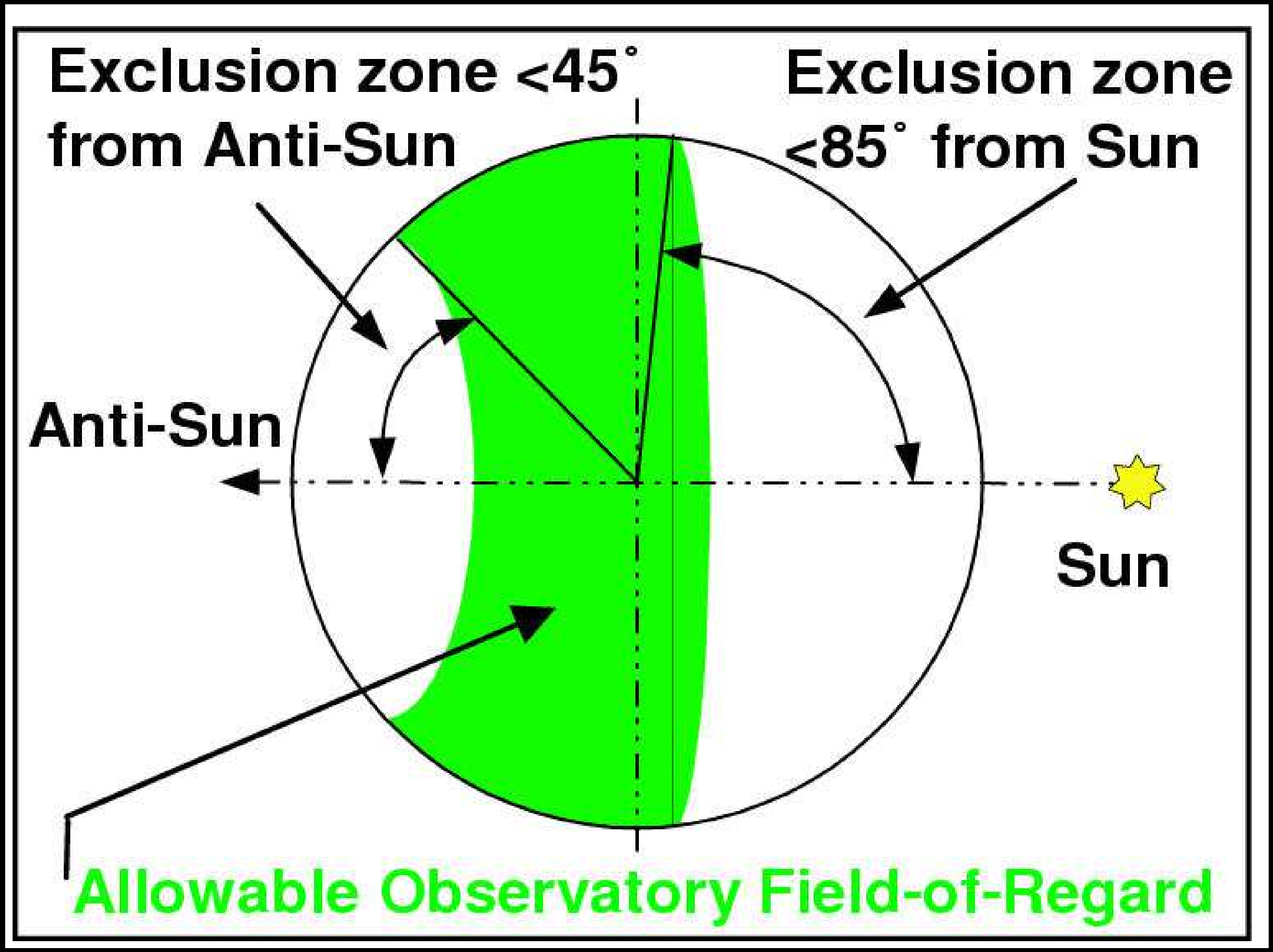


Arriving at the LATF Airlock, Credit: NGSS

Aug 2020: Transport of JWST into Northrop acoustic chamber

Oct. 5, 2020: JWST acoustic tests completed without (further) hick ups!

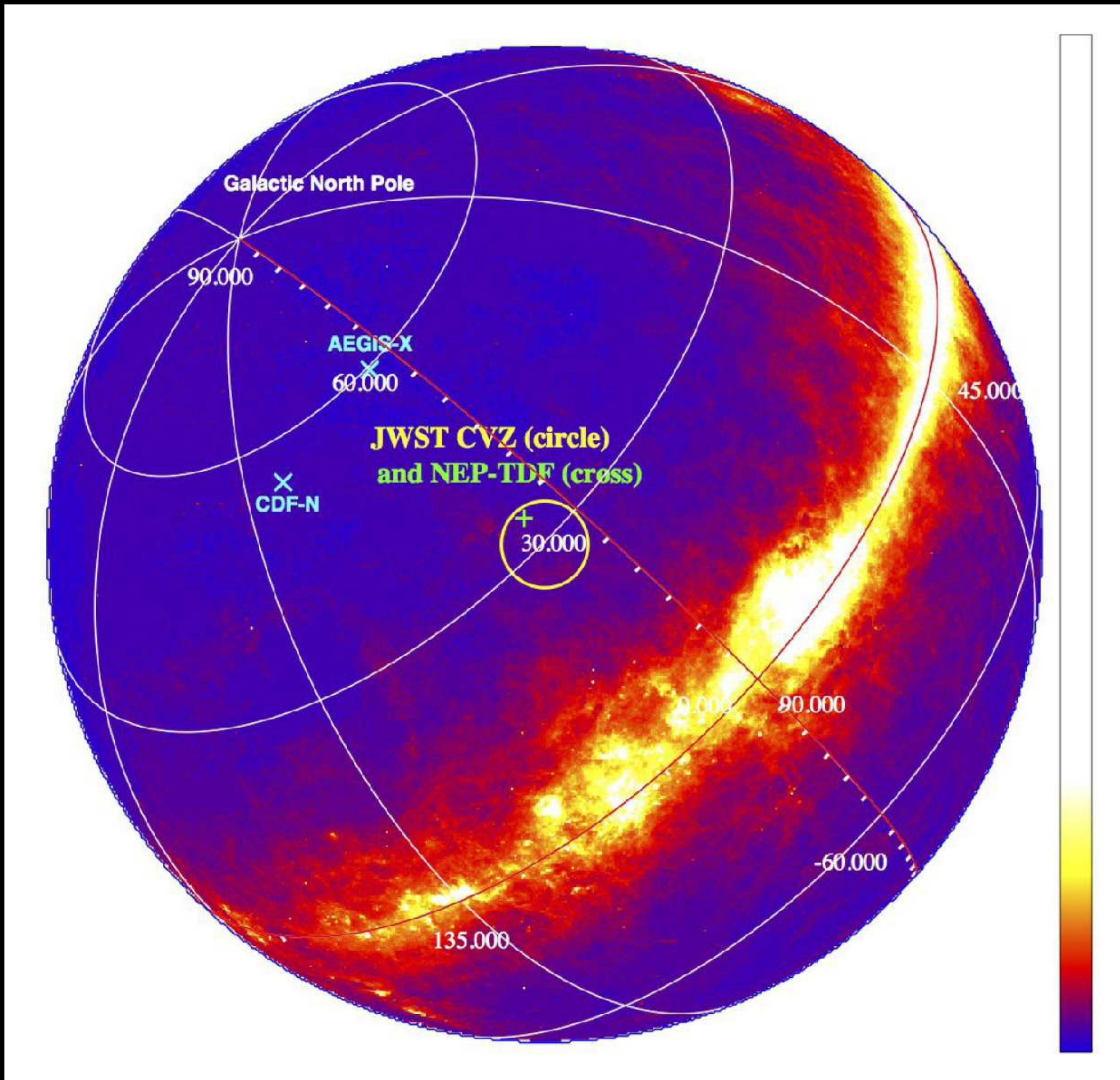
(2) JWST Continuous Viewing Zones (CVZs): North & South Ecliptic Poles.



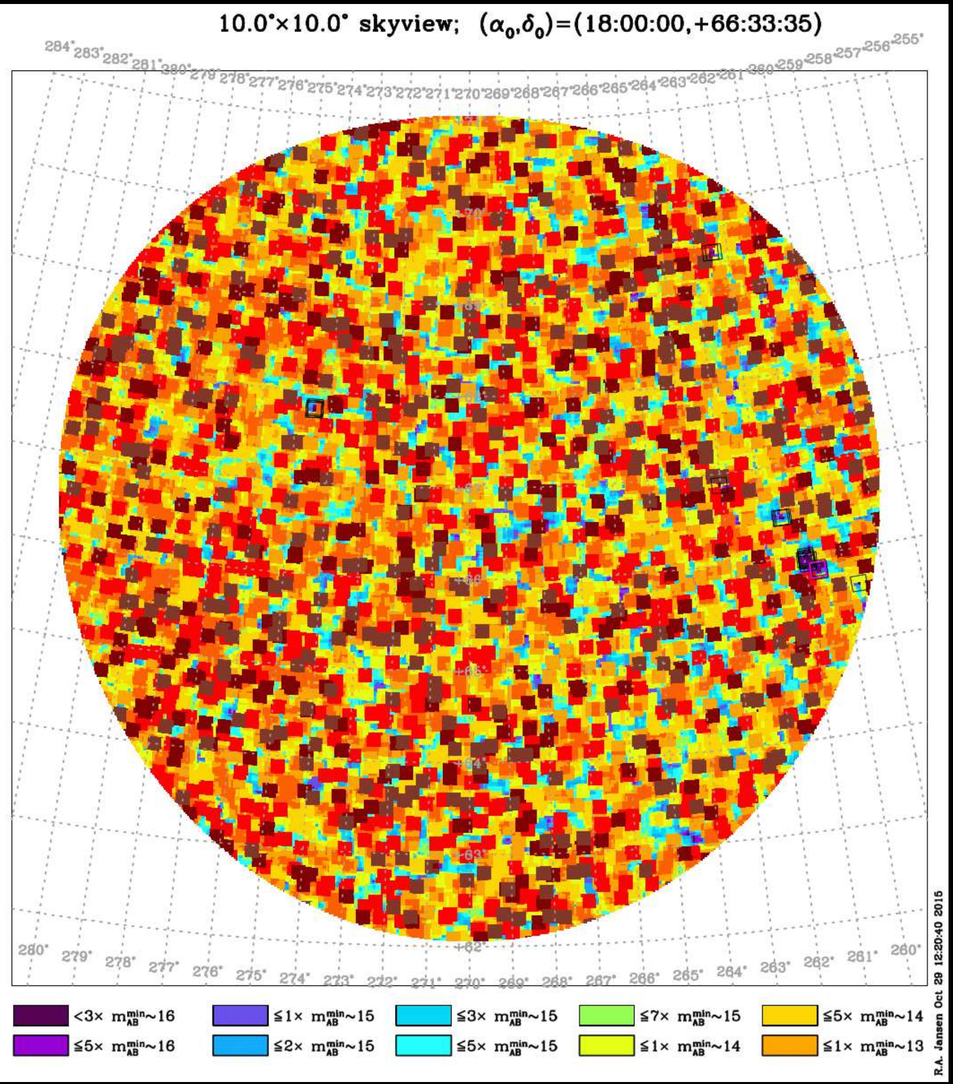
Accessible by JWST 365 days/yr: *only* the NEP & SEP CVZ (r $\lesssim 5^{\circ}$):

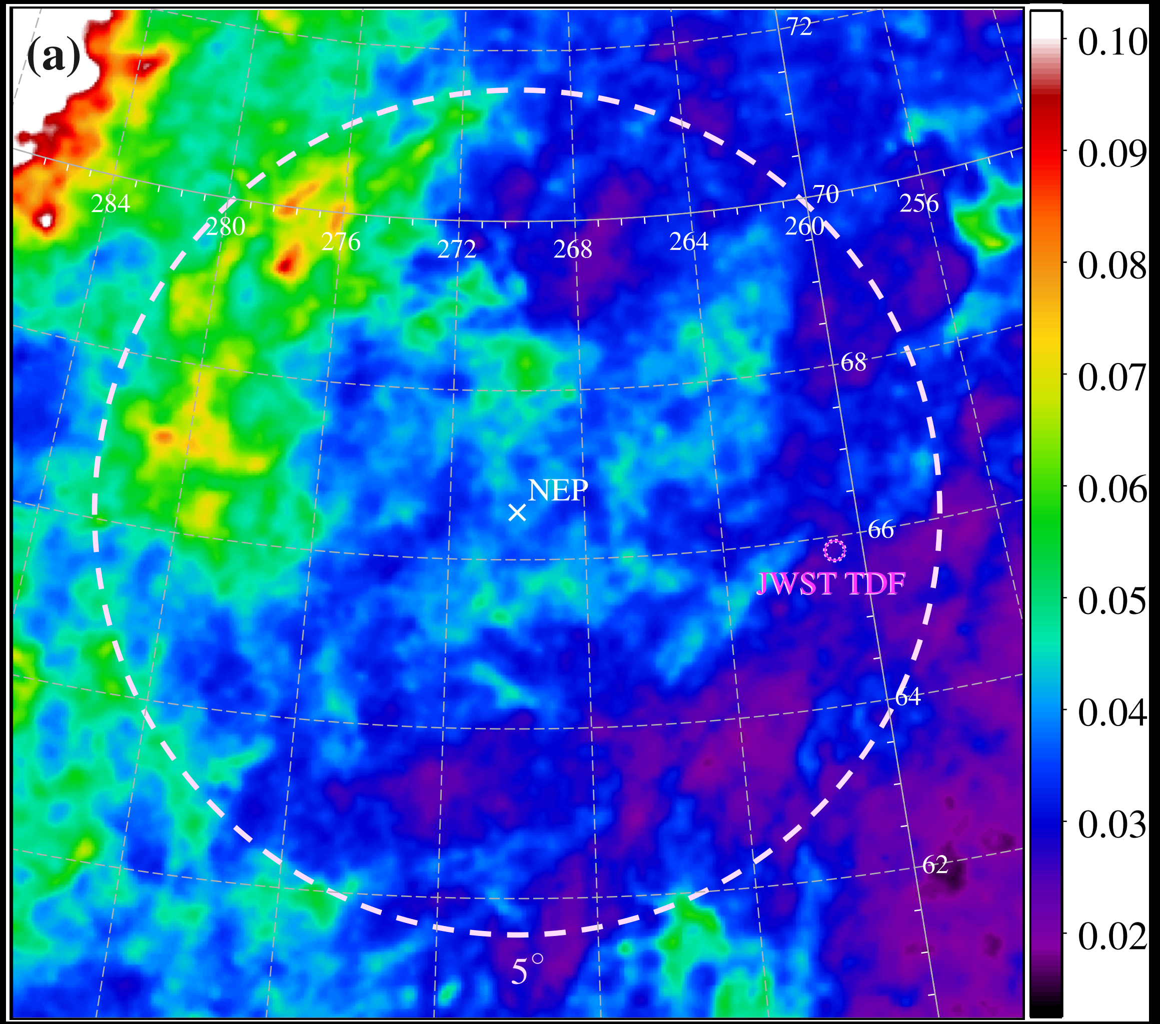
- NEP has great regions for far-extragalactic science. SEP contains LMC.
- CVZs great for parallax, proper motions, high redshift variability, etc.
- JWST NEP survey also provides multi-ORIENT grism spectral separation.

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



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



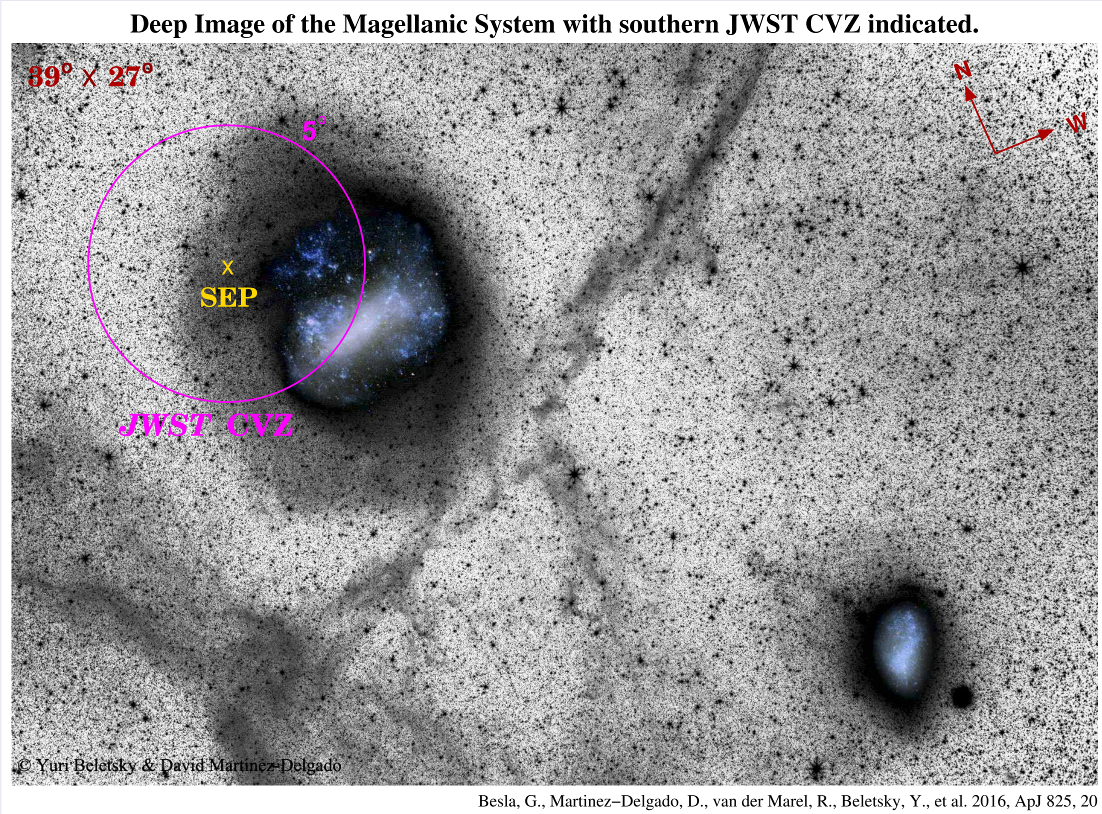


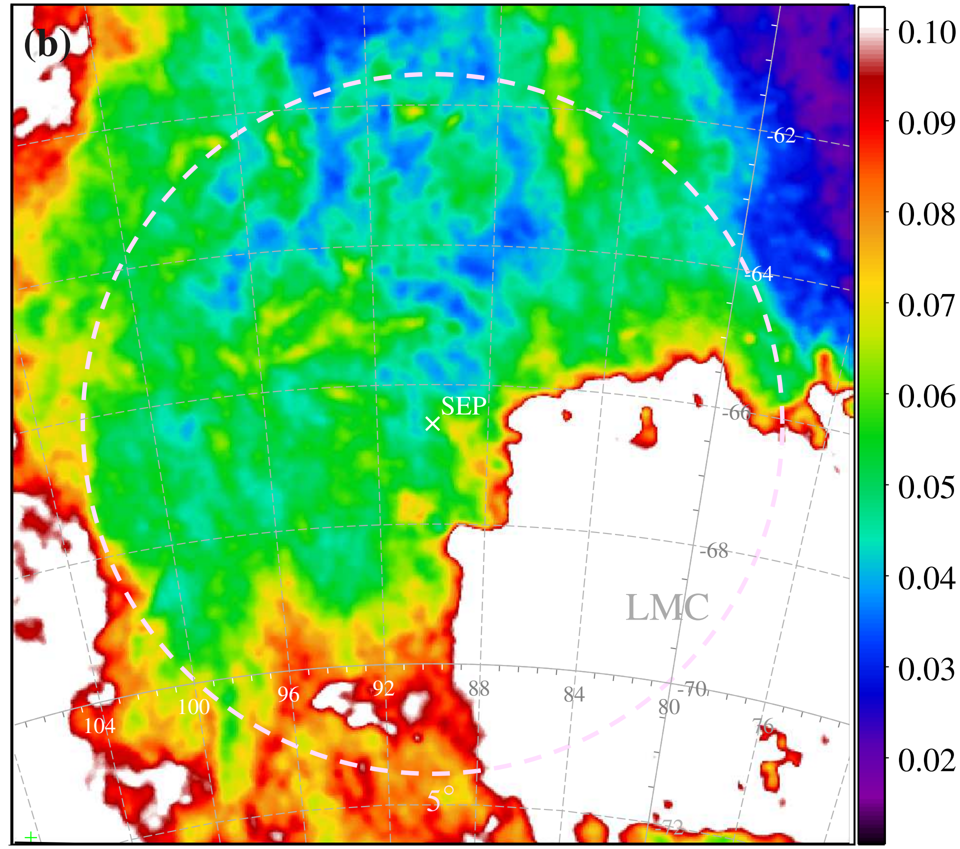
[LEFT]: *WISE* 4μm bright star density: Very few regions (purple) without bright stars (AB$\lesssim$16) to minimize persistence in JWST images

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

[RIGHT]: *E(B−V)* map (Schlegel+ 1998) in same NEP-region ($b^{II}\simeq$33°).

Cleanest r=7′ region for JWST has modest extinction: $E(B-V)\lesssim 0.028^m$.

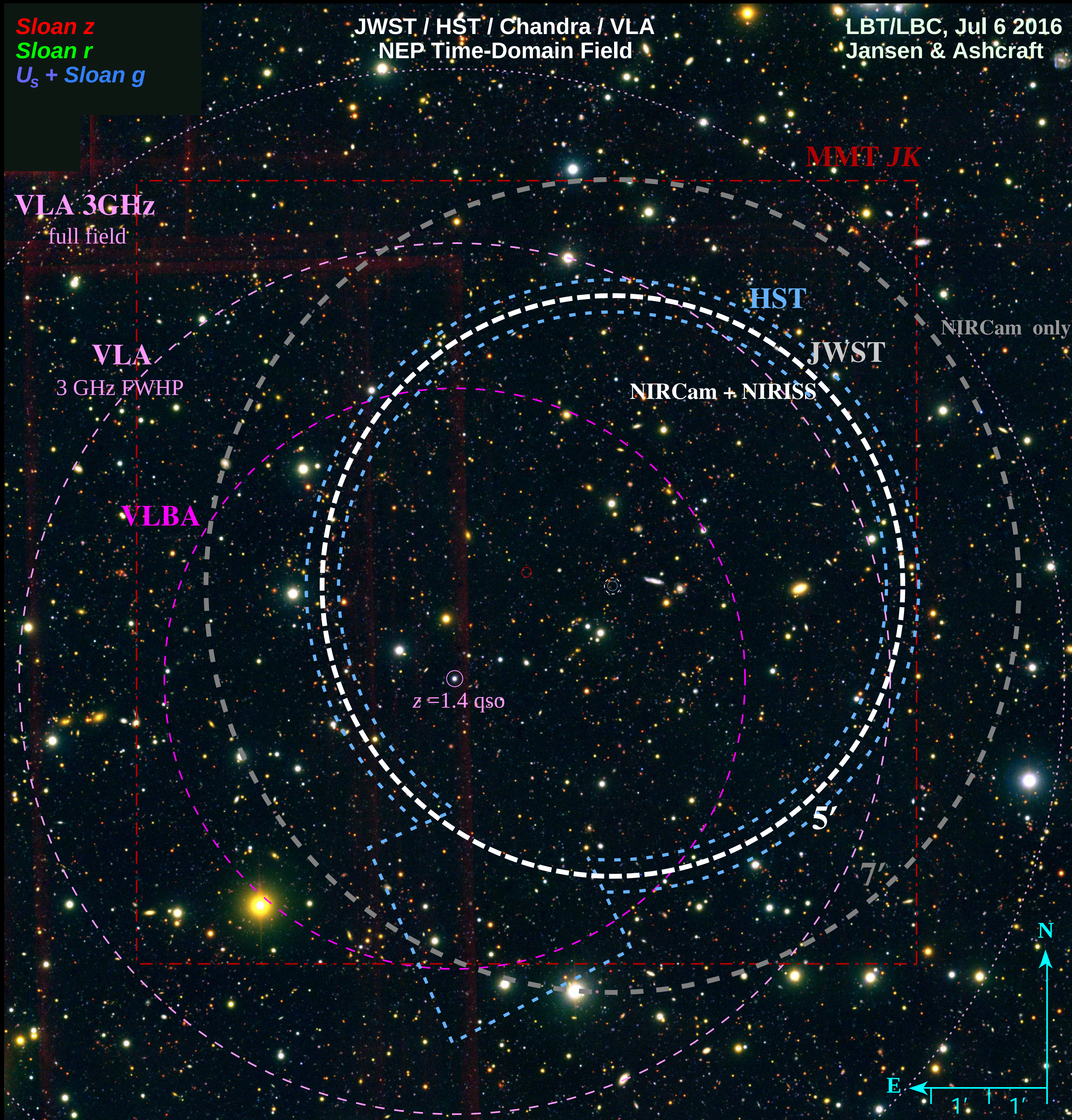




[LEFT] Map of LMC+SMC (Besla et al. 2016, ApJ, 825, 20).

[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.



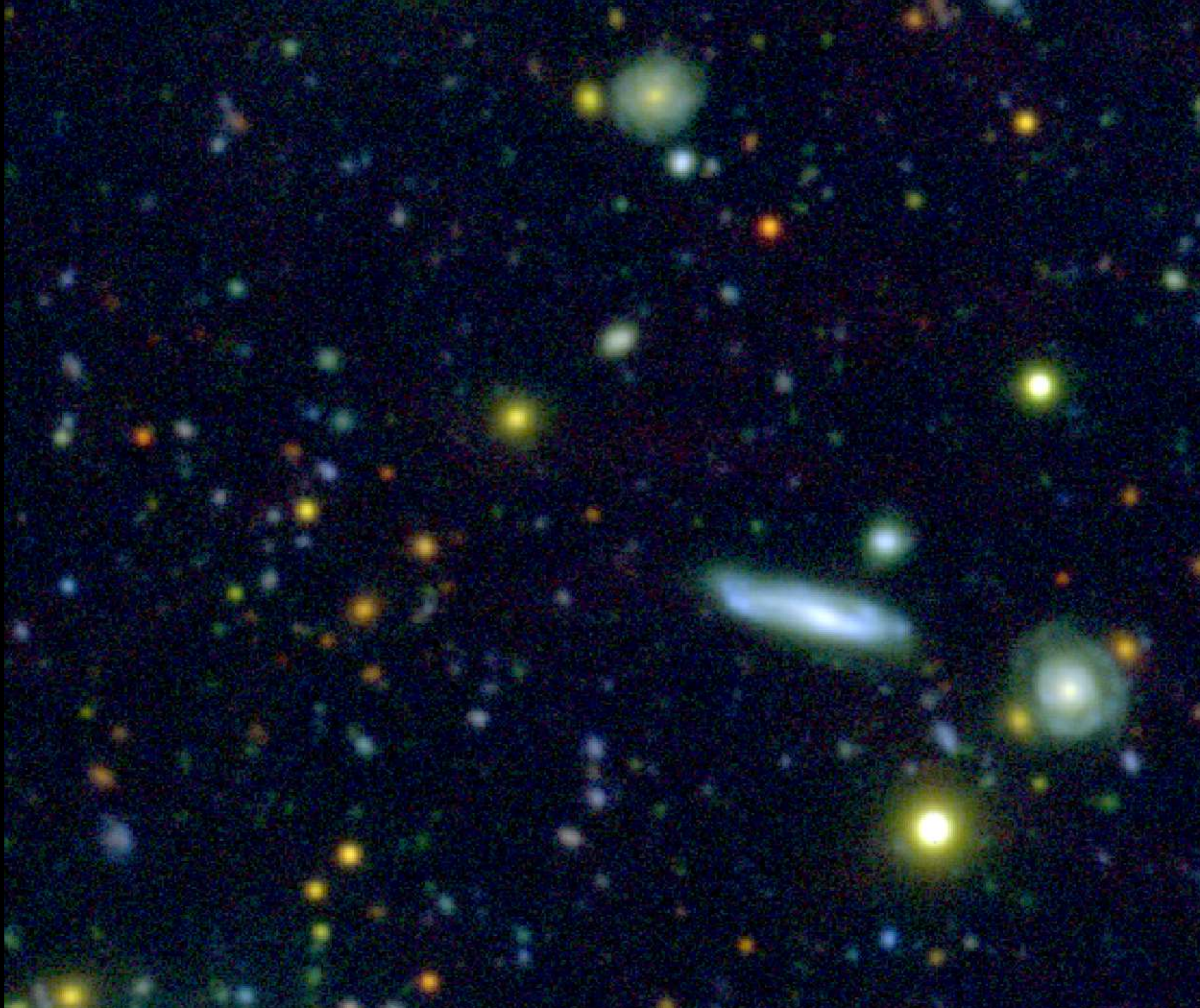
r=7′ JWST NEP Time-Domain Field is free of bright (AB≲16) stars.

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

Telescope	PI	Status	Depth
NuSTAR 3–24 keV	F. Civano	approved	585 ks; $>$50 cts
Chandra/ACIS-I 0.2–10 keV	W.P. Maksym	in hand; 145 sources	300 ks; $\sim$4.1$\times$10^{-16} cgs
”	”	in progress / approved	240 ks / 360 ks
XMM-Newton 0.5–2.0 keV	M. Ward / N. Cappelluti	proposed	600 ks; 3$\times$10^{-16} cgs
HST/WFC3+ACS *F275W,F435W,F606W*	R.A. Jansen	in hand; inner $r<5'$ only GO 15278	36 CVZ orbits; $m\sim$ 27.2, 28.2, 29 mag
”	”	proposed; annulus to $r\sim$14.2$'$	52 CVZ orbits
LBT/LBC $U_{\rm sp}$*grz*	R.A. Jansen	in hand; wide-field	5 hrs; $m\sim$26.5–25.5 mag
”	”	in hand; 2nd epoch + *i*	5 hrs; $m\sim$26.5 mag
Subaru/HSC *giz*,nb816,nb921	G. Hasinger / E. Hu	in hand; wide-field	5 hrs; $m\sim$25.5–25.1 mag
GTC/HiPERCAM *ugriz*	V. Dhillon	proposed; narrow-field	33 hrs; $m\sim$28 mag
TESS (0.6–1.0μm bandpass)	G. Berriman & B. Holwerda	in progress; ultra wide-field	357 days; low-SB (tbd)
MMT/MMIRS (img) *YJHK*$_s$	C.N.A. Willmer	in hand	60 hrs; $m\sim$23–24
JWST/NIRCam+NIRISS 0.8–5 μm + 1.75–2.23 μm	R.A. Windhorst / H.B. Hammel	*guaranteed time* GTO #1176, #1255	$\sim$49 hrs total; $m<$29–28.5 mag
JCMT/SCUBA-2 850μm	I. Smail / M. Im	in progress; $\geq$59 sources	31 hrs; rms$\sim$1 mJy
SMA 0.87 mm	G. Fazio	approved pilot; lost to protests	37.5 hrs; rms$\sim$0.9 mJy
IRAM/Nika2 1.2, 2 mm	S.H. Cohen	in progress	30 hrs; rms$\sim$2 mJy
VLA 3(2–4) GHz	R.A. Windhorst / W. Cotton	in hand; $\sim$2500 sources	47 hrs; rms$\sim$0.9 μJy
VLBA 4.7 GHz	W. Brisken	in hand; $\sim$200 targets	147 hrs; rms$\sim$3 μJy
LOFAR 150 MHz	R. van Weeren	approved	75 hrs; rms$\sim$25 μJy
J-PAS (56 narrow-band spectroph.)	S. Bonoli / R. Dupke	in hand; ultra-wide field	48 hrs; $m\sim$21.5–22.5 mag
MMT/Binospec (mos)	C.N.A. Willmer	in hand; 582 spectra/552 redshifts	18 hrs; $m\sim$22.5–24 mag
”	”	approved	8 hrs; $m\sim$22.5–24 mag
MMT/MMIRS (mos)	C.N.A. Willmer	approved	$m<$22, $z>$0.4

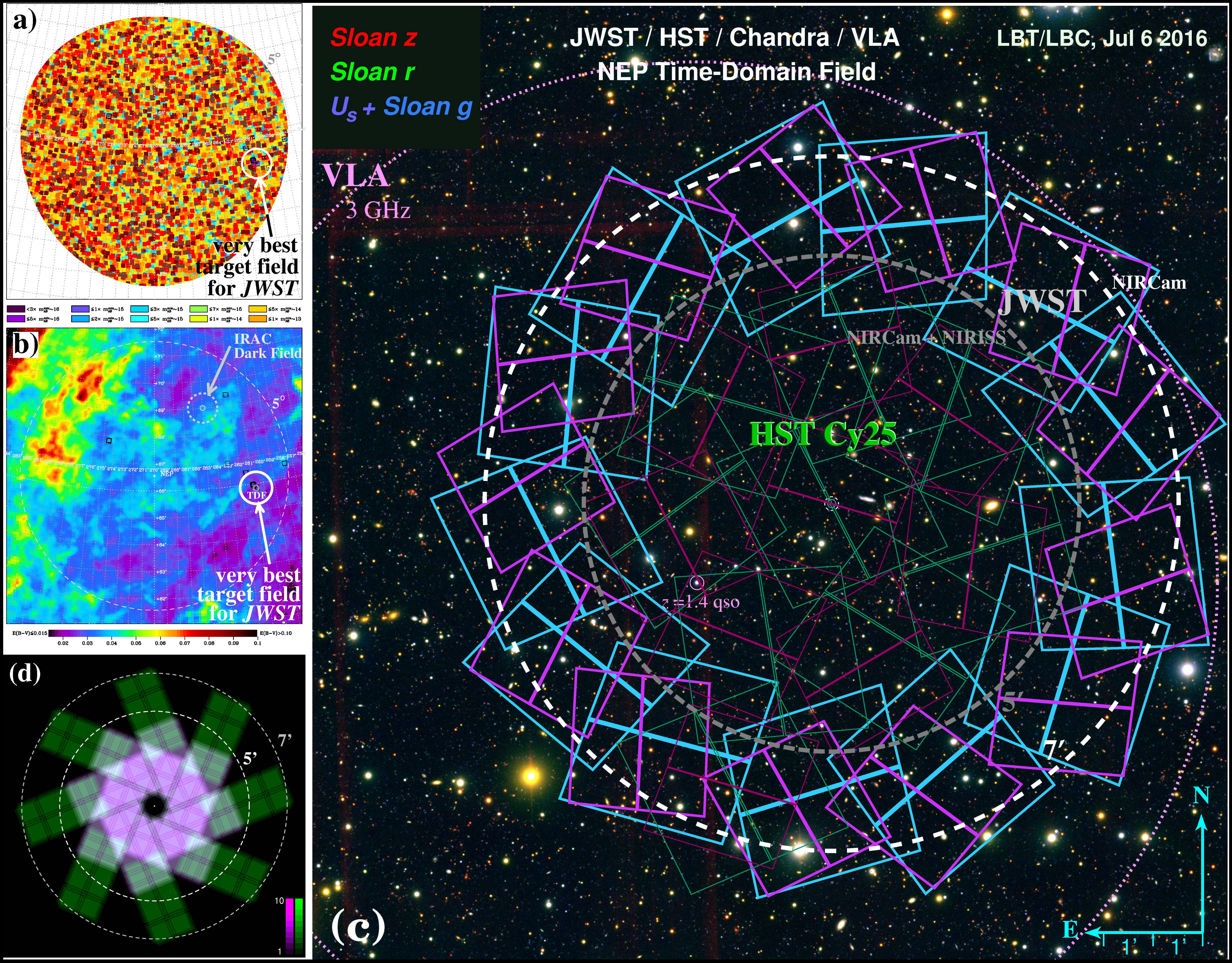
Panchromatic JWST NEP TDF data available or in progress as of 2020.

IDS GTO pgm focus on ground-based data supporting the JWST NEP TDF.

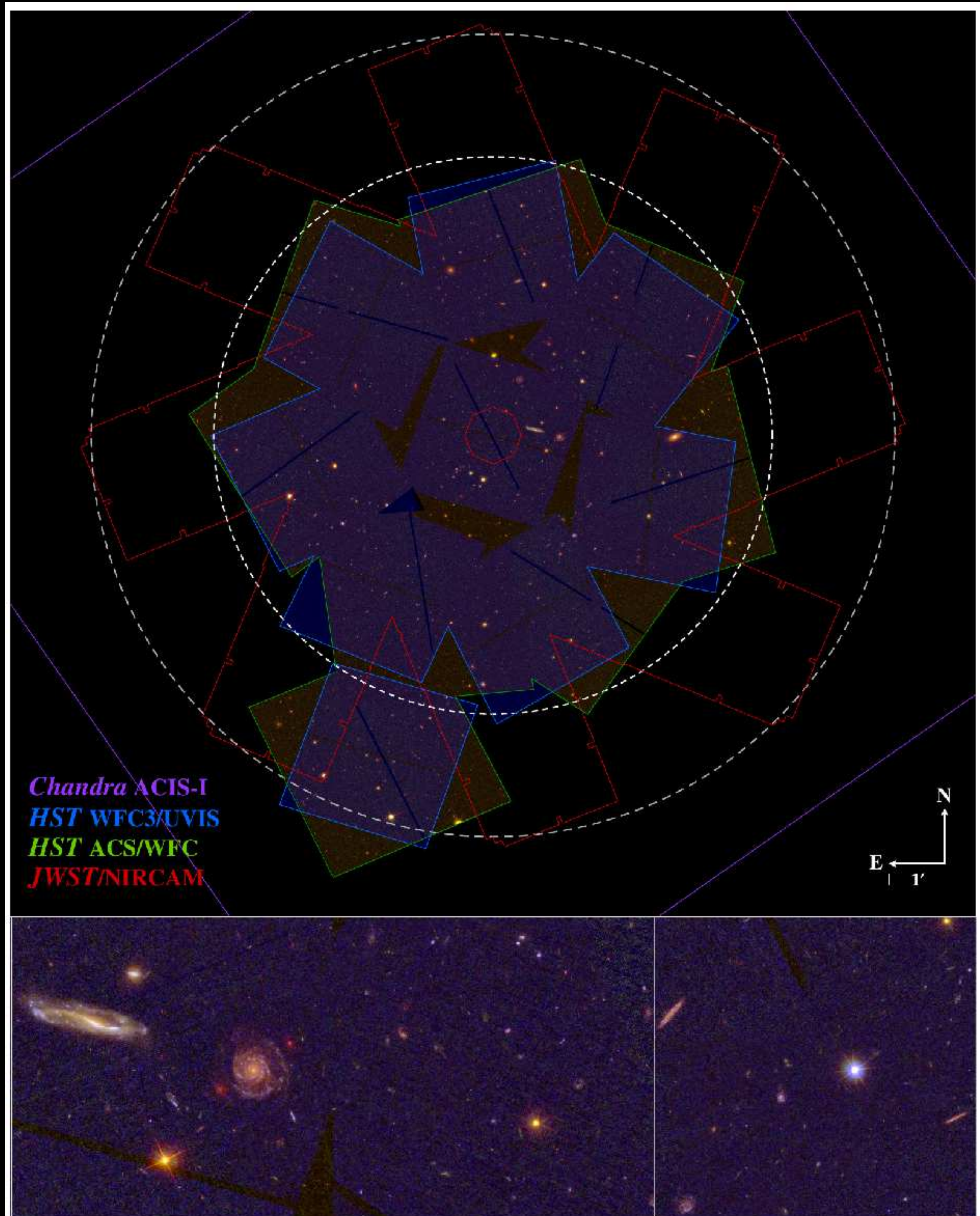


At r$\lesssim$7$'$, JWST NEP TDF is a clean extragalactic survey field (LBT).

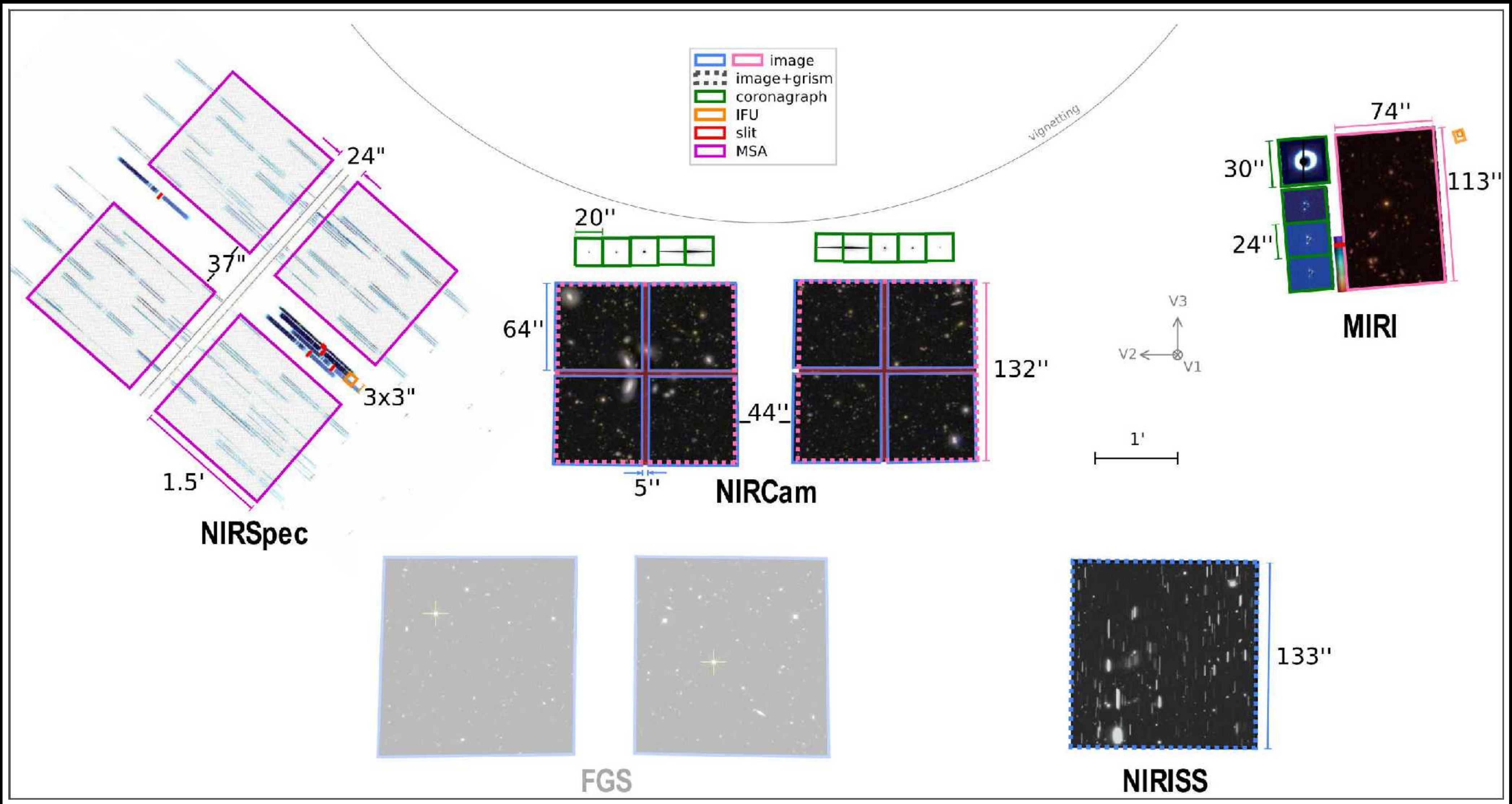
To AB$\lesssim$26 mag, get many faint Galactic brown dwarfs and high-z dropouts.



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

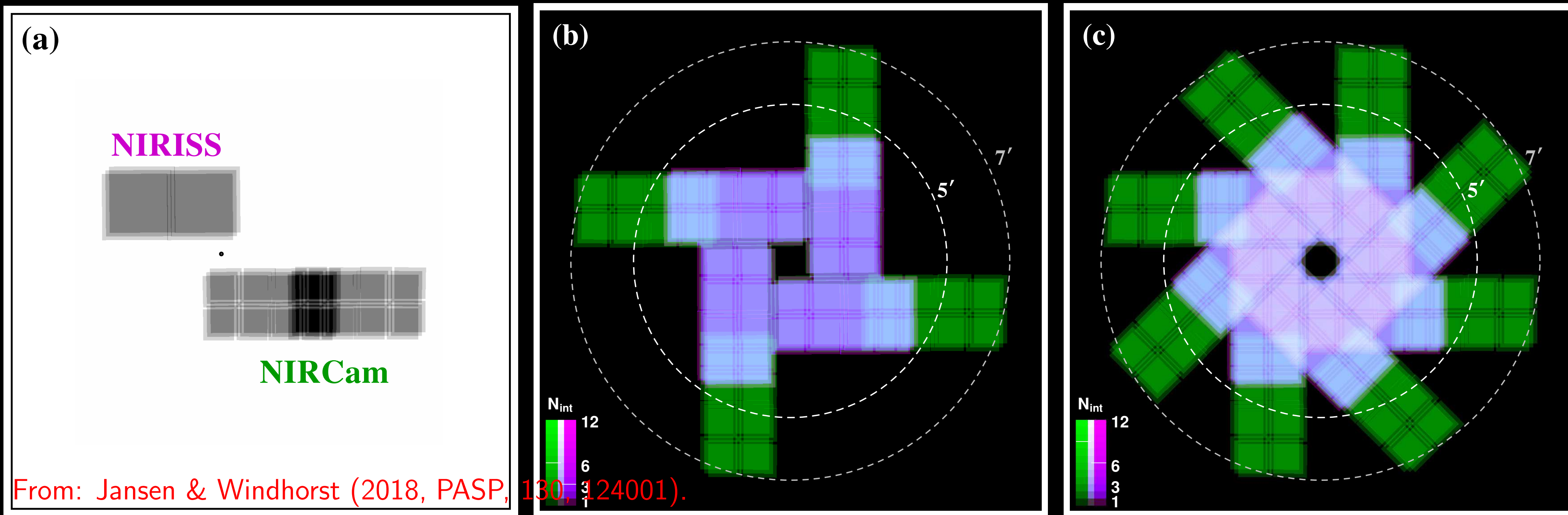

Chandra ACIS-I
HST WFC3/UVIS
HST ACS/WFC
JWST/NIRCAM
N
E
1′

(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:



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

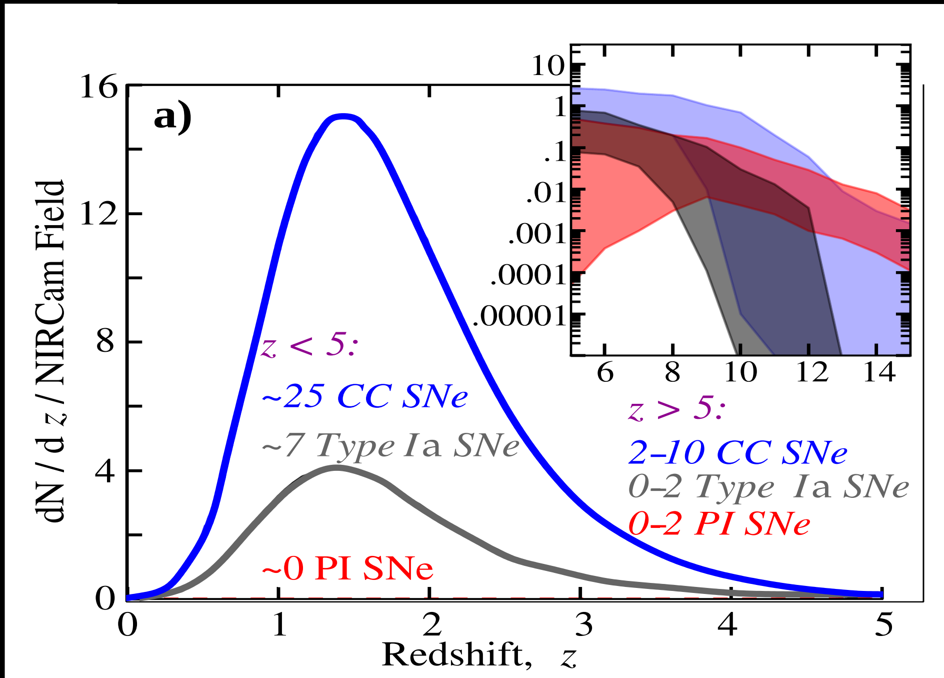
[LEFT]: Exposure map of two contiguous areas: NIRCam primary (green) + NIRISS parallel grism (purple), observable at any PA.

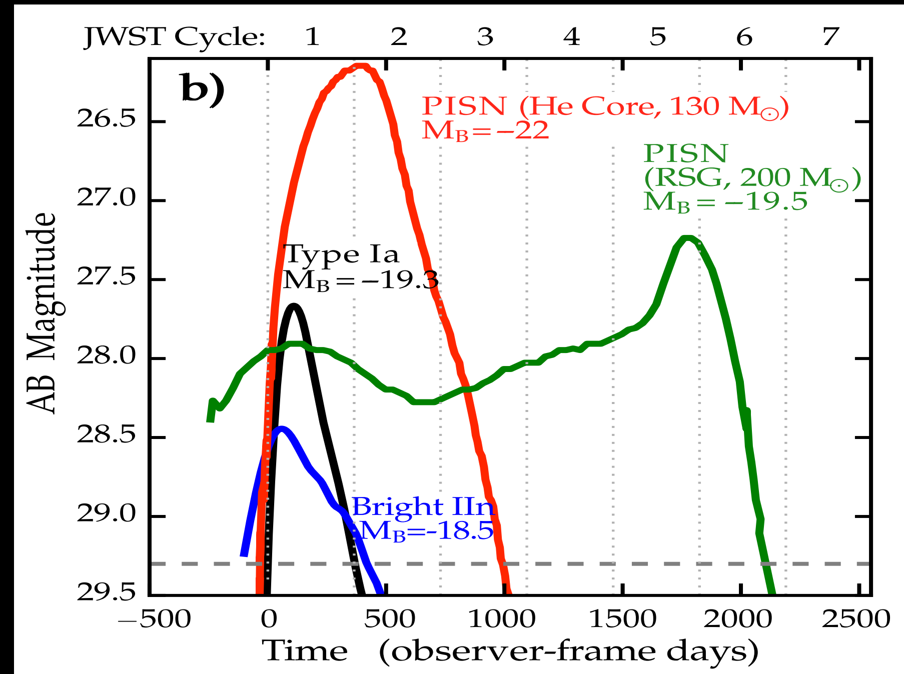
[MIDDLE]: Same with ΔPA=90+180+270° added: our 50-hr GTO plan.

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

NEP 2.0μm sky *always* dark: 0.24±0.03 MJy/sr (GOODS$\simeq$0.19–0.35).

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





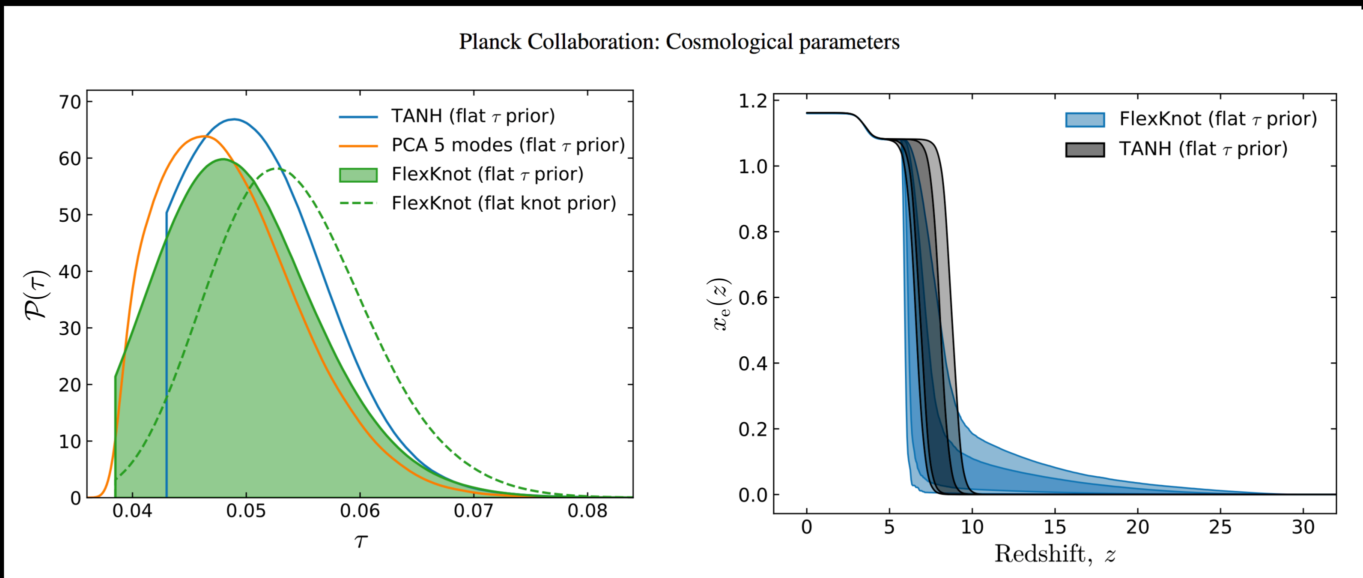
[LEFT] Projected Supernova yield for a single JWST/NIRCam field: JWST NEP TDF provides $\sim 16\times$ more high-z SNe than 1 NIRCam:

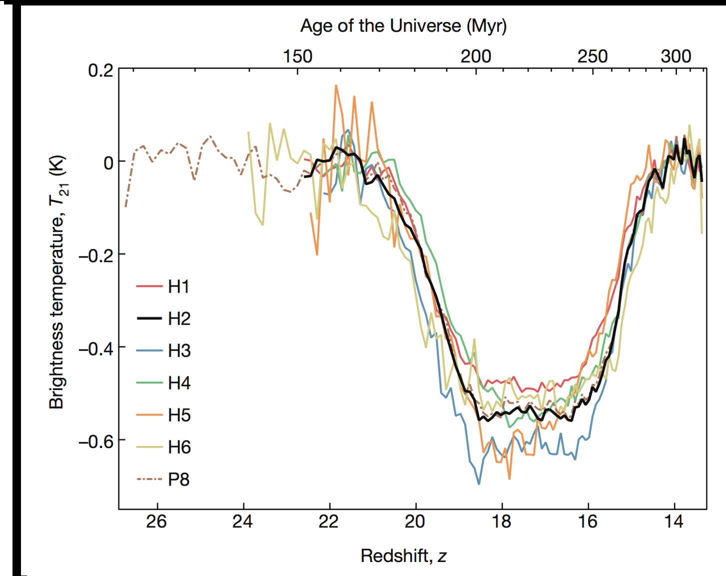
- JWST NEP will detect *all* Type Ia SNe to z$\lesssim$5 (Rodney et al. 2015),
- + 90% of all Core Collapse (CC) SNe to z$\lesssim$1.5 (Strolger et al. 2015).

[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):

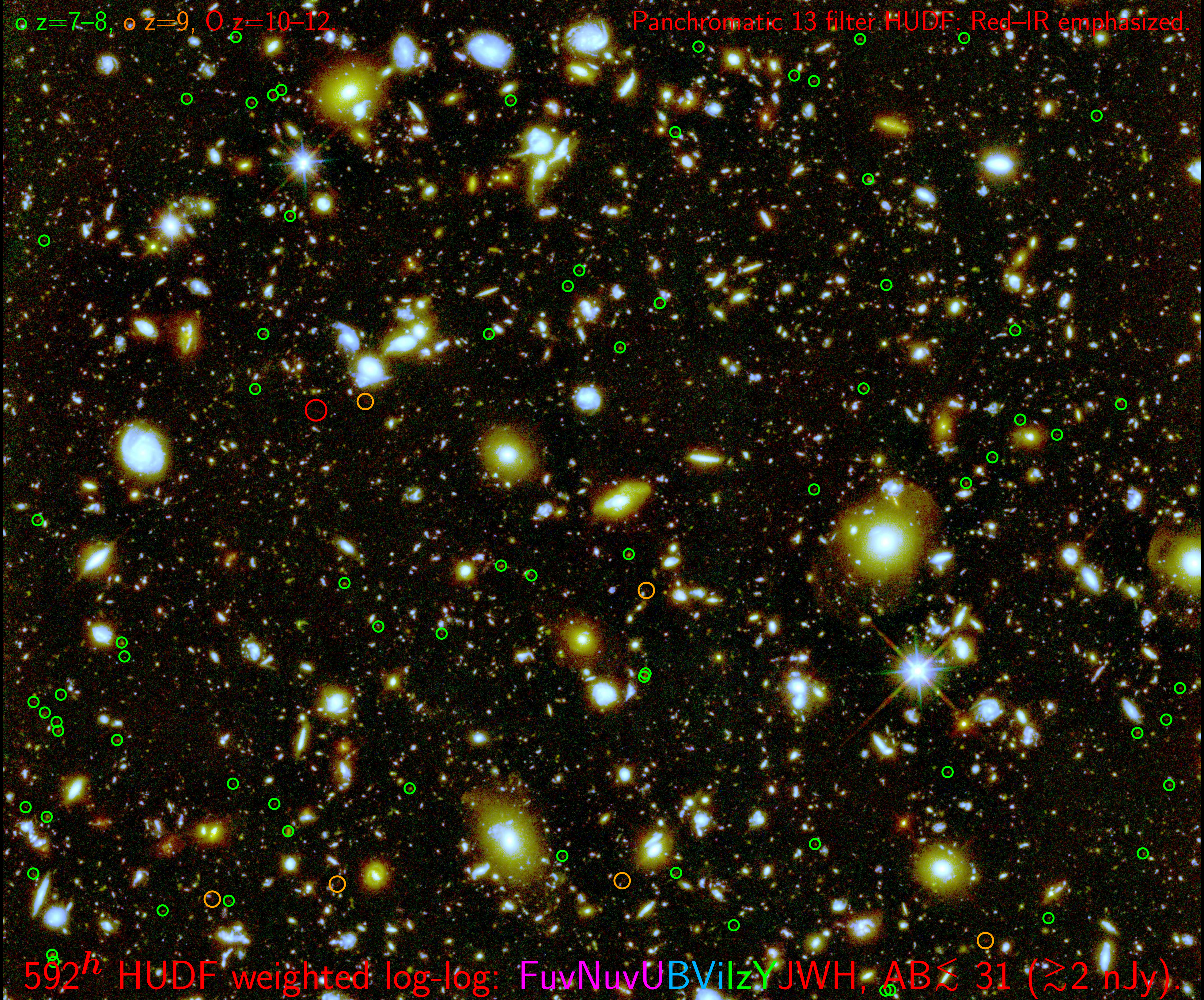
• Possible global 78 MHz HI-signal at $z \simeq 17 \pm 2$ (age 225 Myr).

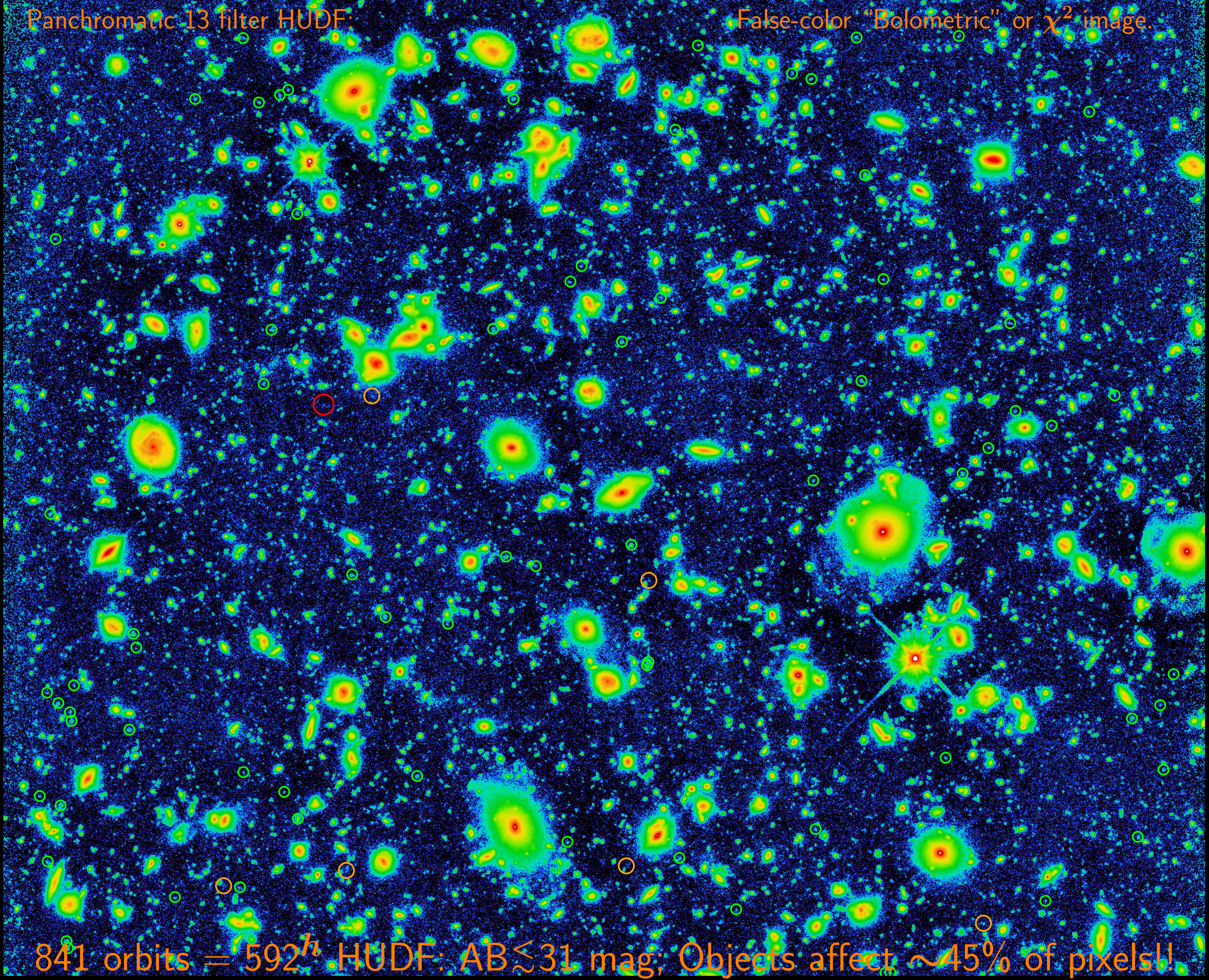
• How can we reconcile this in context of the First Stars?

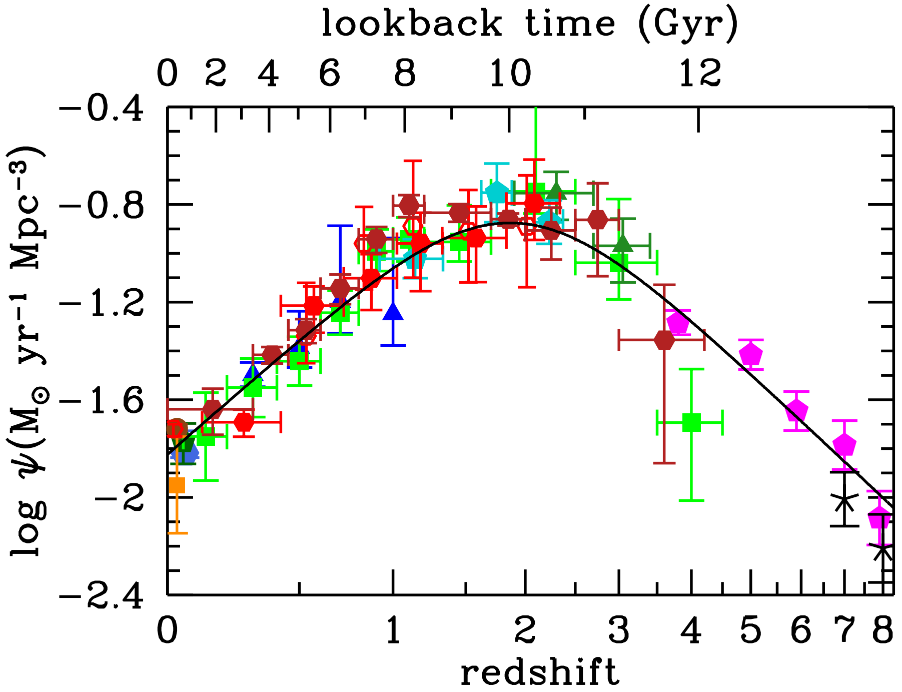
• What does this mean for First Dust, and the first (BH) binary stars?

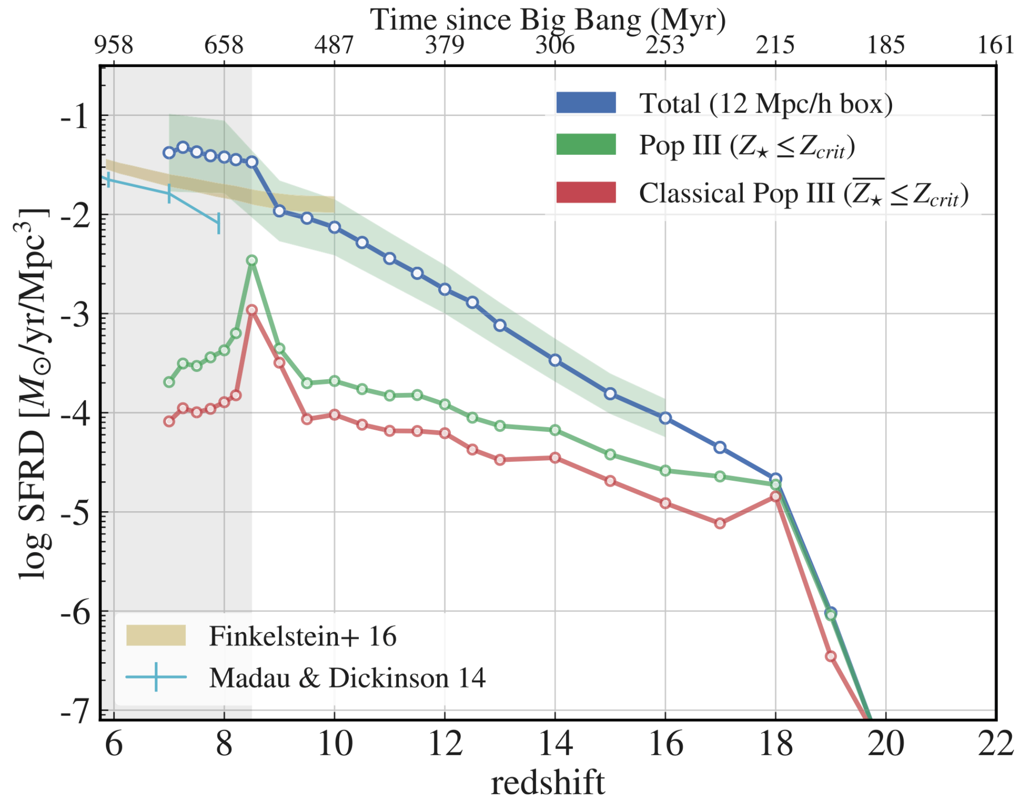
The HST-unique part for JWST: Panchromatic 13 filter HUDF: UV–Blue emphasized.

592^h HUDF weighted log-log: FuvNuvUBViIzYJWH, AB$\lesssim$28–31 ($\gtrsim$2 nJy).


o z=7–8, o z=9, O z=10–12.
Panchromatic 13 filter HUDF: Red–IR emphasized.
592^h HUDF weighted log-log: FuvNuvUBViIzYJWH, AB ≲ 31 (≳2 nJy).


Panchromatic 13 filter HUDF:
False-color "Bolometric" or χ^2 image.
841 orbits = 592^h HUDF: AB$\lesssim$31 mag; Objects affect ~45% of pixels!!





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

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

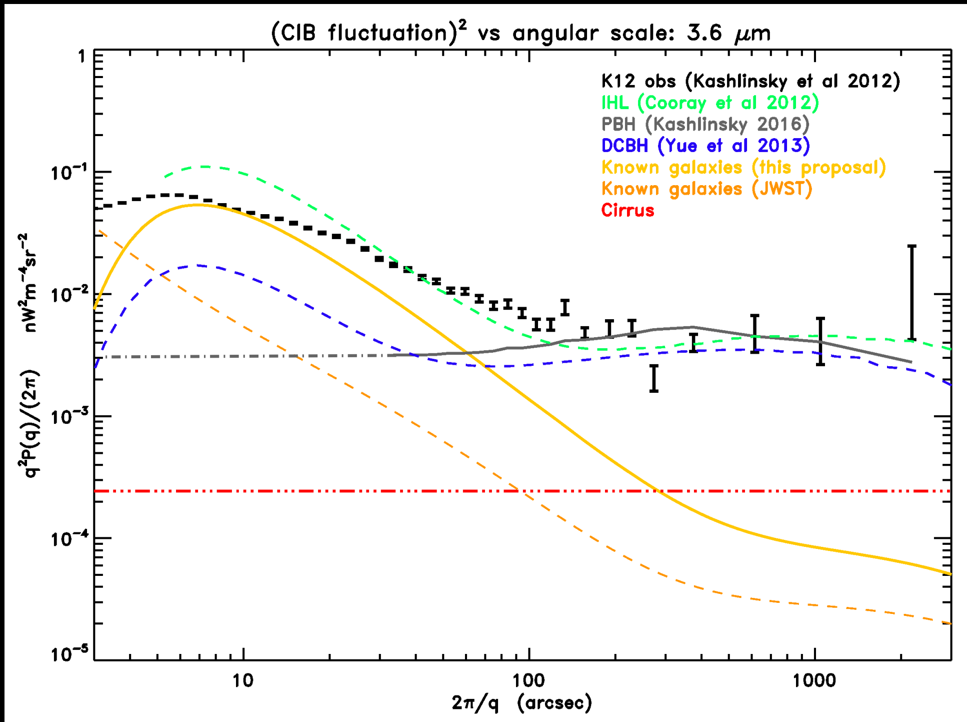
[RIGHT] RAMSES models (*e.g.*, Sarmento et al. 2018, ApJ, 854 75).

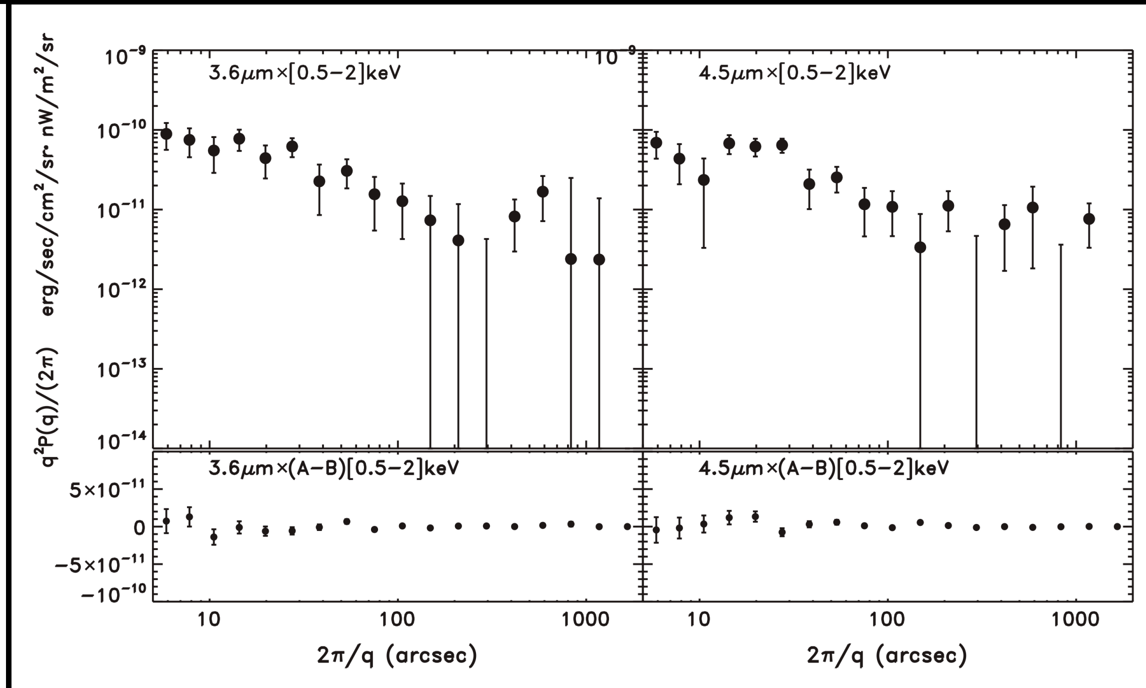
$\Rightarrow$ Adopt this SFR from z$\simeq$17 to z$\simeq$7, implying at the lowest masses:

- 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 μm CIB sky-SB possibly from BH's.

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



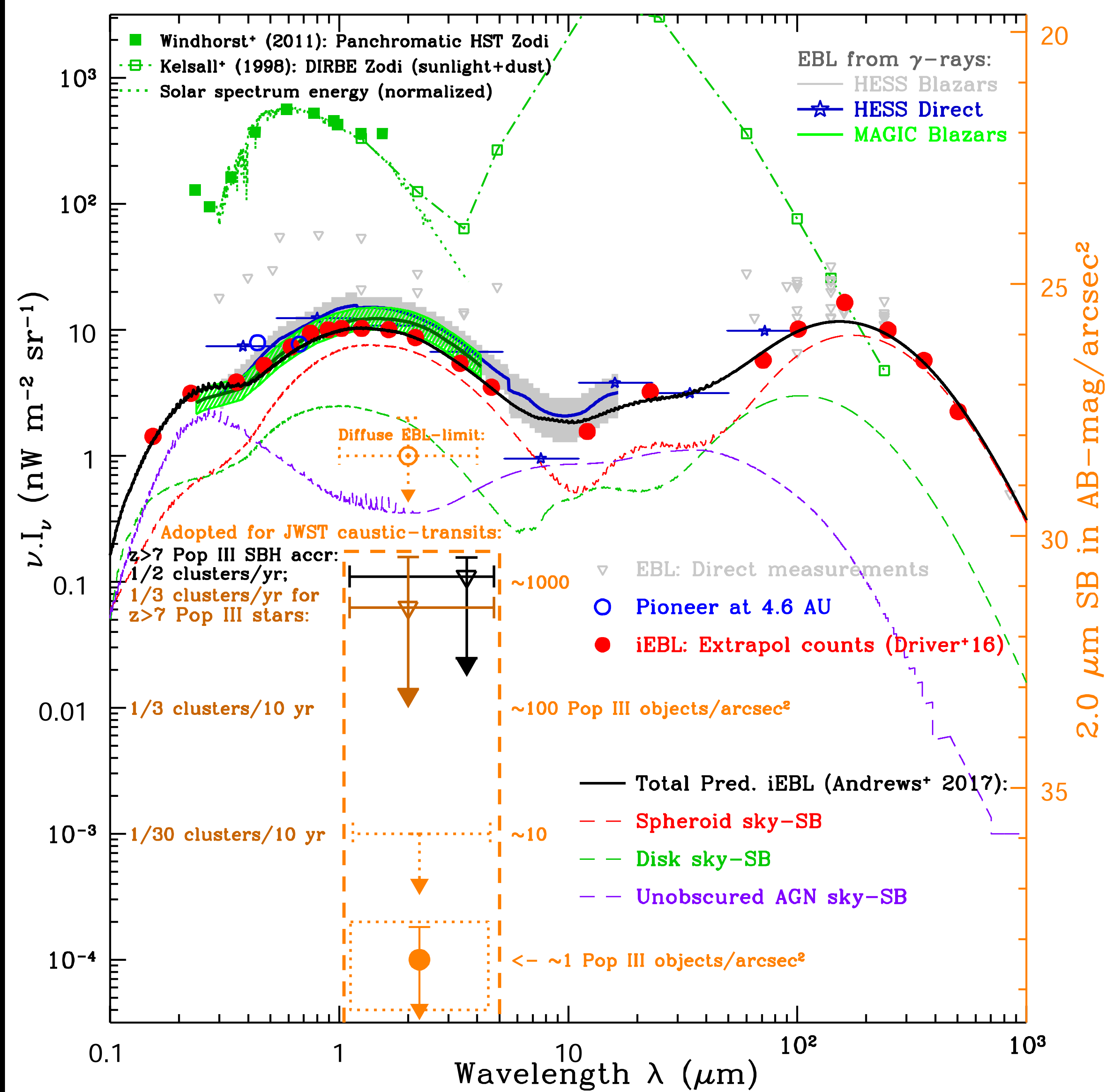


[LEFT] Object-free Spitzer 3.6 μm power-spectrum constrains noise fluctuation models (Cappelluti et al. 2017; Kashlinsky et al. 2012, 2015, 2018):

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

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

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



Extragalactic Background Light (Driver+ 16; Windhorst+ 18):

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

Diffuse 1–4μm sky $\lesssim$0.1 nW/m^2/sr or SB(K)$\gtrsim$31 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 AB$\lesssim$28–29 mag.

- Requires using the best lensing clusters and monitoring caustic transits.

(4) Possible caustic transits from Pop III stars and their BH accretion disks.

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CrossMark

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

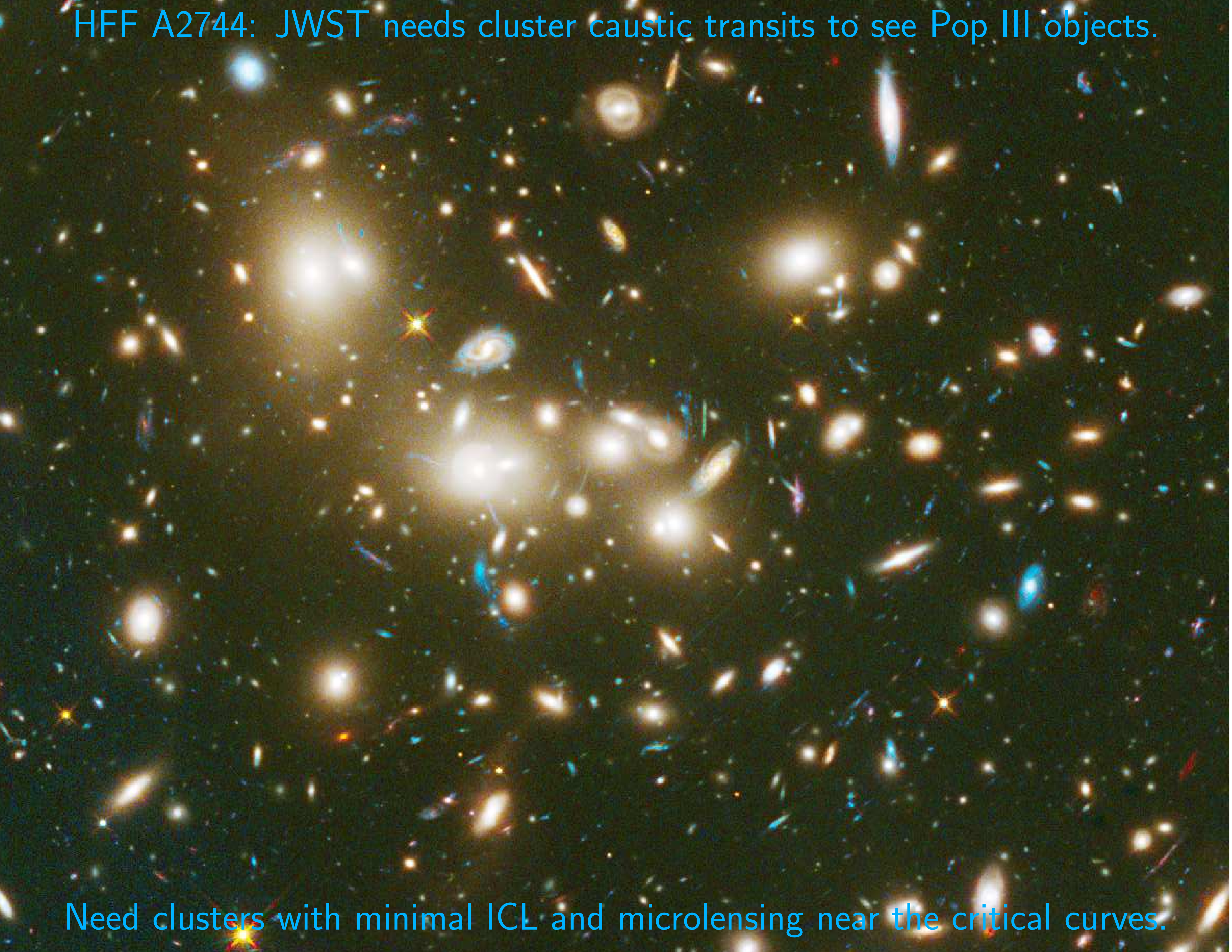
We summarize panchromatic Extragalactic Background Light data to place upper limits on the integrated near-infrared surface brightness (SB) that may come from Population III stars and possible accretion disks around their stellar-mass black holes (BHs) in the epoch of First Light, broadly taken from $z \simeq 7$–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 $\mu \simeq 10^4$–10^5, with rise times of hours and decline times of $\lesssim$1 year for cluster transverse velocities of $v_T \lesssim 1000$ 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

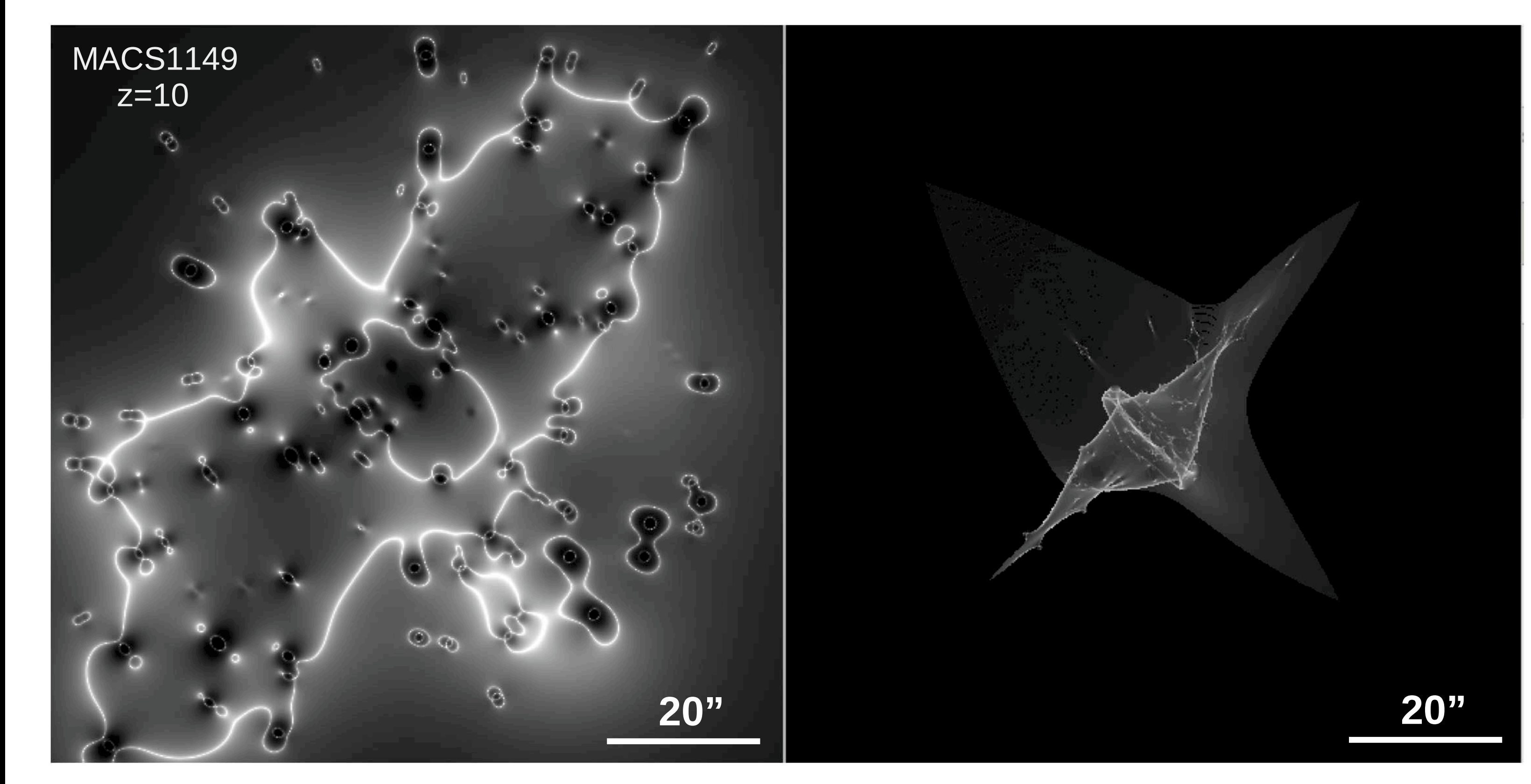
- JWST (and ground-based 25–39 m telescopes) may detect Pop III stars and their stellar-mass BH accretion disks *directly* to AB$\lesssim$28–29 mag via cluster caustic transits (Windhorst$^+$, 2018, ApJS, 234, 41).

- 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.



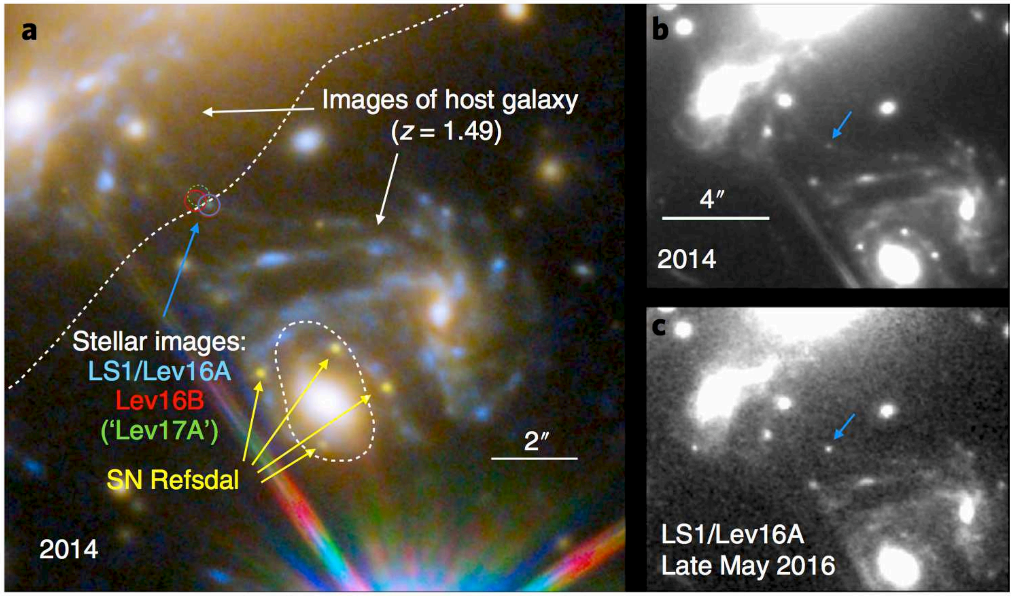
For source at z=10, critical curves for HFF cluster MACS 1149 at z$\simeq$0.54 [LEFT], and main cluster caustics [in the source plane; RIGHT].

• Transverse cluster (sub-component) velocities can be $v_T \lesssim$1000 km/s (Kelly$^+$ 2018; Nature Astr. 2, 334; Windhorst$^+$ 2018, ApJS, 234, 41).

• Main caustic magnification: $\mu \simeq 10.(\mathrm{d}_{caustic}/'')^{-1/2}$. For Pop III objects at z$\gtrsim$7 with 1–30 $R_\odot$, μ 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$^+$ 2018, ApJ, 857, 25).

(4) HST observations of a B-star caustic transit at z≃1.49



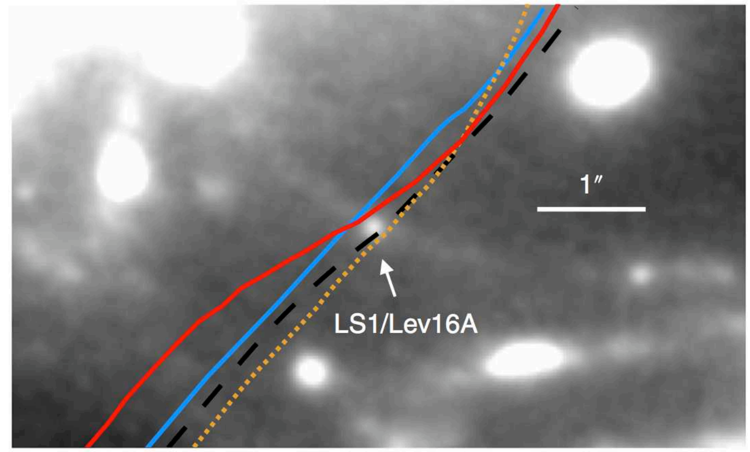


Fig. 2 | Proximity of LS1/Lev16A to the MACS J1149 galaxy cluster's critical curve for multiple galaxy-cluster lens models. Critical curves for models with available high-resolution lens maps including ref. [8] (CATS;

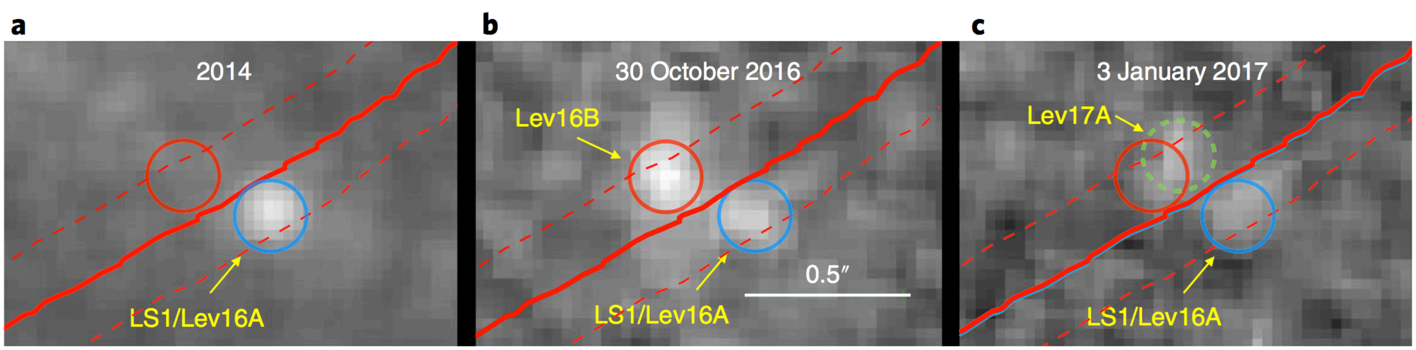
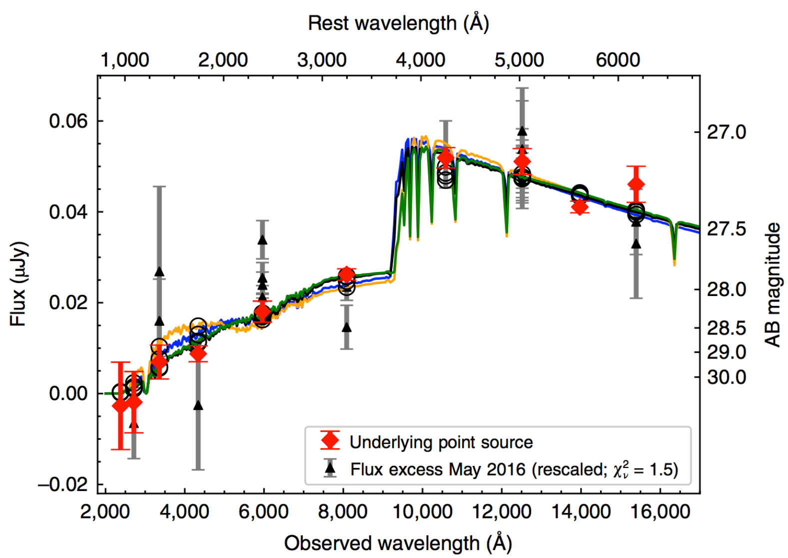


Fig. 5 | Highly magnified stellar images located near the MACS J1149 galaxy cluster's critical curve. a, LS1 in 2014; we detected LS1 when it temporarily brightened by a factor of ~4 in late April 2016, and its position is marked by a blue circle. **b**, The appearance of a new image dubbed Lev16B on 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[8], and the dashed red lines show the approximate 1σ uncertainty from comparison of multiple cluster lens models[5-10]. 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 ~4σ significance detection on 3 January 2017. If a microlensing peak, Lev17A must correspond to a different star.

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



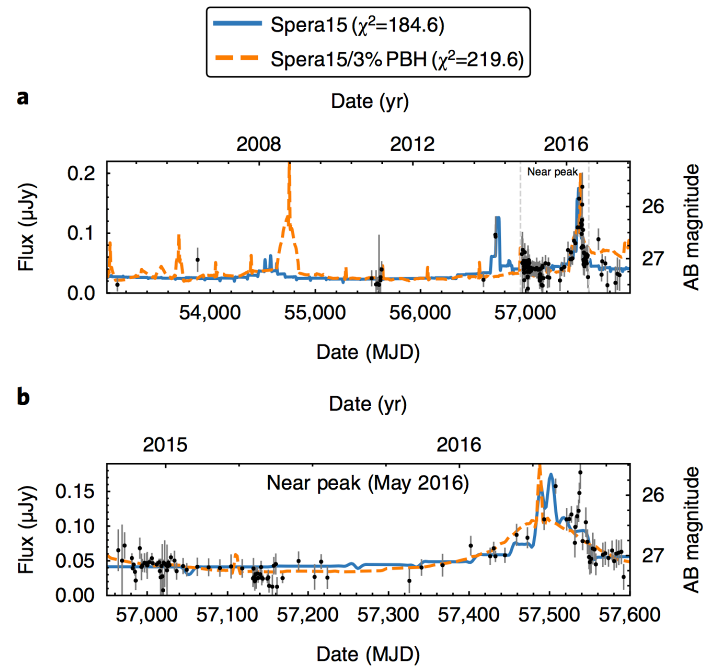


Fig. 3 | The SEDs of LS1 measured in 2013–2015 and of the rescaled excess flux density at LS1's position close to its May 2016 peak. Rescaling the SED of the flux excess (Lev16A; black triangles) to match that of the

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

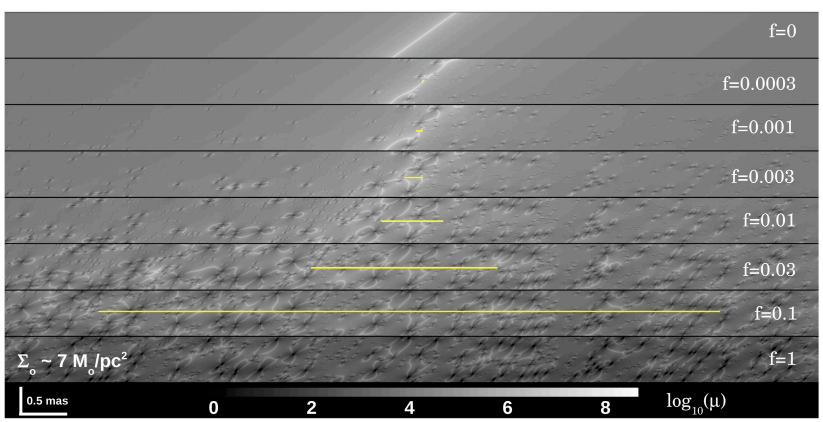
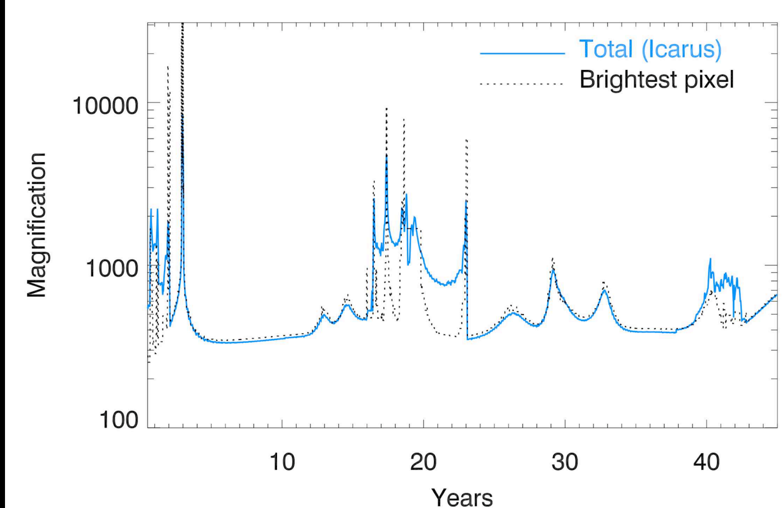
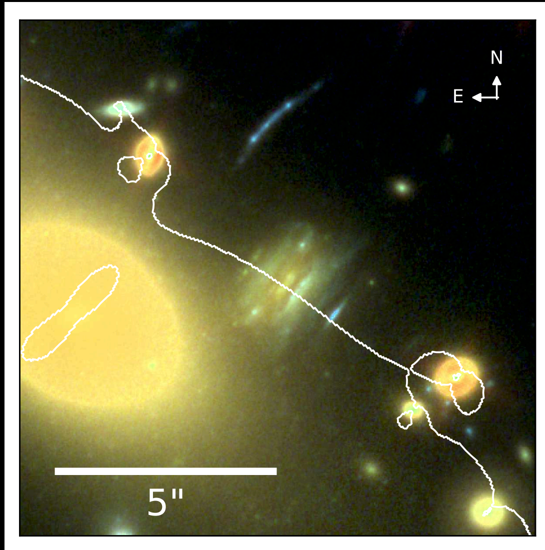
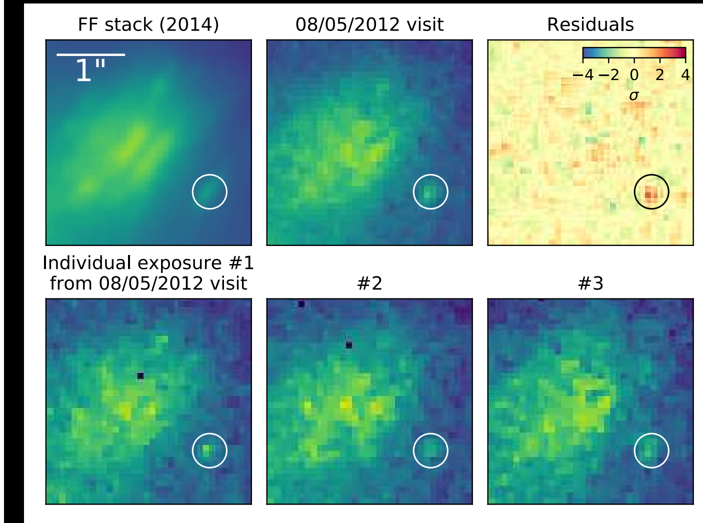


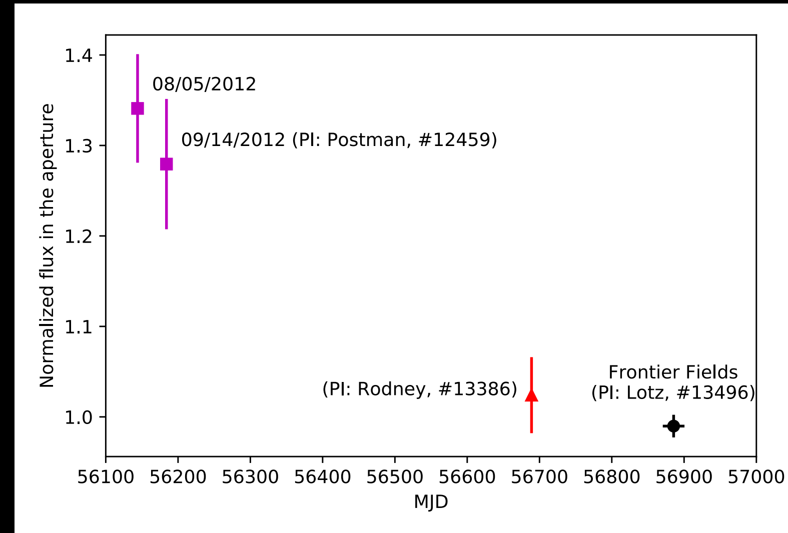
Figure 9. Disruption of the CC as a function of microlens surface mass density. Each panel shows the CC region when a population of microlenses with $\Sigma = f\Sigma_o$ is present. The case $f = 1$ corresponds to the model of Spera et al. (2015) at the position of Icarus. The yellow lines show the approximation in Equation (15). The last panel at bottom does not show the yellow line since it extends beyond the boundaries of the plot. The total surface mass density (i.e., smooth plus microlens) is the same in all panels.

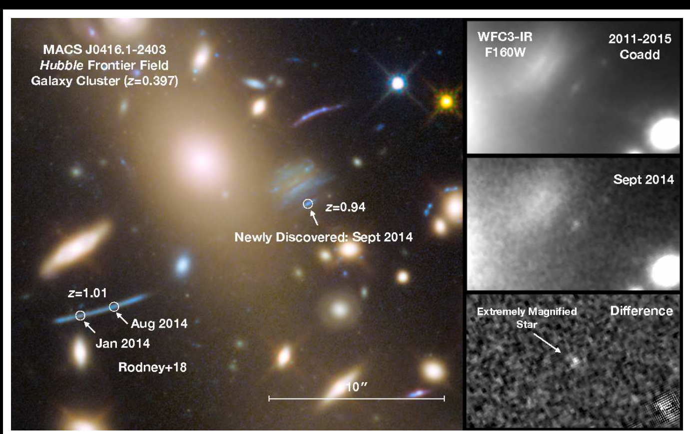


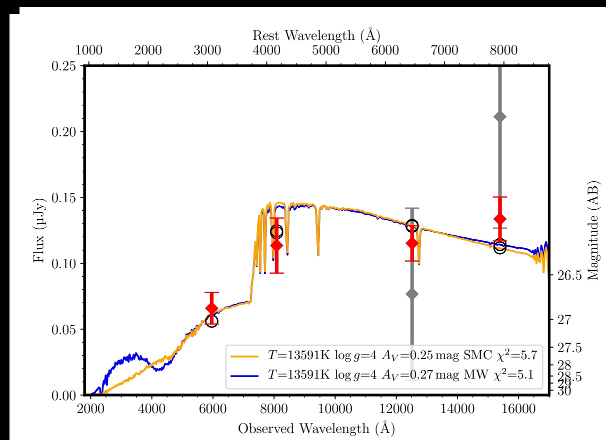
Diego$^+$ 2018 (ApJ, 857, 25): caustic transits in the presence of microlensing.
See also Miralda-Escudé (1991), Venumadhav et al. (2017, ApJ, 850, 49).

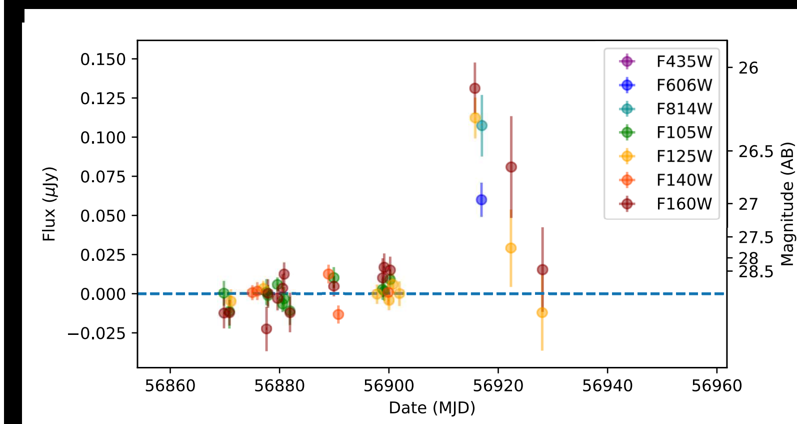








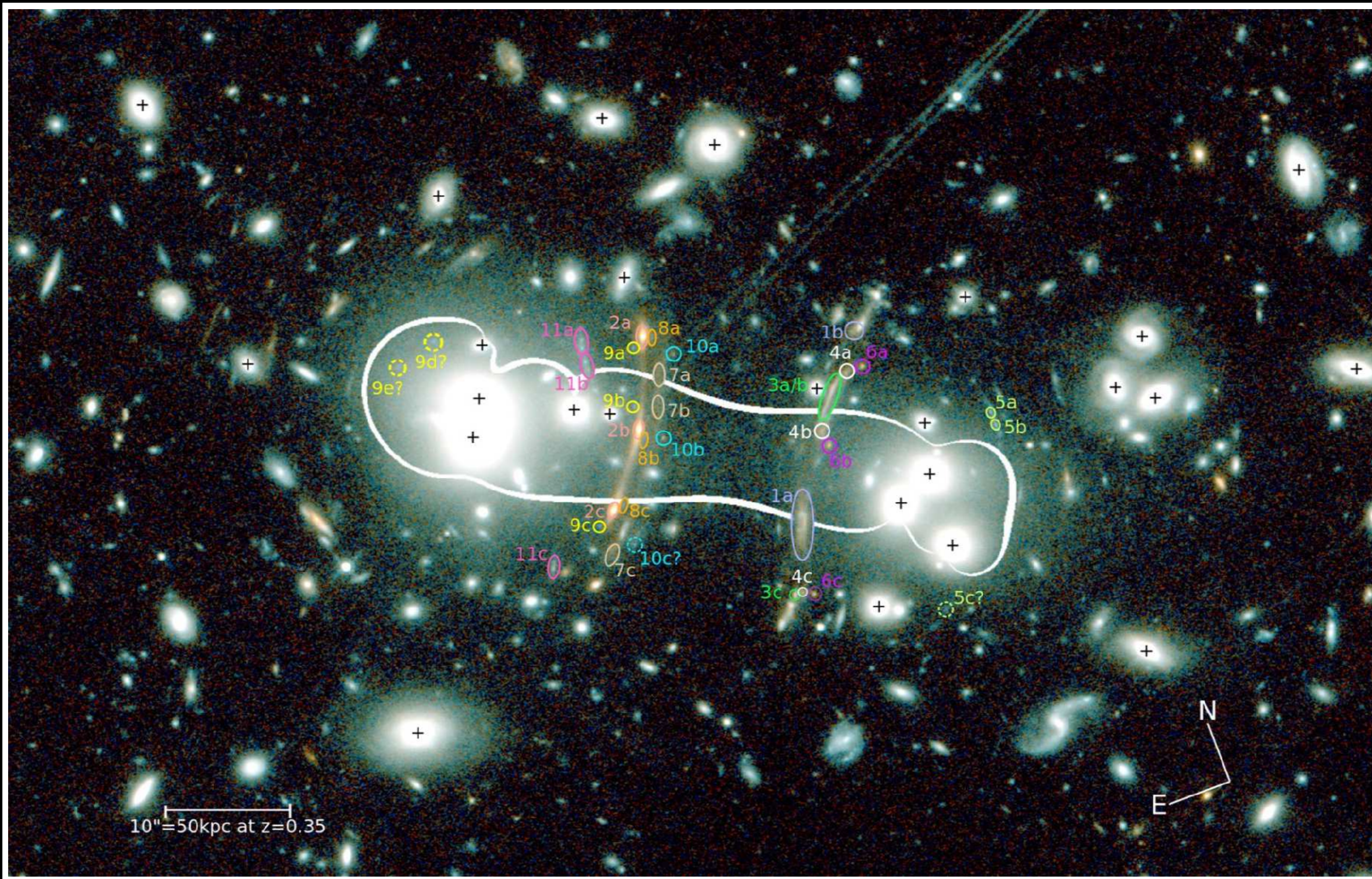




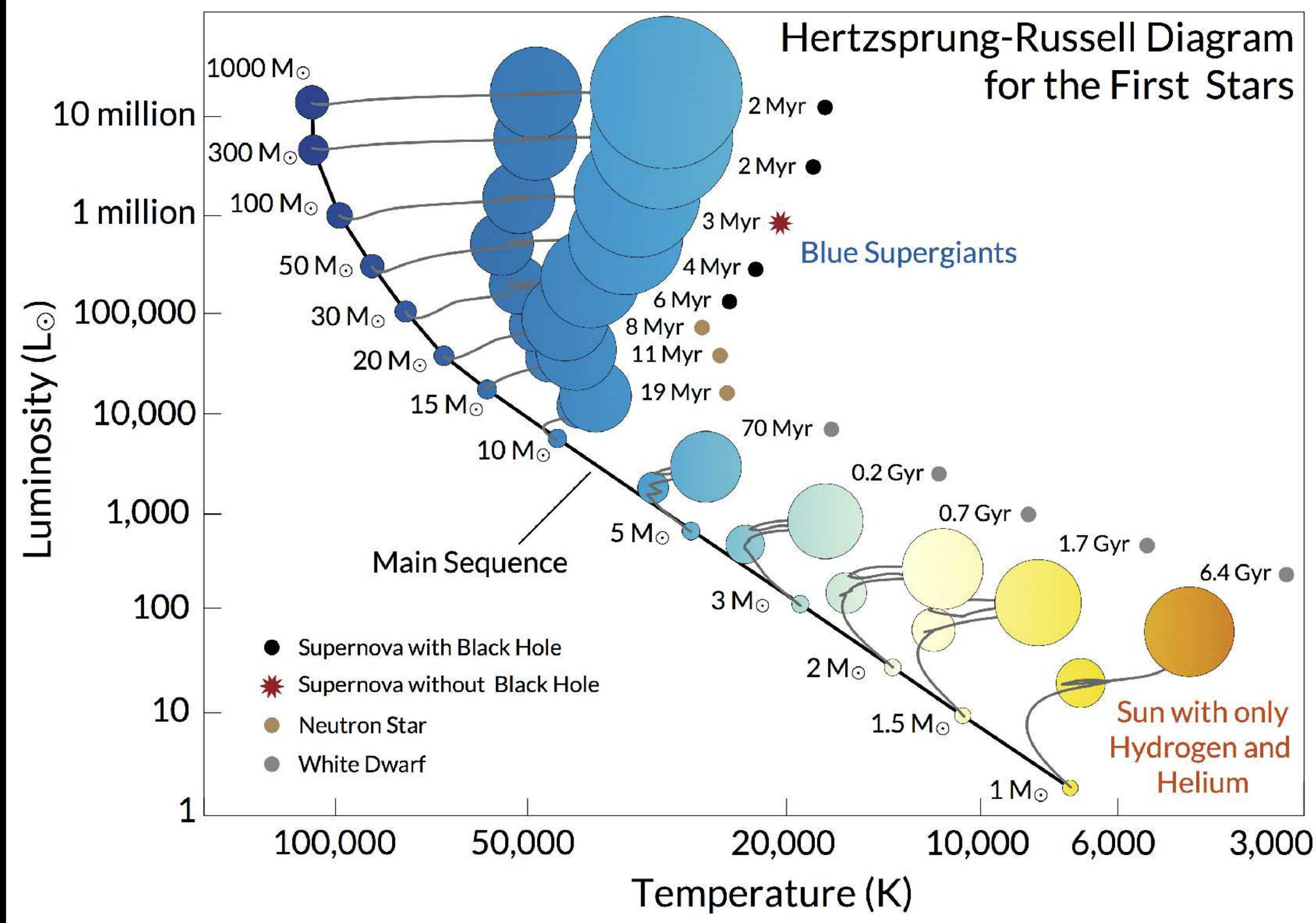
(Top) Caustic Transit at z≃0.94 by Kaurov et al. (2019, ApJ, 880, 58)

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

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



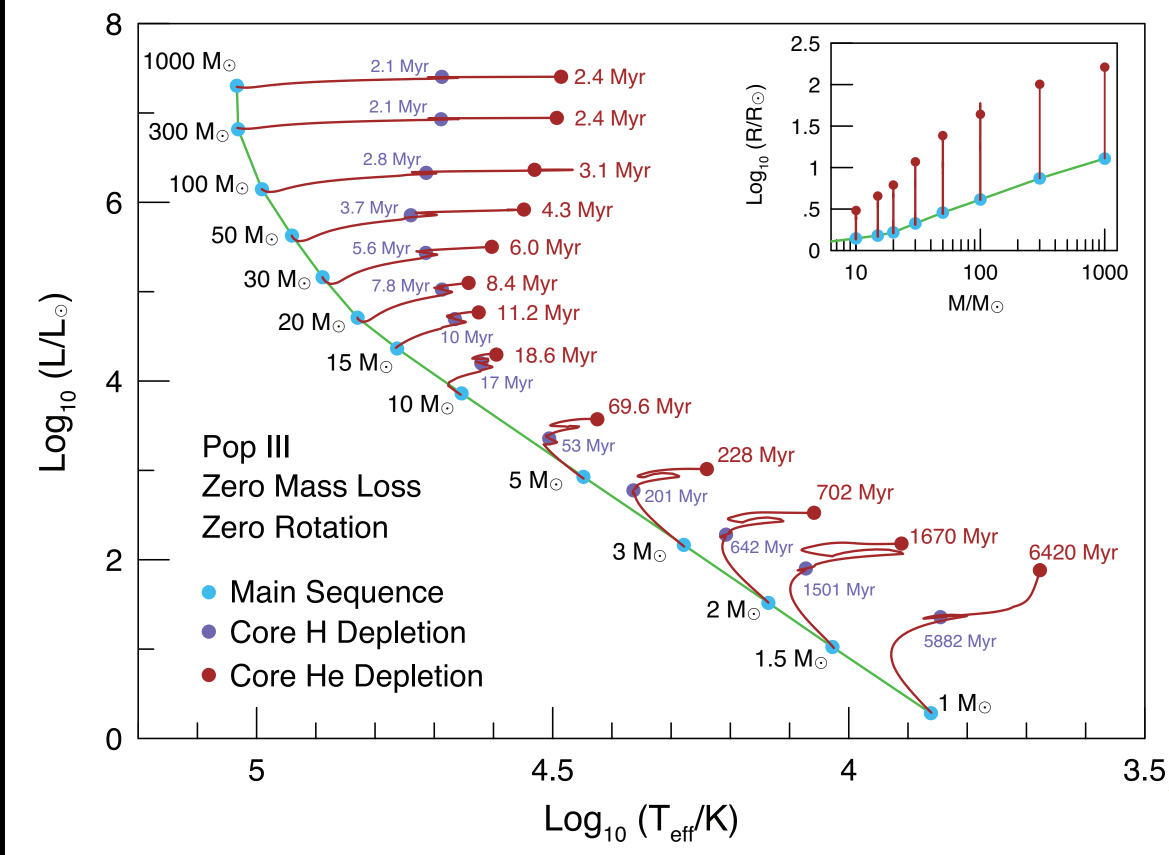
- G165 has two giant lensed arcs at z≃2.2, and 11 lensed image families.
- Very prominent cluster substructure. Combined with its MMT N(z≃0.35), suggests significant transverse velocity needed for caustic transits.



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: 30–1000 $M_{\odot}$ 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).

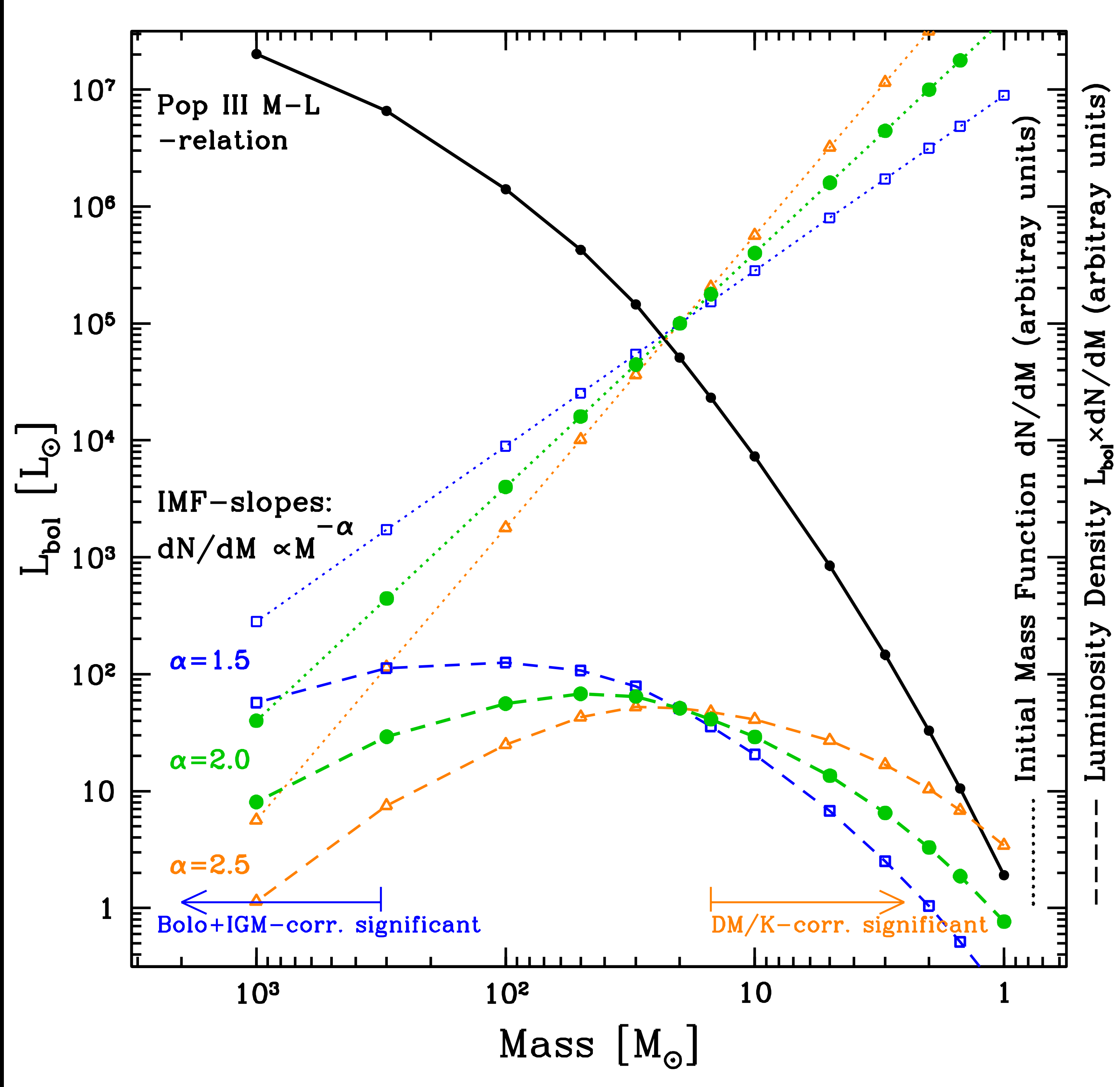


Windhorst+ (2018, ApJS, 234, 41):

• Multicolor accretion-disk models for stellar-mass black holes [RIGHT]: For M_{BH} ≃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× 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 ($\mu \gtrsim 10^4$.



Mass–Luminosity relation for zero metallicity Pop III MESA models:

For range of IMF slopes, most Pop III star sky-SB comes from 20–300 $M_{\odot}$.

Table 1. Adopted Pop III Star Physical Parameters from MESA models[a]

Mass	Age	T_{eff}	$\log R$	$\log L_{bol}$	T_{eff}	$\log R$	$\log L_{bol}$	Age	$T_{\rm eff}$	$\log R$	$\log L_{bol}$	Age	Time[b]
	Pre-MS	— at ZAMS —			— at Hydrogen-depletion —				— at Helium-depletion —				AGB-MS
($M_\odot$)	(Myr)	(K)	($R_\odot$)	($L_\odot$)	(K)	($R_\odot$)	($L_\odot$)	Myr	(K)	($R_\odot$)	($L_\odot$)	Myr	(Myr)
1.0	9.28	7.266e3	−0.0581	0.2825	6.999e3	0.5119	1.3576	5882	—[c]	—	—	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 ∼10× 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[a] ZAMS ($M_\odot$)	$T_{\rm eff}$[b] (K)	Radius[c] at ZAMS ($R_\odot$)	$L_{\rm bol}$[d] at ZAMS ($L_\odot$)	$M_{\rm bol}$[e] (AB)	Bolo+IGM+K-corr[f] z=7 (AB-mag)	z=12	z=17	ZAMS $m_{\rm UV}$[g] z=7 (AB-mag)	z=12	z=17	t_{rise}[h] caust (hr)	transit[i] rate (/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	8×10^5
1.5	1.065e4	0.95	10.5	+2.18	+1.45	+0.42	–0.06	52.87	53.18	53.55	0.18	1.1×10^4
2.0	1.367e4	1.03	32.9	+0.95	+0.30	–0.59	–1.06	50.49	50.93	51.31	0.20	1.5×10^3
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 $\mu\gtrsim10^4$–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.

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 $\mu\gtrsim10^4$–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 $\mu\simeq10^4$–10^5 (where ICL microlensing doesn't dominate caustics).

• JWST GO community is anticipating this, and planning for it.

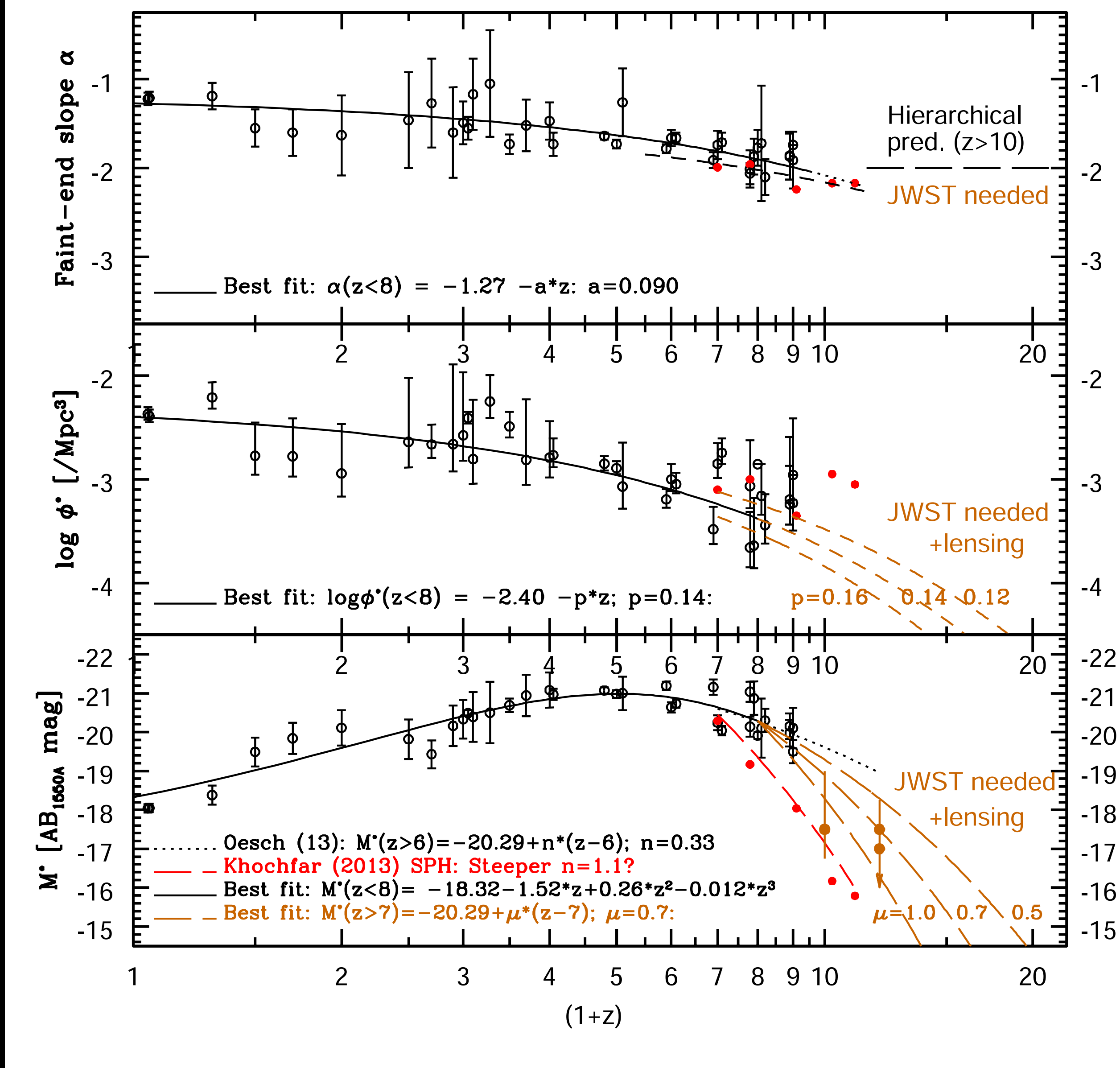
Reminder: Your Webb Cycle 1 proposals are due Nov. 24, 2020

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

Reminder: Your Webb Cycle 1 proposals are due May 1, 2020

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

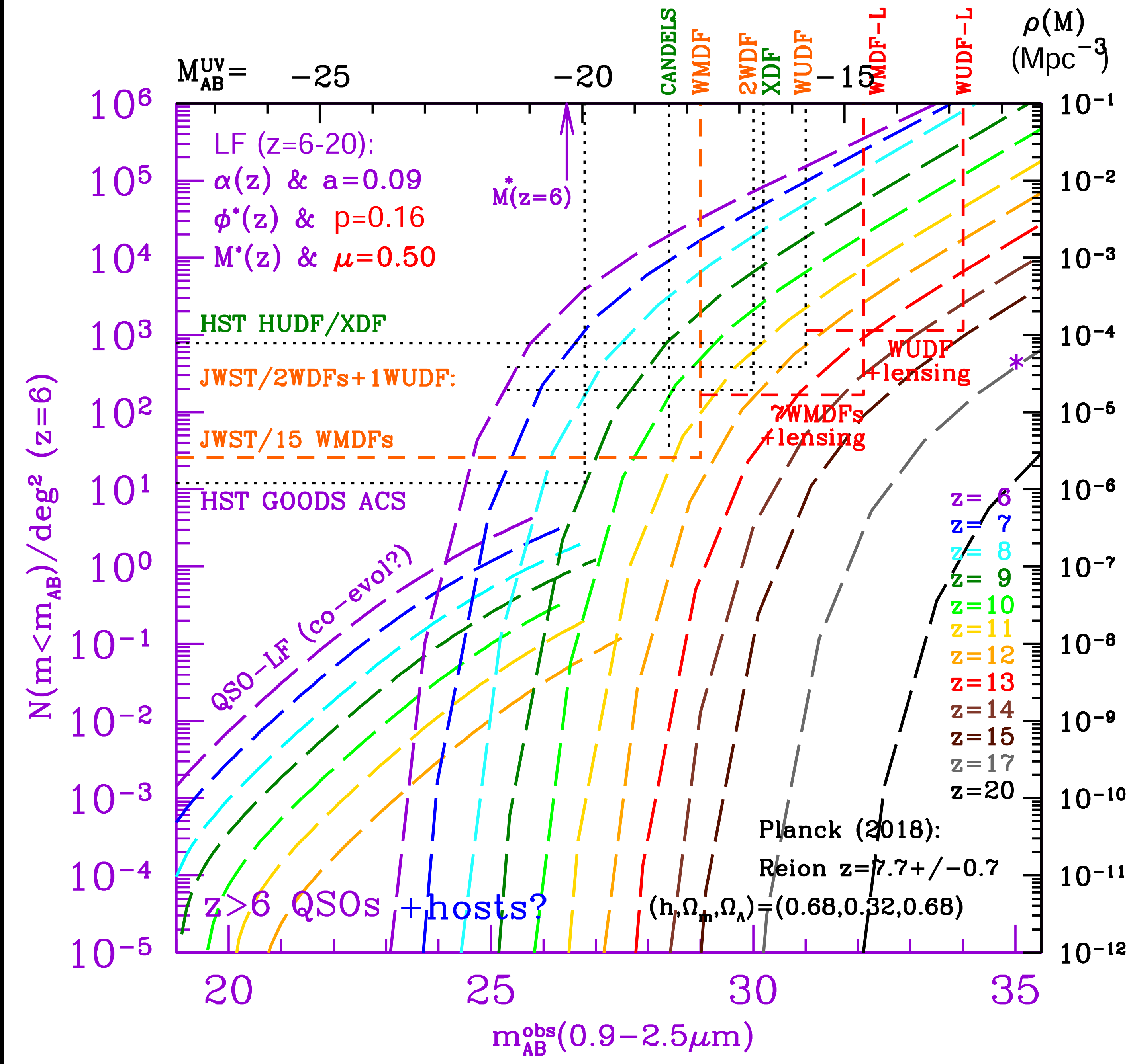
SPARE CHARTS



Evolution of Schechter UV-LF: faint-end LF-slope α(z), Φ^* (z) & M^* (z):

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

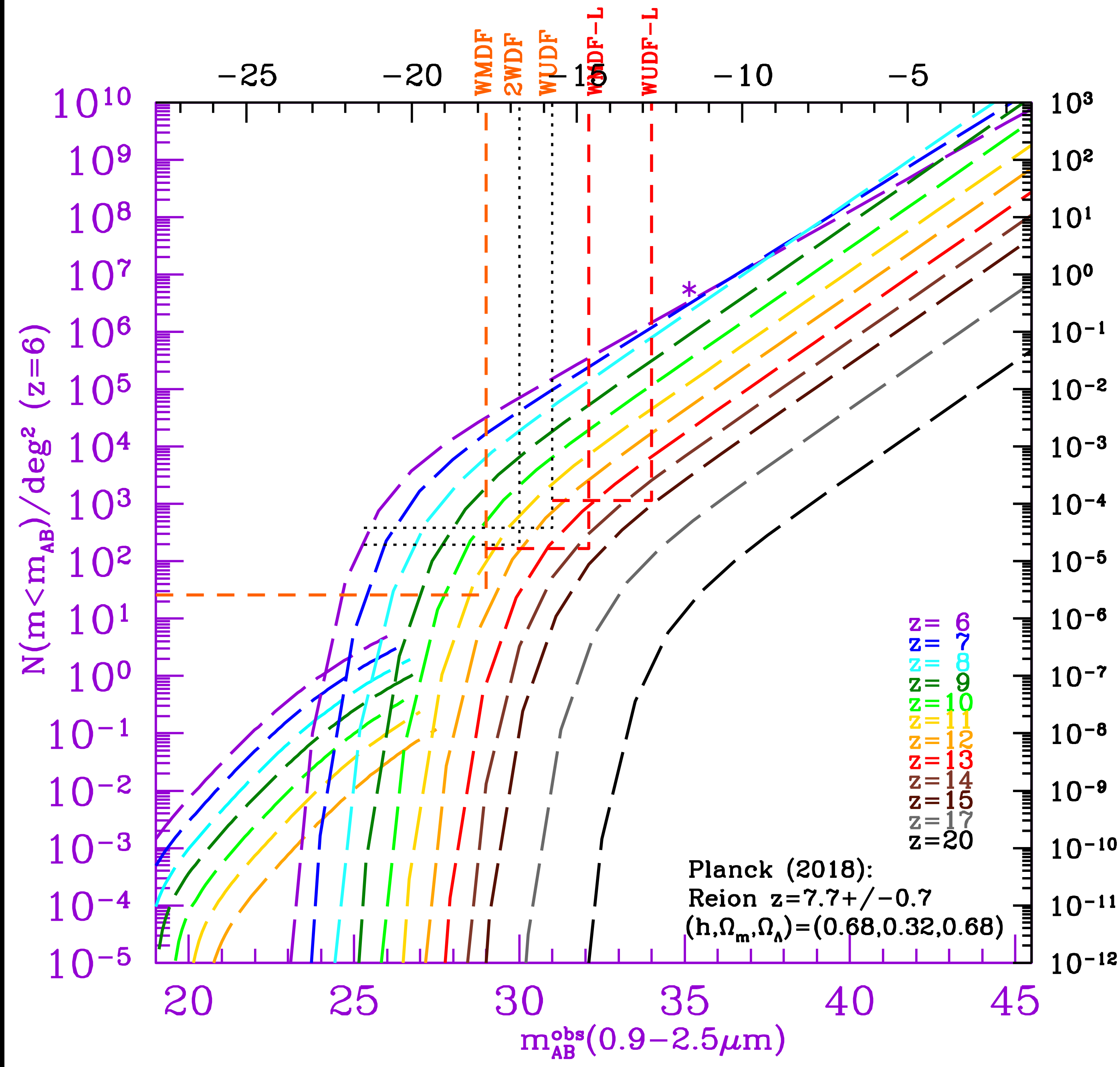
$\Rightarrow$ Has significant consequences for JWST survey strategy.



Schechter LF ($z \lesssim 6 \lesssim 20$) with best-fit α(z), Φ^* (z), M^* (z) & μ=0.50.

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

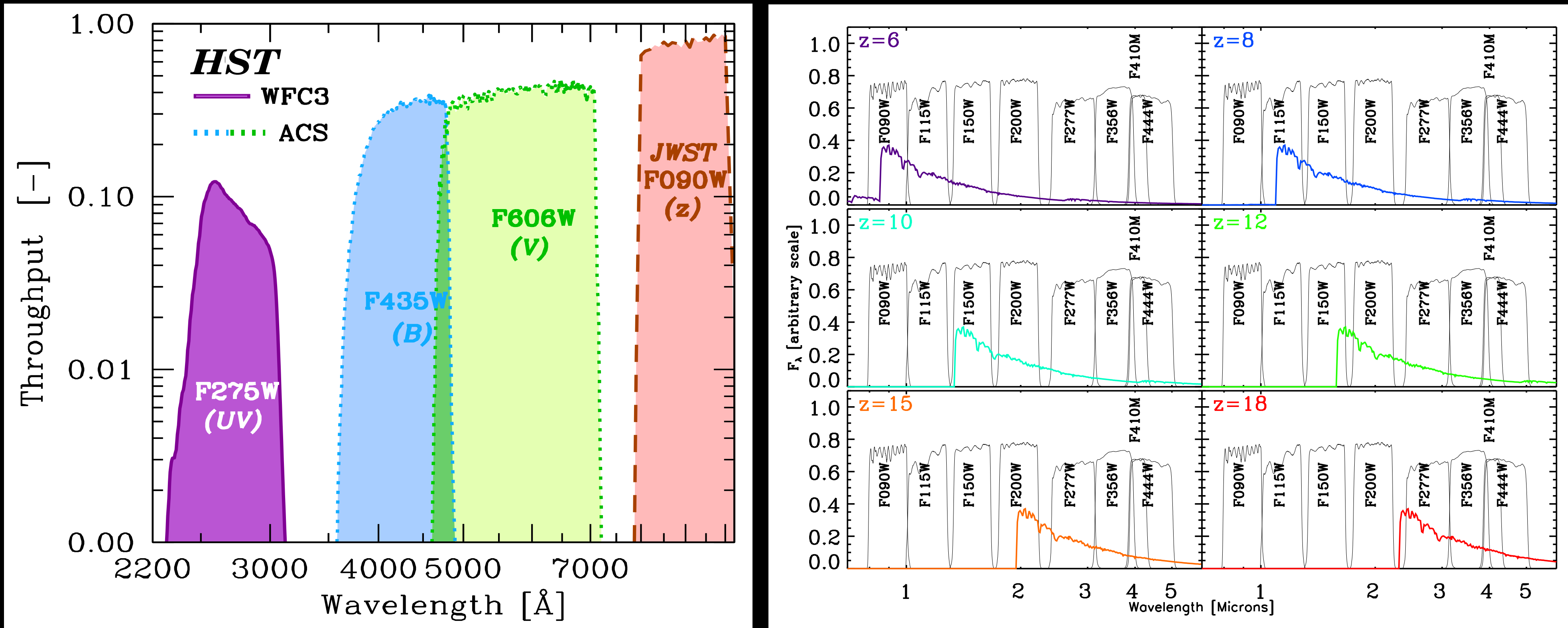
- Need lensing targets for WMDF–WUDF to see z≃14–15 objects.



Schechter LF (z≲6≲20) with best-fit α(z), Φ^* (z), M^* (z) & μ=0.50.

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

- At M_{AB} ≳–12 mag, LF dominated by individual Pop III stars (α≡2.0).



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

- HST adds λ's inaccessible to JWST, or where HST has better PSF.

[RIGHT] Standard 8-band 0.8–5 μm filter set for JWST NIRCam.

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

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

Mass[a] GB ($M_\odot$)	$T_{\rm eff}$[b] (K)	Radius[c] ($R_\odot$)	$L_{\rm bol}$[d] ($L_\odot$)	$M_{\rm bol}$[e] (AB)	Bolo+IGM+K-corr[f] z=7 (AB-mag)	z=12	z=17	Giant Branch m_{UV}[g] z=7 (AB-mag)	z=12	z=17	t_{rise}[h] caust (hr)	transit[i] rate (/cl/yr)
	— at Hydrogen-depletion —											
1.0	6.999e3	3.25	22.8	+1.35	+4.83	+3.48	+2.96	55.42	55.41	55.73	0.63	9×10^4
1.5	1.181e4	2.13	79.7	–0.01	+0.91	–0.06	–0.53	50.13	50.51	50.88	0.41	1.0×10^3
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 $\mu\gtrsim10^4$–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[a] AGB ($M_\odot$)	$T_{\rm eff}$[b] (K)	Radius[c] ($R_\odot$)	$L_{\rm bol}$[d] ($L_\odot$)	$M_{\rm bol}$[e] (AB)	Bolo+IGM+K-corr[f] z=7 (AB-mag)	z=12	z=17	AGB $m_{\rm UV}$[g] z=7 (AB-mag)	z=12	z=17	t_{rise}[h] caust (hr)	transit[i] rate (/cl/yr)
	— at Helium-depletion —											
1.0	6.312e3[j]	5.23[j]	39.8[j]	+0.74	+6.01	+4.57	+4.03	55.99	55.89	56.19	1.01	1.4×10^5
1.5	8.149e3	6.18	151.	–0.71	+3.36	+2.14	+1.64	51.89	52.01	52.35	1.19	4.0×10^3
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 $\mu\gtrsim10^4$–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)!

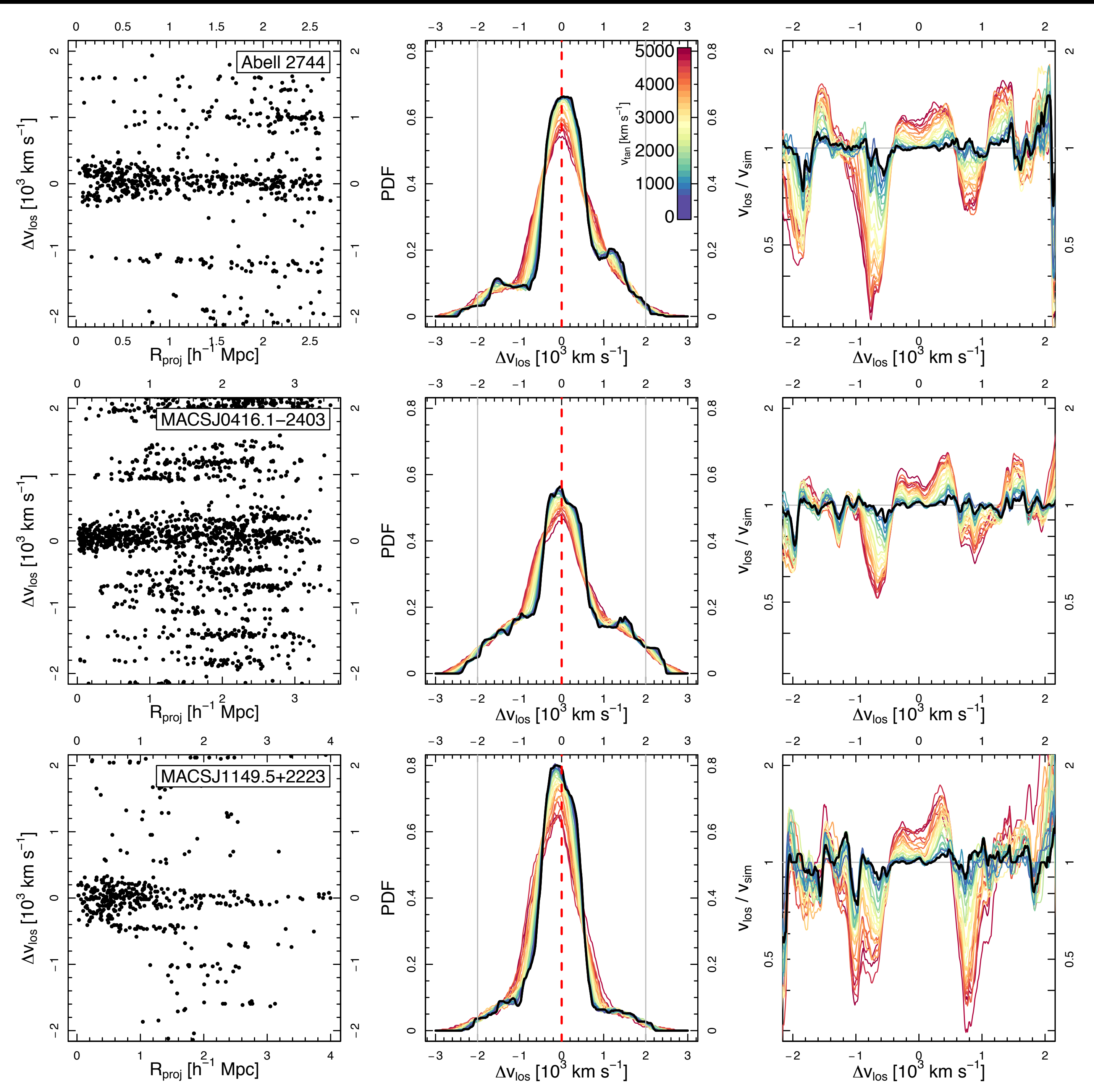
Table 5. Pop III Stellar Mass Black Hole Accretion Disk Parameters Adopted for Caustic Transit Calculations

Mass[a] ZAMS ($M_\odot$)	$M_{compact}$[b] ($M_\odot$)	R_s[c] BH (km)	Radius[d] — of the UV accretion disk — ($R_\odot$)	L_{bol}[e] ($L_\odot$)	M_{bol}[f] AB-mag	bolo+IGM+K-corr[g] z=7 (AB-mag)	z=12	z=17	m_{AB}-limits at[h] z=7 (AB-mag)	z=12	z=17	t_{rise}[i] (z=12) (hr)	Transit[j] rate (/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	$\lesssim 4.2\times10^4$	$\gtrsim -6.8$	−0.6	−1.4	−1.7	$\gtrsim$41.8	$\gtrsim$42.4	$\gtrsim$42.9	0.27?	$\gtrsim$0.58?
50	∼24 BH	72	3.0	$\lesssim 2.0\times10^5$	$\gtrsim -8.5$	−0.4	−1.2	−1.5	$\gtrsim$40.3	$\gtrsim$40.9	$\gtrsim$41.4	0.58*	$\gtrsim$0.15*
100	∼65 BH	195	4.9	$\lesssim 5.4\times10^5$	$\gtrsim -9.6$	−0.2	−0.9	−1.3	$\gtrsim$39.4	$\gtrsim$40.0	$\gtrsim$40.5	0.95*	$\gtrsim$0.06*
300	∼230 BH	690	9.2	$\lesssim 1.9\times10^6$	$\gtrsim -11.0$	−0.2	−1.0	−1.3	$\gtrsim$38.1	$\gtrsim$38.6	$\gtrsim$39.2	1.8*	$\gtrsim$0.02*
1000	∼720 BH	2160	16.3	$\lesssim 6.0\times10^6$	$\gtrsim -12.2$	−0.2	−0.9	−1.3	$\gtrsim$36.8	$\gtrsim$37.5	$\gtrsim$37.9	3.2*	$\gtrsim$0.01*
BH accretion-disk bolometric luminosities and UV half-light radii estimated from multi-color thin-disk model													
30	∼5.0 BH	15	1.9	$\lesssim 3.1\times10^4$	$\gtrsim -6.5$	−0.6	−1.4	−1.7	$\gtrsim$42.1	$\gtrsim$42.8	$\gtrsim$43.2	0.37?	$\gtrsim$0.84?
50	∼24 BH	72	4.5	$\lesssim 1.8\times10^5$	$\gtrsim -8.4$	−0.4	−1.2	−1.5	$\gtrsim$40.4	$\gtrsim$41.1	$\gtrsim$41.5	0.87*	$\gtrsim$0.18*
100	∼65 BH	195	7.8	$\lesssim 5.9\times10^5$	$\gtrsim -9.7$	−0.2	−0.9	−1.3	$\gtrsim$39.3	$\gtrsim$40.0	$\gtrsim$40.4	1.51*	$\gtrsim$0.06*
300	∼230 BH	690	15.8	$\lesssim 2.0\times10^6$	$\gtrsim -11.0$	−0.2	−1.0	−1.3	$\gtrsim$38.0	$\gtrsim$38.6	$\gtrsim$39.1	3.1*	$\gtrsim$0.02*
1000	∼720 BH	2160	29.8	$\lesssim 6.6\times10^6$	$\gtrsim -12.3$	−0.2	−0.9	−1.3	$\gtrsim$36.7	$\gtrsim$37.4	$\gtrsim$37.8	5.8*	$\gtrsim$0.01*

- If M$\gtrsim$20 $M_\odot$ Pop III stellar mass black hole accretion disks 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. Rise times ∼hours–1 day; Decay times $\lesssim$0.4 yr.

- Note the combined Bolometric+IGM+K-corrections are also more advantageous for Pop III stellar-mass black hole accretion disks.

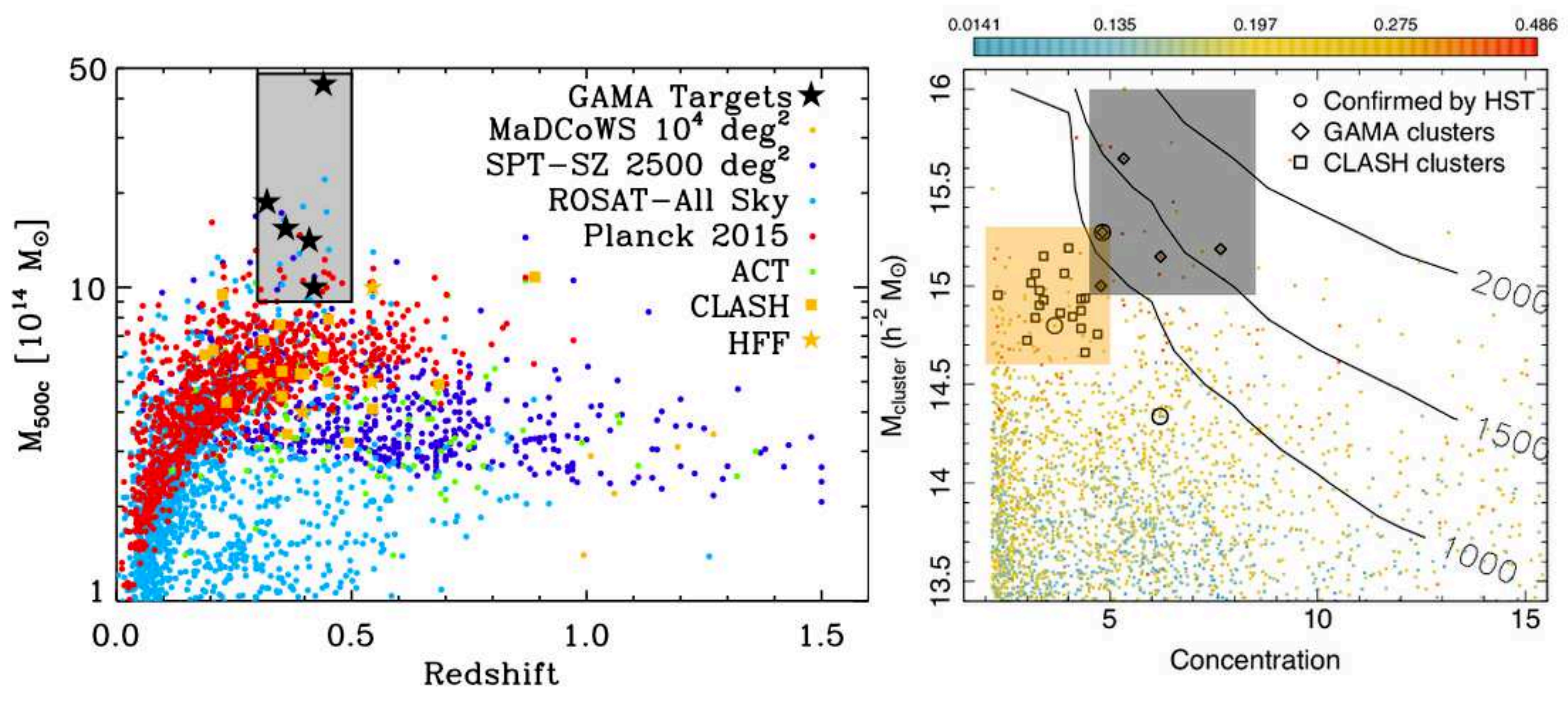
Multi-λ model: $T \propto r^{-3/4}$; $T_{max} \simeq 10\left(\frac{M_{BH}}{100}\right)^{-3/8}$ keV; $r_{hl} \propto M_{BH}^{1/2}$.



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

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

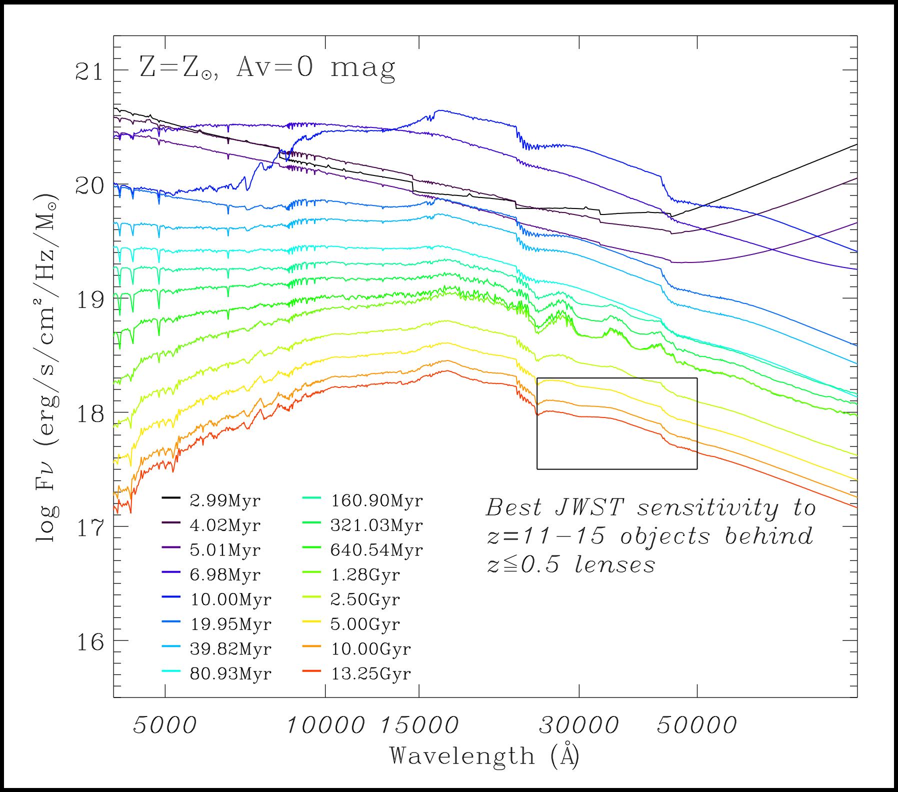
[LEFT] Best lensing clusters vs. ROSAT, Planck, SPT, MaDCoWS.

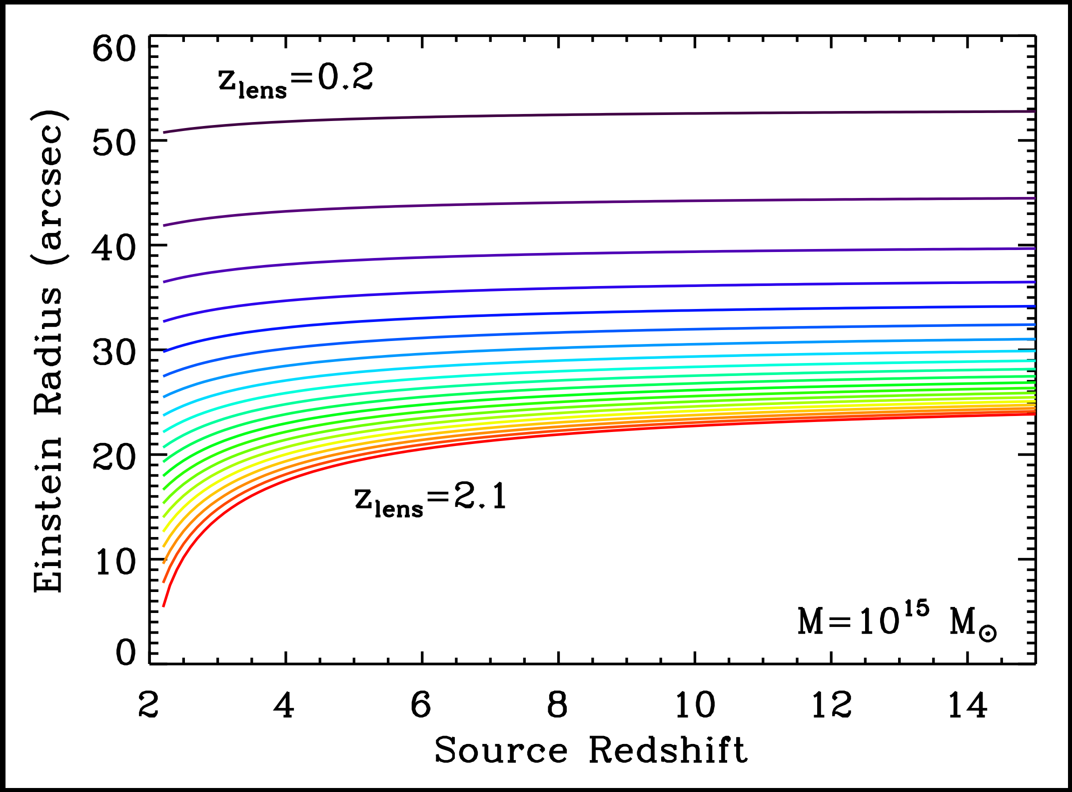
[RIGHT] Best lensing clusters compared to CLASH clusters.

(Contours: Number of lensed JWST sources at z$\simeq$1–15 to AB$\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 $\lambda_{rest} \simeq 1.6 \mu$m (Kim et al. 2017).

JWST-NIRCam peaks in sensitivity for λ=3–5μm, 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?

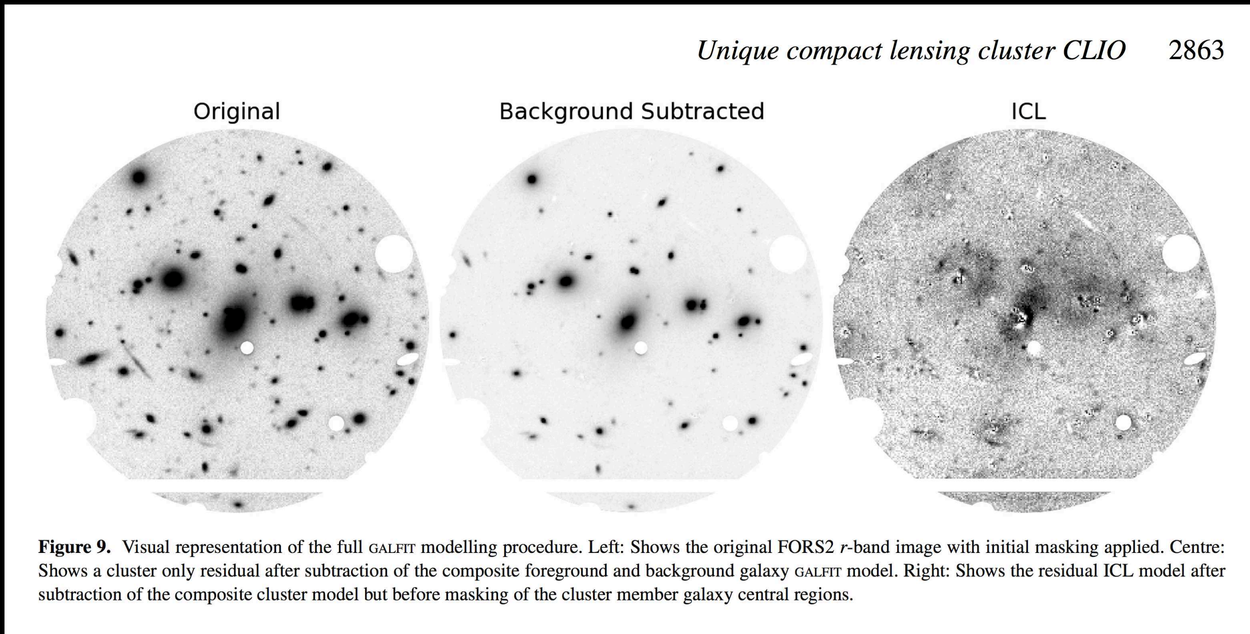
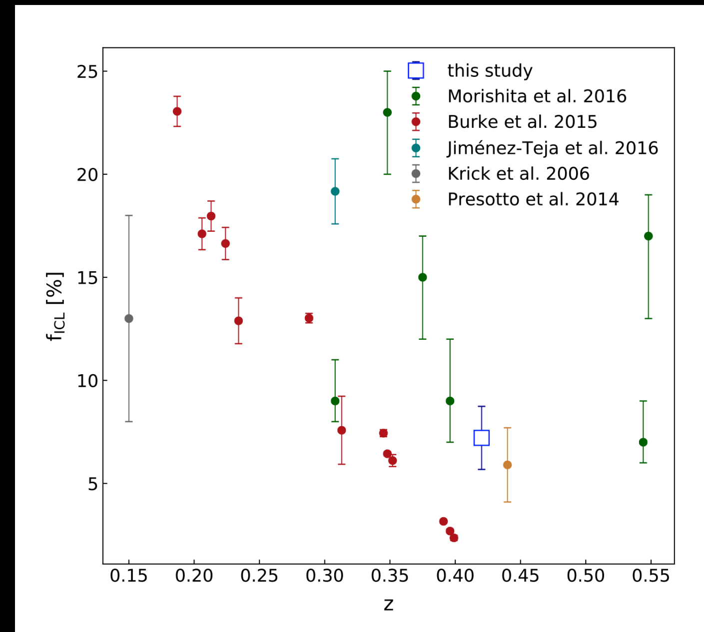


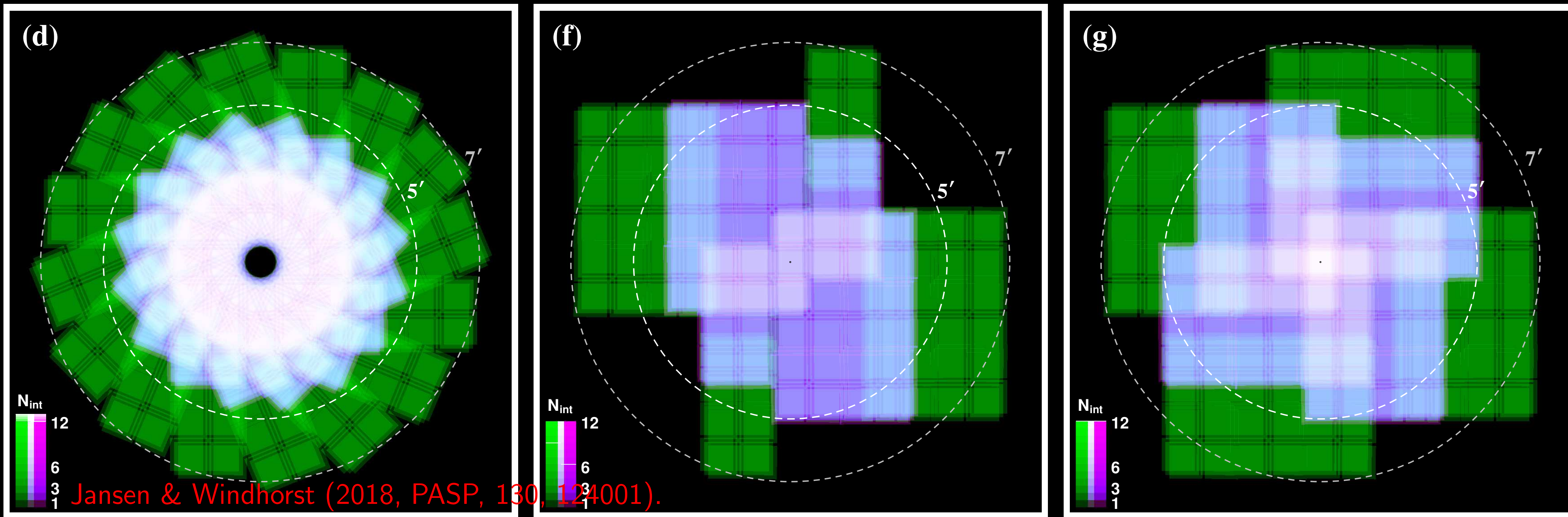
Figure 9. Visual representation of the full GALFIT modelling procedure. Left: Shows the original FORS2 *r*-band image with initial masking applied. Centre: Shows a cluster only residual after subtraction of the composite foreground and background galaxy GALFIT model. Right: Shows the residual ICL model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

- References and other sources of material shown:

http://www.asu.edu/clas/hst/www/jwst/ [Talk, Movie, Java-tool]

http://www.asu.edu/clas/hst/www/ahah/ [Hubble at Hyperspeed Java–tool]

http://www.asu.edu/clas/hst/www/jwst/clickonHUDF/ [Clickable HUDF map]

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

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).

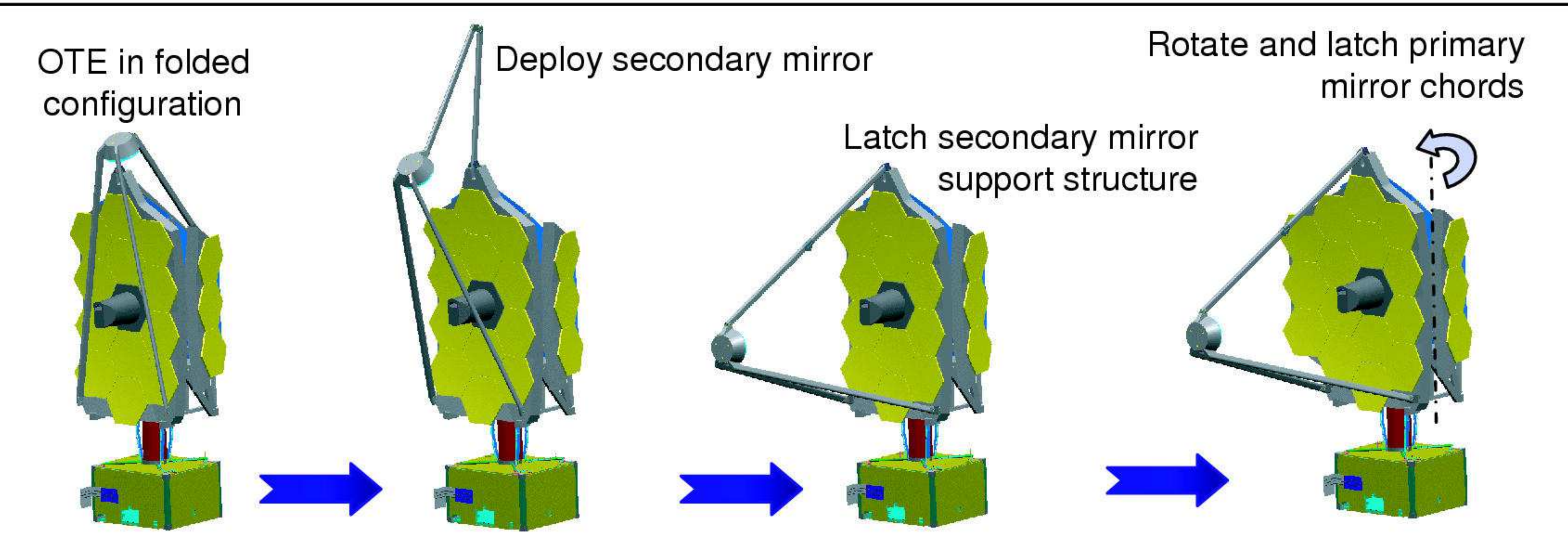
Any (space) mission is a balance between what science demands, what technology can do, and what budget & schedule allows ... (courtesy Prof. R. Ellis).

• (6) Update of JWST programmatics as of 2020

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

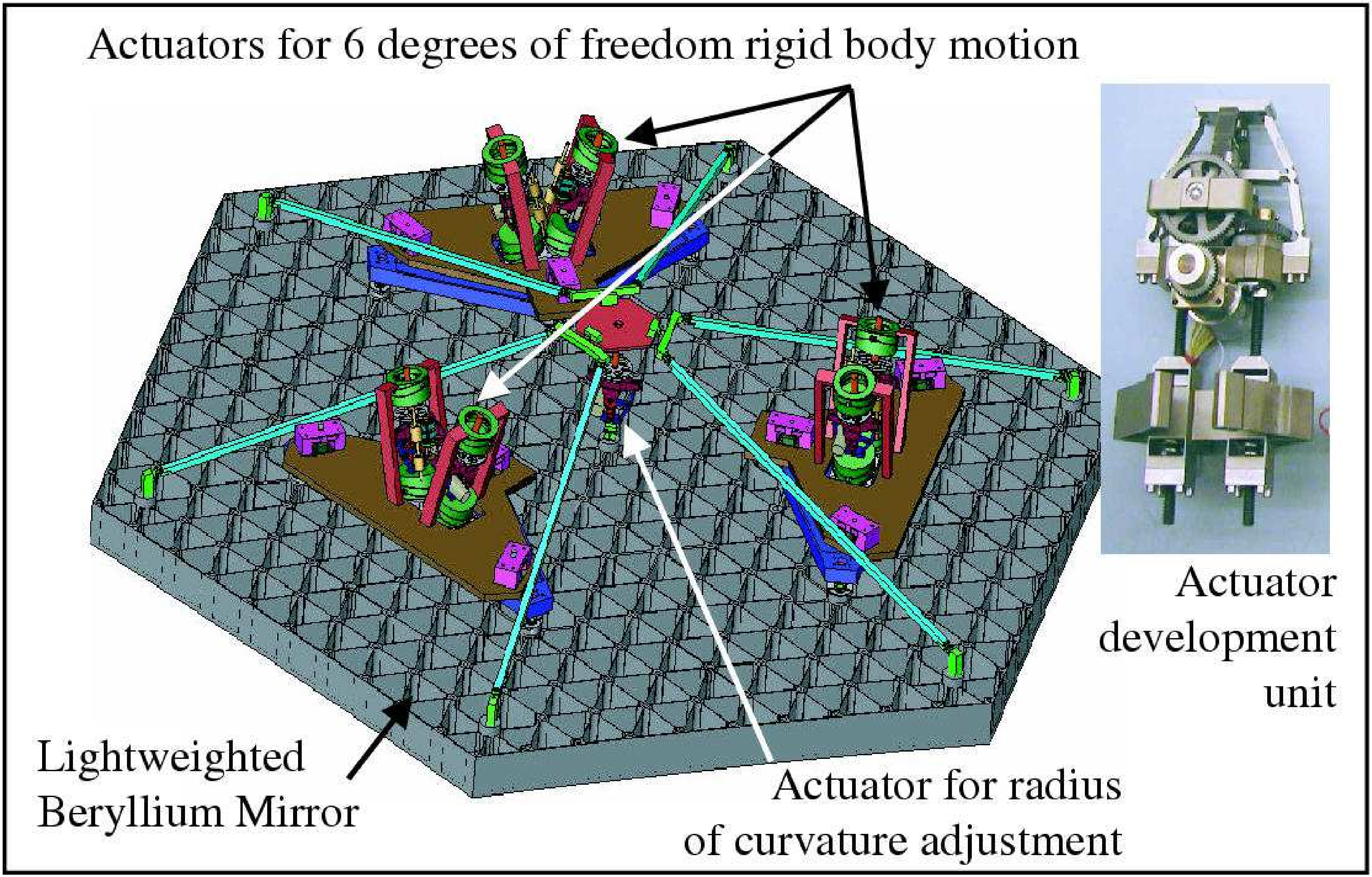
• (1b) How will JWST be automatically deployed?



• During its two month journey to L2, JWST will be automatically deployed, its instruments will be cooled, and be inserted into an L2 orbit.

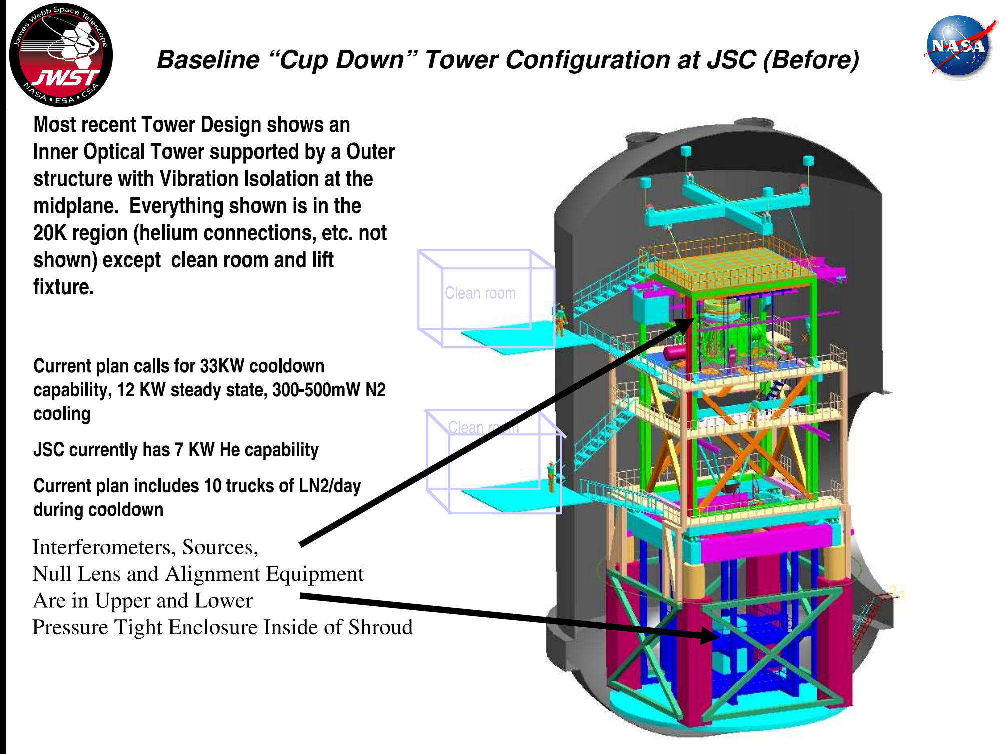
• The entire JWST deployment sequence is tested several times in 1-G from 2014–2019 at GSFC (MD), Northrop (CA), and JSC (Houston).

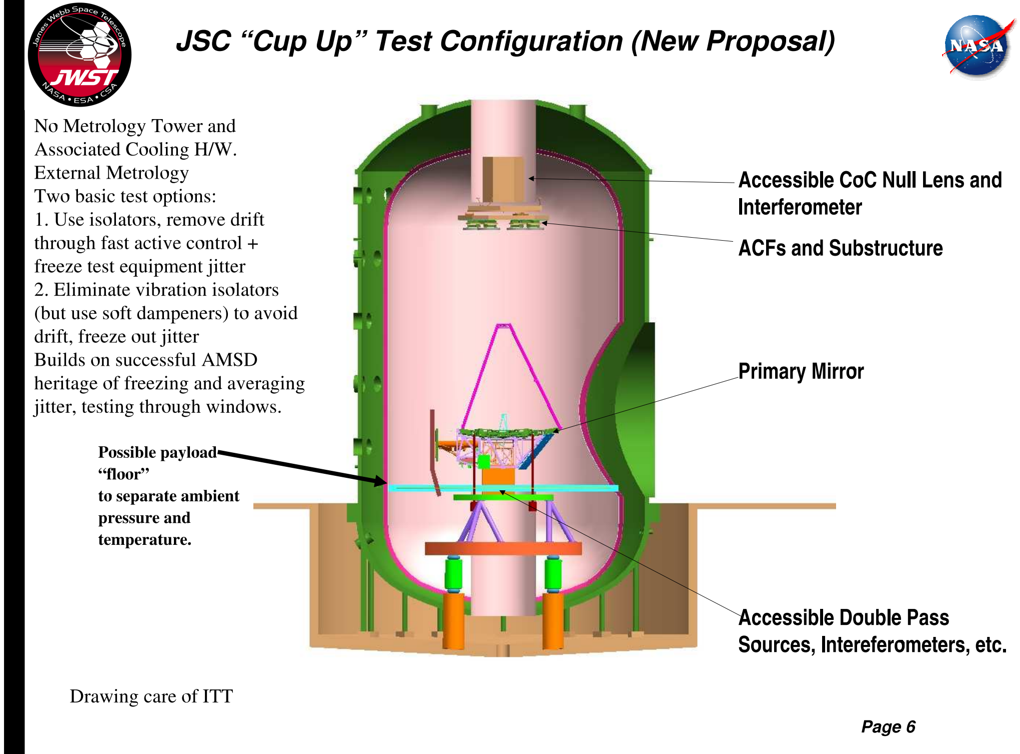
• All 18 flight mirrors completely done, and meet the 40K specifications.



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

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





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 μm performance specs (kept 2.0 μm).
- 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 $\Rightarrow$ Oct. 2021 launch.

Fiscal Year 2019 JWST HQ Milestones

Month		Milestone	Comment
Oct-18	1	Conduct Wavefront Sensing rehearsal #2 at the Missions Operations Center (MOC)	Completed 10/6/18
	2	Stow the sunshield into launch position following repairs of the membrane covers	Completed 9/28/18
	3	Spacecraft Element (SCE) ready for resumption of environmental testing following MCA repairs	Completed 10/19/18
Nov-18	4	Complete Spacecraft Element Acoustic Test	Completed 10/28/18
	5	Deliver Observatory Science and Operations software build	Completed 10/19/18
Dec-18	6	Conduct Science Operations rehearsal #4 at the MOC	Completed 12/21/18
	7	Begin Spacecraft Element vibration testing	Completed 11/15/18
	8	Complete the validation of science payload software	Completed 10/27/18
Jan-19	9	Conduct a SCE Comprehensive System Test in preparation for thermal vacuum testing	Completed 9/26/18
Feb-19	10	Deliver final results for SCE environmental testing	Complete 4/5/2019
	11	Conduct Early Commissioning Exercise #2 at the MOC	Completed 3/6/2019 (Government shutdown delay)
Mar-19	12	Begin Spacecraft Element thermal vacuum test	Completed 4/7/19
	13	Deliver the flight version of launch vehicle coupled loads analysis #2 Observatory model	Completed 5/6/19
Apr-19	14	Open thermal vacuum chamber door following testing	Completed 5/19/19
	15	Conduct Wavefront Sensing rehearsal #3 at the MOC	Completed 4/12/19
May-19	-	NONE	
Jun-19	16	Complete Spacecraft Element post-launch environmental testing deployment	replanned to follow science payload installation (FY20)
	17	Complete the secondary mirror structure deployment driven by the Spacecraft Element	Completed 7/13/19
Jul-19	18	Received updated Cycle 1 proposals from the Guaranteed Time Observers	Completed 6/25/19
	19	Conduct Science Operations rehearsal #5 at the MOC	Completed 7/12/19
Aug-19	20	Complete Spacecraft Element post-launch environments and thermal vacuum testing folding	replanned to follow science payload installation (FY20)
	21	Observatory System Integration Review (SIR)	Completed 7/25/2019 (Part 1), 10/19 (Part 2)
Sep-19	22	Install science payload onto the Spacecraft Element	Completed 8/23/19
	23	Deliver the flight version of launch vehicle coupled loads analysis #2 results and detailed assessment	replanned to follow science payload installation (FY20)
	24	Spacecraft Element Integration complete	Completed 6/29/19
	25	Conduct Contingency Planning rehearsal #3 at the MOC	Completed 9/27/19

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

Project back on track in Fall 2018/early 2019 to launch in Oct 2021.

Milestone Performance

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

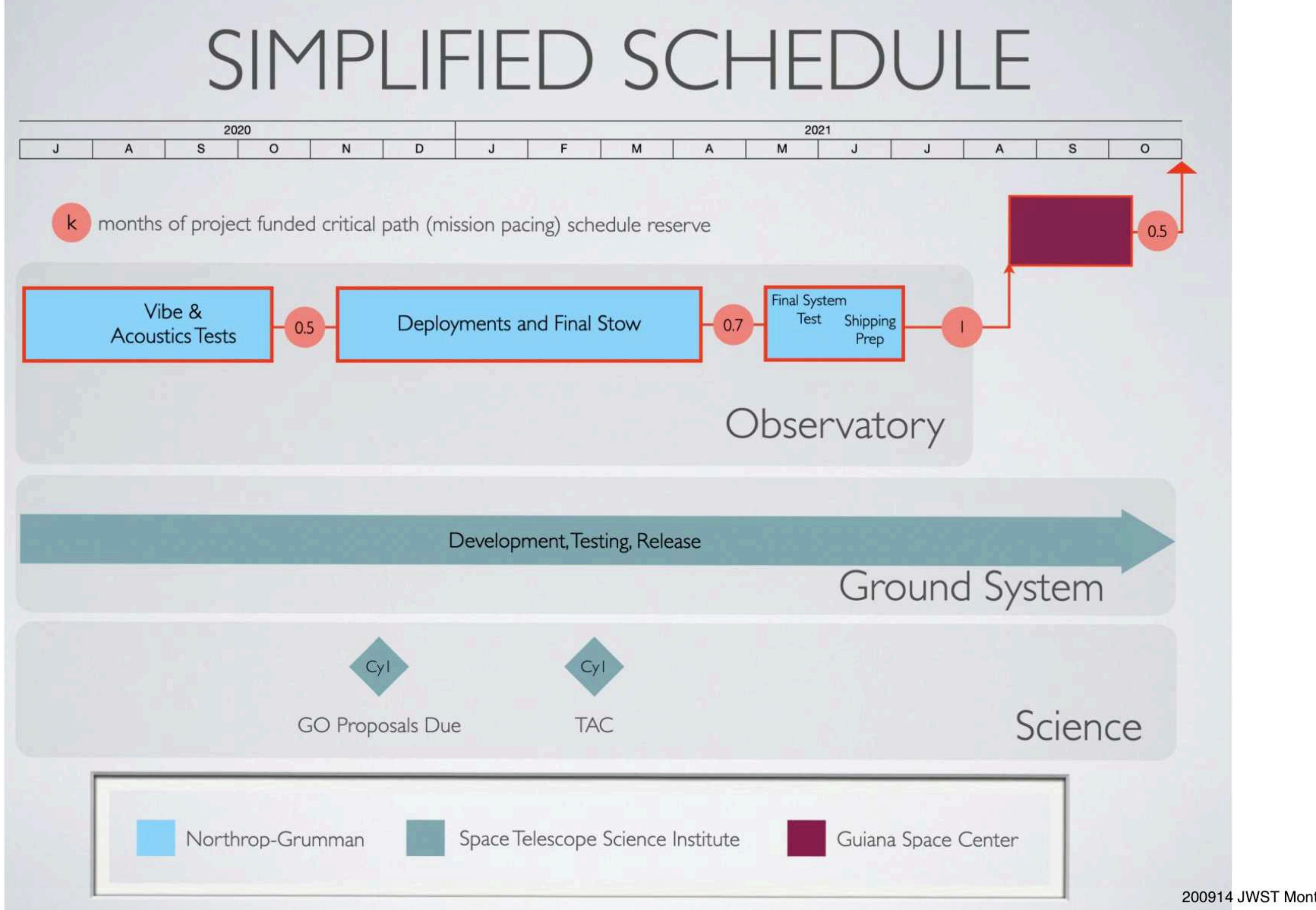
	Total Milestones	Total Milestones Completed	Number Completed Early	Number Completed Late	Deferred to Next Year	Deferred more than one quarter
FY2011	21	21	6	3	0	0
FY2012	37	34	16	2	3	3
FY2013	41	38	20	5	3	2
FY2014❖	36	23	10	8	11	10
FY2015	48	44	22	12	4	3
FY2016	45	39	25	7	6	2
FY2017	38	32	12	13	8	5
FY2018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

FY14: 8 milestones late by 1 month due to Oct 13 Government shutdown.

FY15: Most "Lates" not on critical path.

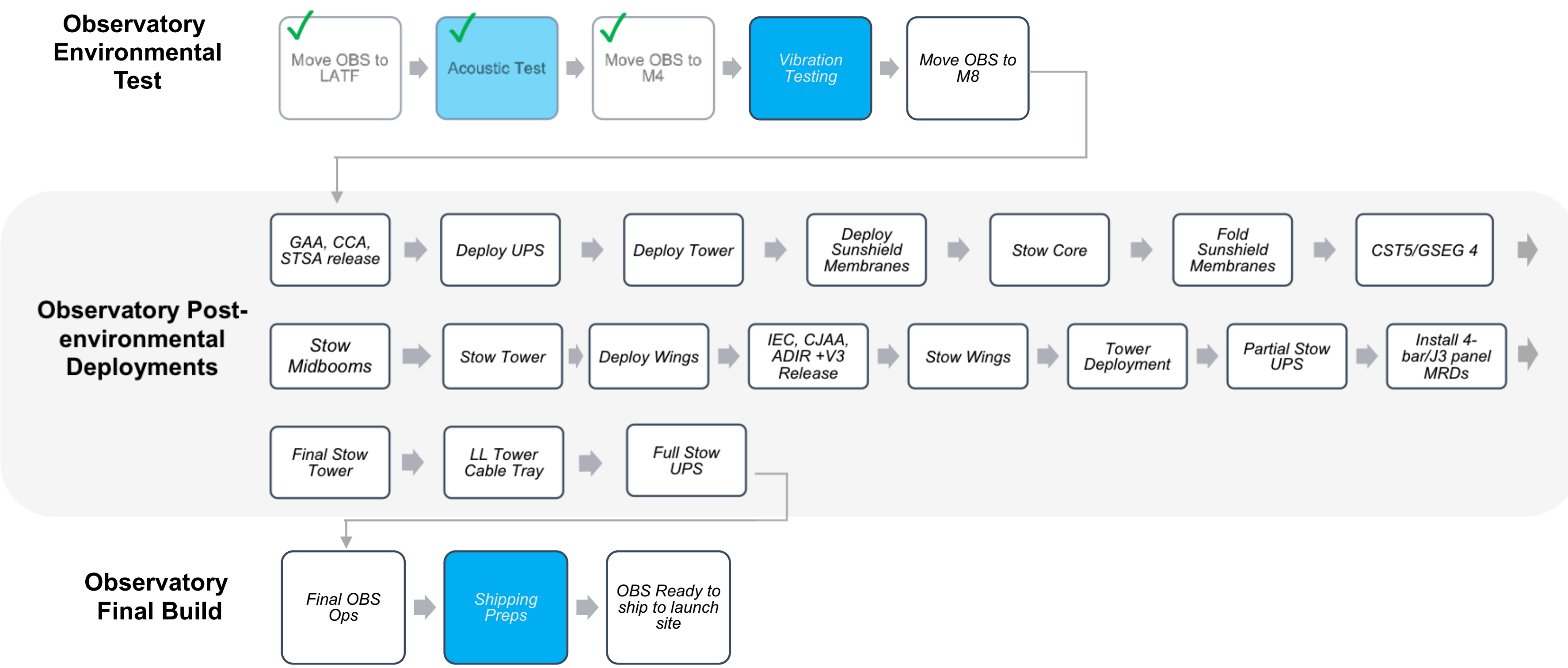
FY17: Lates started to outnumber Early's $\Rightarrow$ Replan Integration & Testing.



Path forward to Launch (NOW: Oct 2021): $\lesssim$2.7 mos schedule reserve.

- Final testing done in Fall 2020/Spring 2021 (at Northrop).

Remaining I&T Activities



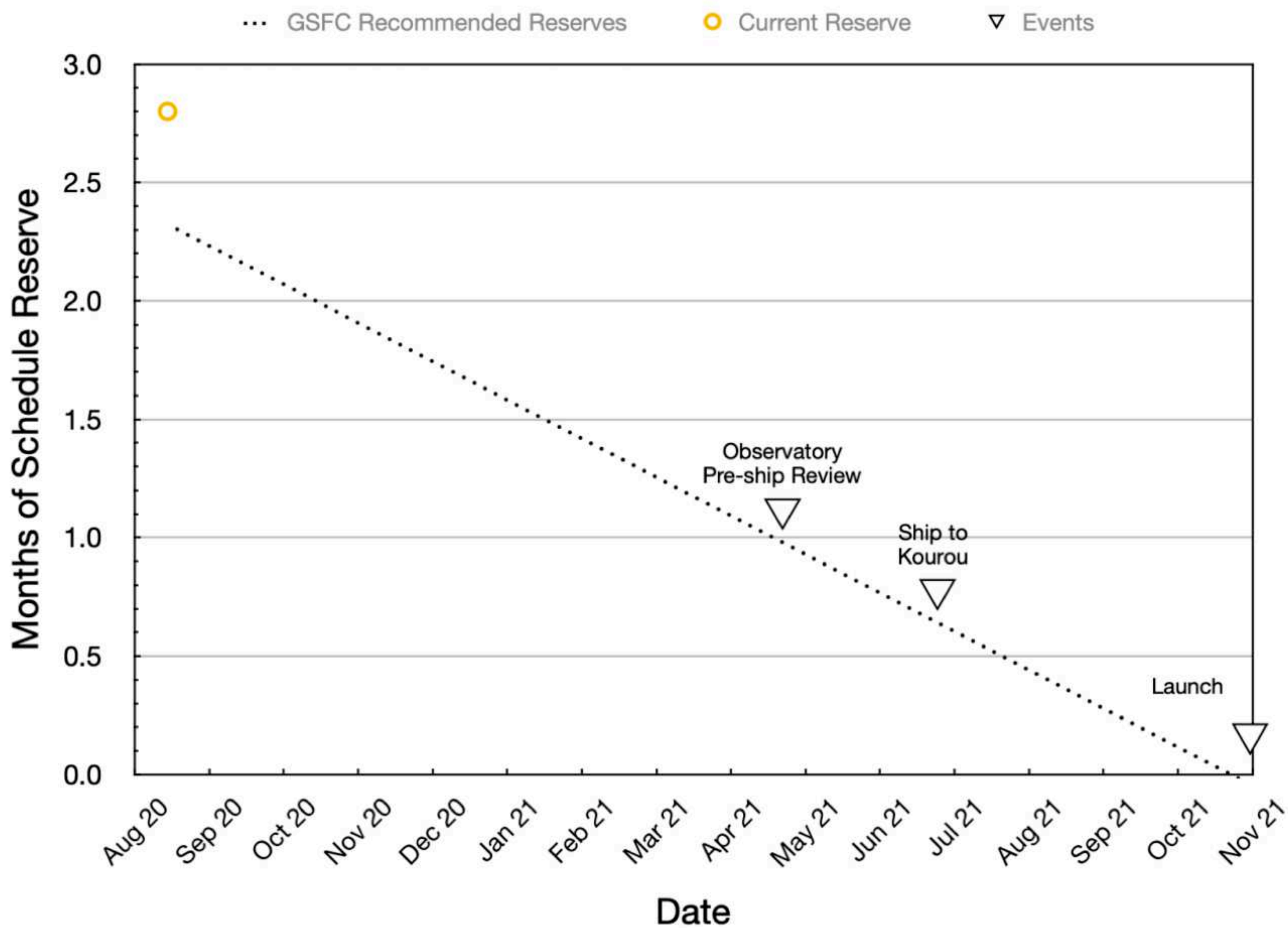
✓ = Completed activities

Blue boxes are first time activities

Flowchart of future Project tasks for FY21.

Blue = First-time System test (but done before at the sub-system level).

Current Funded Schedule Reserve



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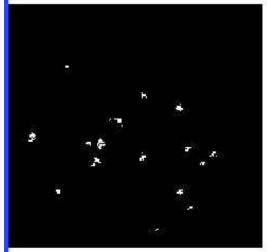
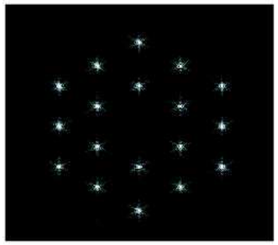
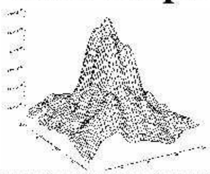
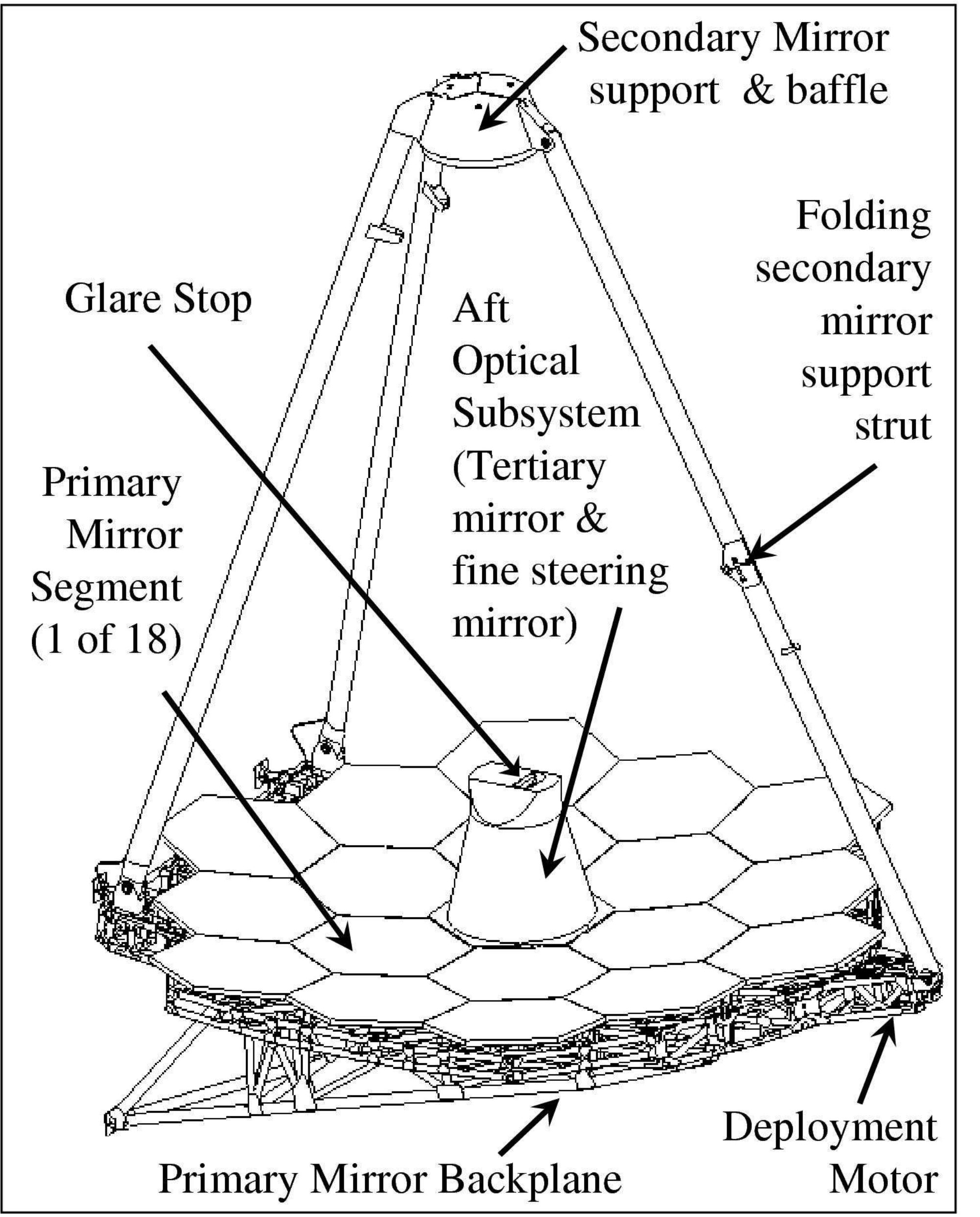
Project reserves in Fall 2020 for launch in Oct 2021.

		Initial Capture	Final Condition
First light NIRCam  1. Segment Image Capture	After Step 1 	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 μm, < 2 arcsec tilt SM: < 3 mm, < 5 arcmin tilt
2. Coarse Alignment Secondary mirror aligned Primary RoC adjusted	After Step 2 	Primary Mirror segments: < 1 mm, < 10 arcsec tilt Secondary Mirror : < 3 mm, < 5 arcmin tilt	WFE < 200 μm (rms)
3. Coarse Phasing - Fine Guiding (PMSA piston)	After Step 3 	WFE: < 250 μm rms	WFE < 1 μm (rms)
4. Fine Phasing	After Step 4 	WFE: < 5 μm (rms)	WFE < 110 nm (rms)
5. Image-Based Wavefront Monitoring	After Step 5 	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.



Wave-Front Sensing tested hands-off at 40 K in 1-G at JSC in 2015–2017.

Ball 1/6 scale-model for WFS: produces diffraction-limited 2.0 μm images.