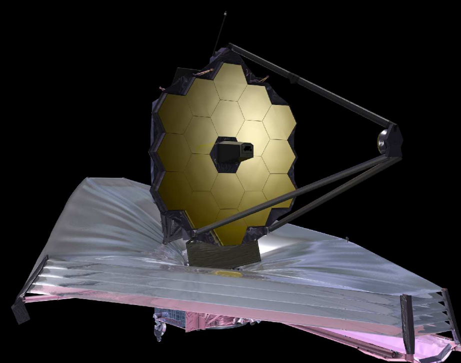
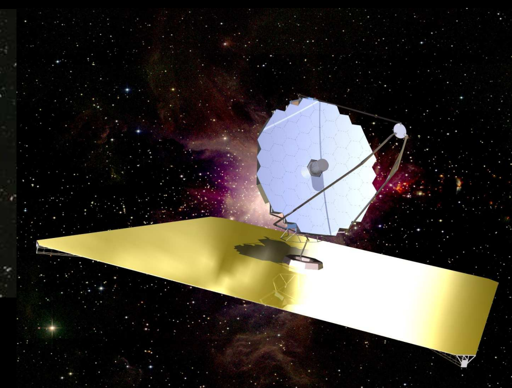
# Lessons learned from JWST:
# What is required to make Mega-Science projects succeed?

**Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist**

**and Robert W. Smith (U. Alberta, Edmonton, Canada; HST& JWST historian)**



*Lunch talk at various institutions; Fall 2020*

*All presented materials are ITAR-cleared. These are my opinions only, not necessarily NASA's or ASU's.*

# Outline: Lessons from JWST

• JWST Lessons: Mega-project lessons also apply to HST & Supercollider. Key is that scale of efforts goes beyond what people are used to.

• Mega-projects demand new rules, in particular regarding building and keeping together a *strong Coalition* of project supporters and advocates.

Consumers Report: Very Good ⇒ Good ⇒ Neutral ⇒ Fair ⇒ Poor.

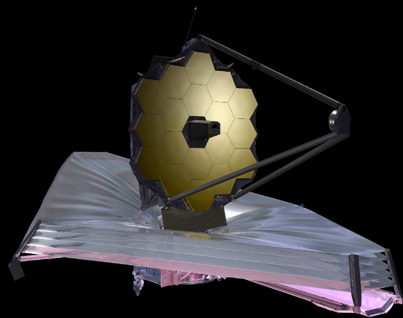
- (A) Scientific/Astro-Community Lessons
- (B) Technical Lessons
- (C) Management/Budget/Schedule Lessons
- (D) Political/Outreach Lessons

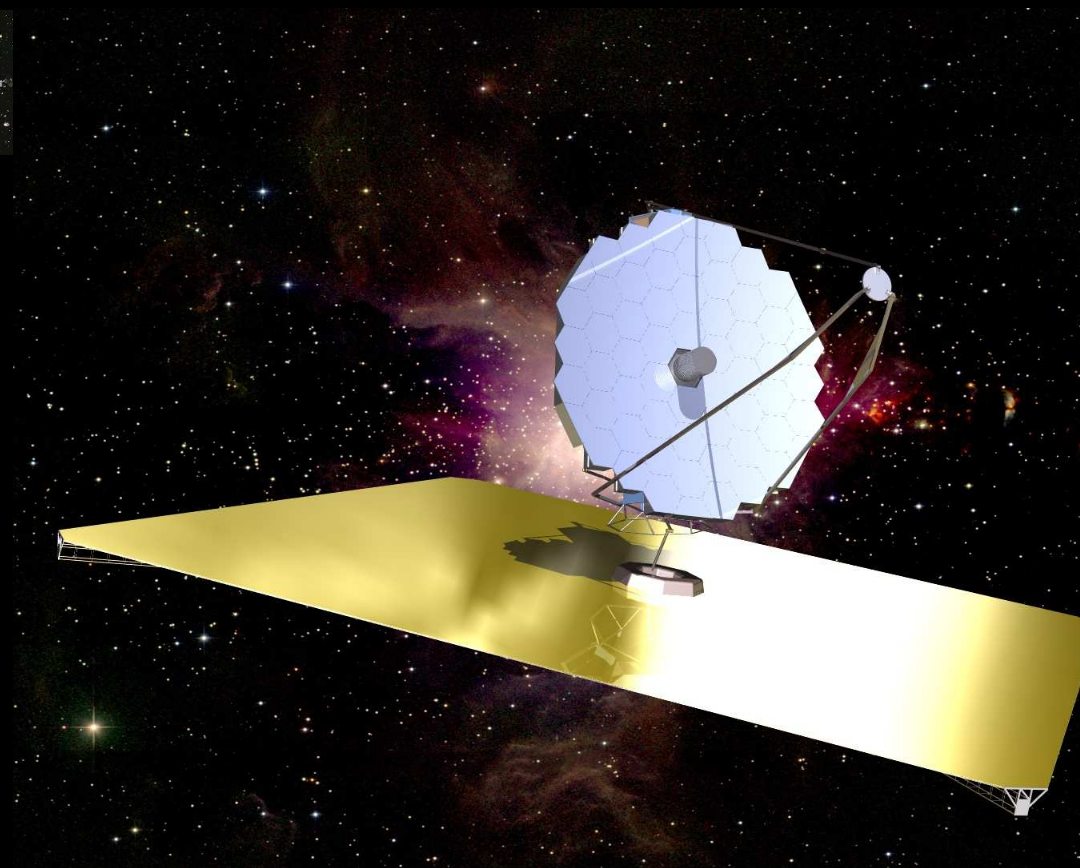
*I thank Dr. Seth Cohen, Garth Illingworth, Rolf Jansen, John Mather, Eric Smith and Harley Thronson for useful comments.*

Talk is on: `http://www.asu.edu/clas/hst/www/jwst/jwsttalks/groningen17_jwstlessons.pdf`

# Past, Present and Future: Can and will the dream continue?

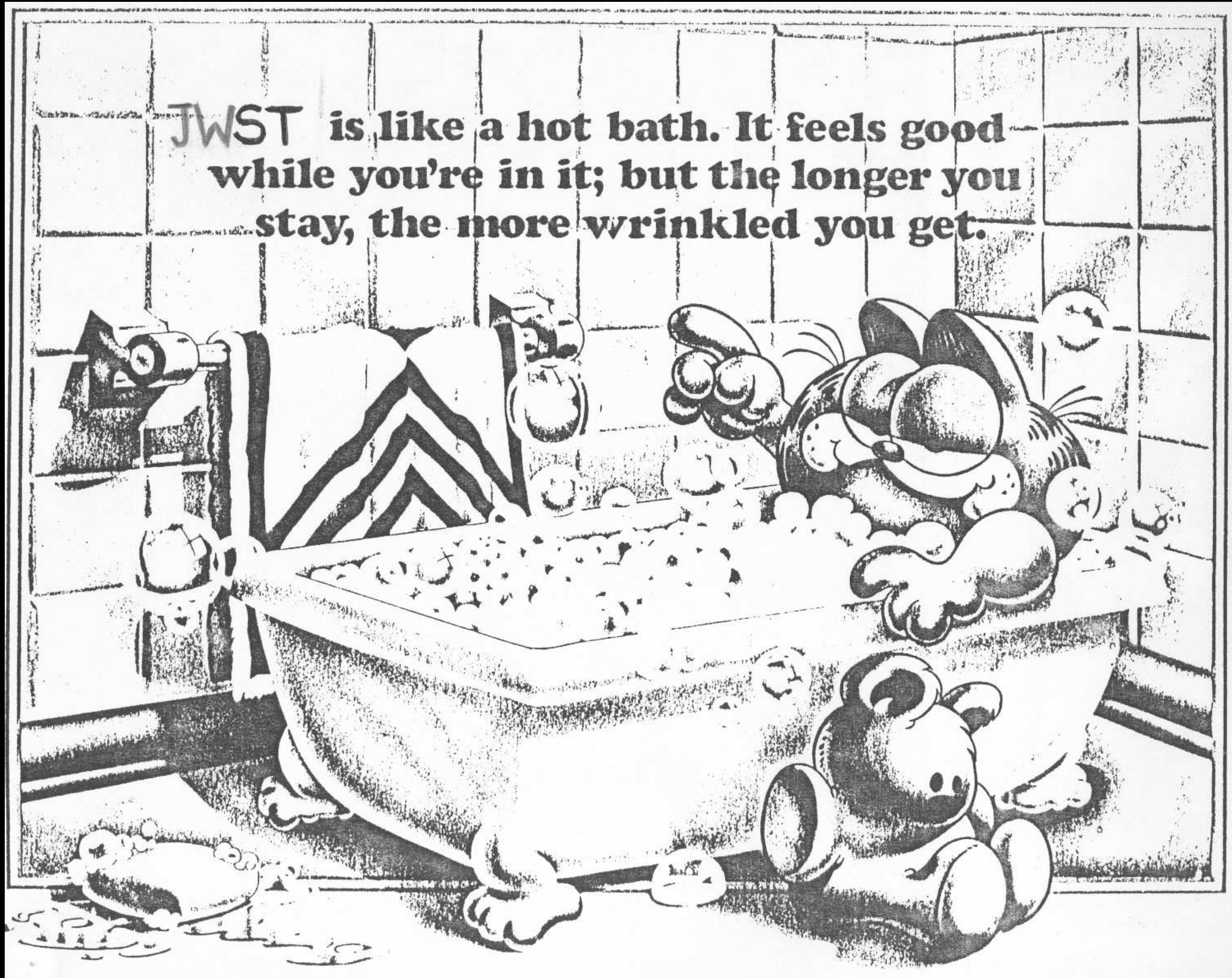
## True relative size: Hubble, James Webb, WFIRST, & ATLAST (HDST)



| | | | |
|---|---|---|---|
| 1965–2020$^+$(!) | 1996–2031 | 2012–2035? | 2020–2050$^+$? |
| Launch: 1990 | 2021 | $\gtrsim$2025? | $\gtrsim$2035? |
| $\Sigma_{FC}$: $\sim$20 B$ | $\sim$10 B$ | $\gtrsim$3 B$? | 15–20 B$? |

My goal today: Inspire the younger folks to successfully build WFIRST and ATLAST (Advanced Technology Large Area Space Telescope; HDST).




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

You will feel wrinkled before you know it ... :) (chart from Jim Westphal's office, 1987).

James Webb said in 1969: "In our pluralistic society, any major public undertaking requires for success a working consensus among diverse individuals, groups, and interests. A decision to do a large, complex job cannot simply be reached "at the top" ad then carried through. Only through an intricate process can a major undertaking be gotten under way, and only through a continuation of that process can it be kept going."

(See quotes in front of Robert Smith's 1993 book: "The Space Telescope").

- Main message: Build and maintain a "Coalition" of strong project supporters for a "Mega-Project".

- A Mega-project not only has to be technically feasible, but it also must be and remain politically feasible.

Edmund Burke (1729–1797): "Those who carry on great public plans must be proof against the worst delays, the most mortifying disappointment, the most shocking insult, and what is worst of all, the presumptuous judgment of the ignorant upon their design. "

Avoid: "History *teaches* us that mankind *learned* nothing from history" (G. W. F. Hegel 1832).

# (1) JWST Lessons: (Hubble WFC3 images, $\gtrsim$15 years after it was nearly "canceled" twice ...)

10 filters HST/WFC3 & ACS in ERS reaching AB=26.5-27.0 mag (10-$\sigma$) over 40 arcmin$^2$ at 0.07–0.15" FWHM from 0.2–1.7$\mu$m (UVUBVizYJH).

JWST provides 0.05–0.2" FWHM images to AB$\simeq$31.5 mag (1 nJy) at 1–5$\mu$m, and 0.2–1.2" FWHM at 5–29$\mu$m, tracing young+old SEDs & dust.

# (A) Scientific/Astro-community lessons from JWST

For a Mega-project to succeed, make sure that you DO:

- 1) Have ($\gtrsim$1) killer apps with full community support. (Be exciting enough that some dedicate most of their careers to make it happen).
- 2) Project is a must-do scientifically and cannot be done any other way.
- 3) Project highly ranked by community reviews/Decadal surveys.
- 4) Identify and highlight complementarity with other large facilities.
- 5) Still like the science and the project $\gtrsim$10–20 years later.
- 6) Offer project science and grant support to the whole community.
- 7) Keep *advocating* Mega-project to community until launch/first light.

(J. Bahcall and L. Spitzer said they had to "Sell" the HST Project to shepherd it through the approval process. We prefer to call it: "Advocate". We must make all stakeholders aware of mission purpose and progress throughout its long life cycle).

# (A) Scientific/Astro-community lessons from JWST

For a Mega-project to succeed, make sure that you DON'T:

- 1) Have community infighting ("My mission is better than yours" — One key reason for Supercollider (SSC) demise).

(John Mather: "Management levels above the Mega-project need to help avoid community infighting, and work with advisory groups to ensure that everyone can see the choices. Complete openness is the key").

- 2) Have other projects canceled because of your Project, or perception thereof. Don't make enemies whenever possible.

- 3) Have science and grant support for a selected few.

- 4) Have GTO's be elite: they must serve & represent the community.

- 5) Ignore community input on project science priorities.

- 6) Ever ignore importance of great communication with U.S. patrons: Scientists, contractors, tax-payers, Congress, White House.

- 7) Ever ignore importance of great communication with foreign partners. (International projects are more robust politically, see e.g., SSC).


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

## (B) Technical Lessons from the JWST Project

For a Mega-project to succeed, make sure that you DO:

- 1) Use advanced technologies being developed elsewhere, if possible.
- 2) Use latest proven technology where you can for killer science apps.
- 3) Know when not to select the most risky technologies.
- 4) Do your hardest technology development upfront. Have all critical components at TRL-6 before Mission Preliminary Design Review (PDR).

(Eric Smith: "Even after insuring TRL-6, you need to prove and test manufacturability of the technologies. Creation in a laboratory is not the same as proving something can be built reliably by industry.")

- 5) Only design to specs you need and can afford to fabricate & test.
- 6) Test, test, and retest where needed.
- 7) Have strong central control of systems engineering.

## (B) Technical Lessons from the JWST Project

For a Mega-project to succeed, make sure that you DON'T:

- 1) Use technologies below TRL-6 at Mission PDR.

- 2) Defer project component PDR's or CDR's to well after Mission PDR or CDR, resp.

- 3) Do system tests whose outcome do not make you change course.

- 4) Ask for 1$\mu$m diffraction limit unless you must have & can afford it.

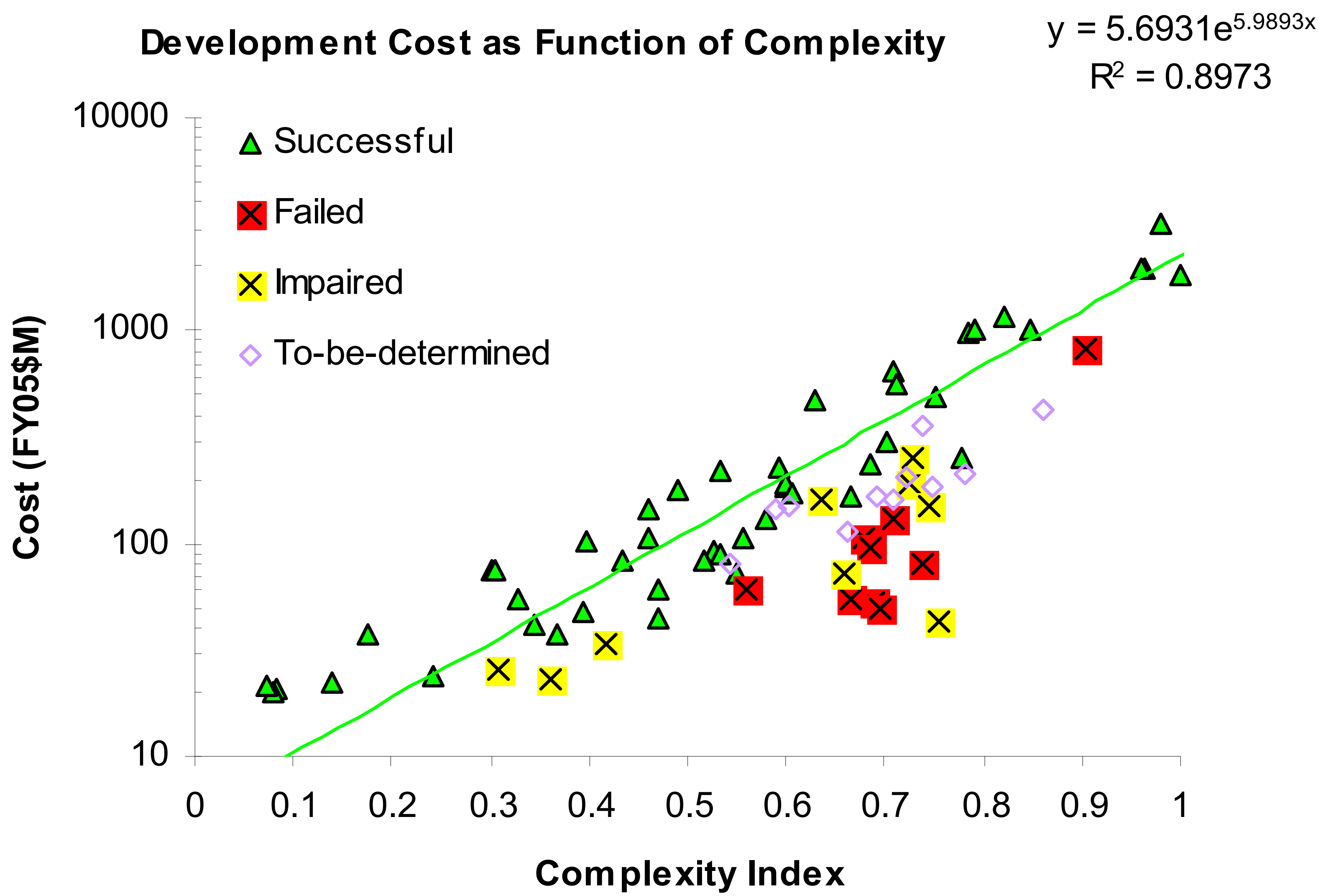
- 5) [If you can't afford 1$\mu$m JWST diffraction limit, HOLD ground at 2.0$\mu$, AND insist best effort made at 1$\mu$ without being cost-driver.]

- 6) Allow scientists to change requirements after Phase A (unless to reduce risk).

Def: TRL-6 = "(Sub-)system model or prototyping demonstration in a relevant end-to-end environment (ground or space)."

Def: PDR = Preliminary, CDR = Critical Design Review.

# When is a Mission Too Cheap?*




* "A Complexity-based Risk Assessment of Low-Cost Planetary Missions: When is a Mission Too Fast and Too Cheap?", Bearden, D. A.





AEROSPACE

# (C) Management/Budget/Schedule Lessons from JWST

For a Mega-project to succeed, make sure that you DO:

- 1) Have competent *AND* project-friendly management in *ALL* of NASA.

- 2) Make conservative full end-to-end budget before Mission CDR.

(John Mather: Need correct cost analysis before final commitments are made. NASA has the responsibility to get it right).

- 3) Make sure budgets are externally reviewed, and at $\gtrsim$80% joint cost+ schedule confidence level. (Could not do $\lesssim$2010; Did so early 2011).

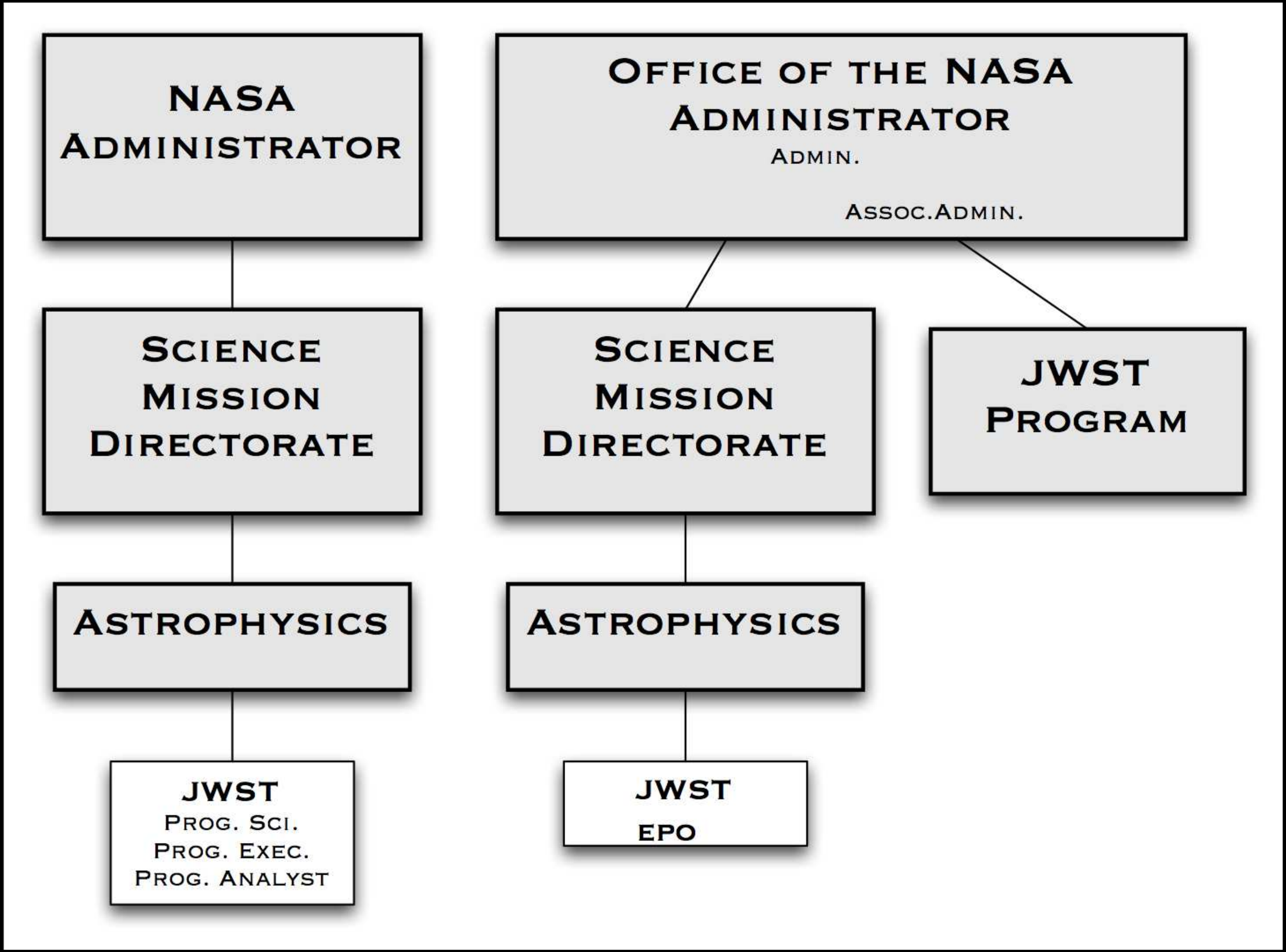
- 4) Plan & effectively use 25–30% ($+schedule!) contingency each FY.

(Harley Thronson: "Corollary of (3)–(4): Although cost and schedule control must be introduced from the start, do not (cannot) undertake costing too early in the process.")

- 5) Have a viable list of cost-saving and meaningful descopes.

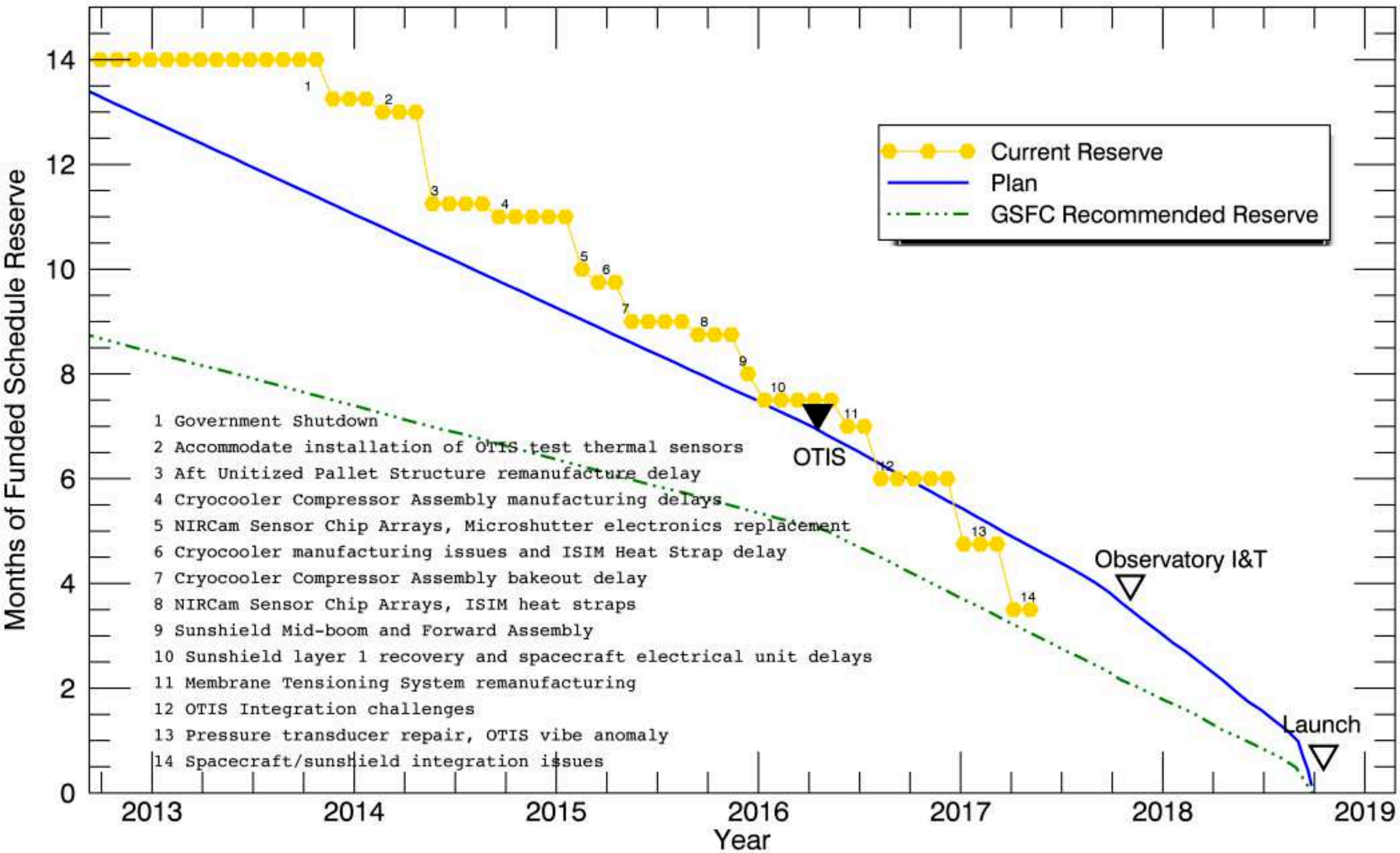
(John Mather/Eric Smith: "Don't overestimate the benefit of descopes. After a commitment is made (in Phase C/D), it is extremely expensive — and may be an international incident — to delete components that have been accepted into the mission. Scientists must learn to accept descopes in Phase A — the power-point phase — when they are still feasible, and often essential to have a mission survive.")

# How to launch JWST while minimizing impact on NASA Space Science?




NASA HQ Reorg: JWST budget no longer comes from SMD/ASD (Left); JWST was moved to be directly under the NASA Administrator (Right).

# Funded Schedule Reserve




Keys to stay on schedule: 1) Sufficient Project contingency ($\gtrsim$25% of total).
2) Well replanned and managed Project (starting late summer 2011).

# Fiscal Year 2017 JWST HQ Milestones

| Month | | Milestone | FY2016 Deferral | Comment |
|---|---|---|---|---|
| Oct-16 | 1 | Complete portable clean room for Telescope and Science Instruments (OTIS) | | Completed 10/13/16 |
| | 2 | Complete final checkout of new shaker tables at Goddard Space Flight Center | • | Completed 10/13/16 |
| | 3 | Begin making electrical connections between spacecraft panels | | Completed 10/7/16 |
| | 4 | Complete Sunshield Mid-Boom Assembly #2 functional test | • | Completed 12/5/16 |
| Nov-16 | 5 | Start optical measurements of OTIS prior to vibration and acoustic tests | | Completed 10/24/16 |
| | 6 | Deliver Science and Operations Center release 1 | | Completed 9/30/16 |
| | 7 | Perform Cryocooler installation into the spacecraft bus and begin functional testing | | Completed 10/29/16 |
| | 8 | Complete Aft Unitized Pallet Structure assembly | • | Completed 10/29/16 |
| | 9 | Deliver Aft Unitized Pallet Structure to Observatory I&T | • | Completed 3/14/17 |
| Dec-16 | 10 | Deliver Forward Sunshield Pallet Structure to Observatory Integration and Test (I&T) | • | Completed 3/28/17 |
| | 11 | Start OTIS vibration and acoustic testing program | | Completed 11/19/16 |
| | 12 | Complete final test of engineering model of telescope center section at Johnson Space Center (JSC) | | Completed 10/31/16 |
| | 13 | Deliver sunshield flight membranes to Observatory I&T | | Completed 12/15/16 |
| Jan-17 | 14 | Complete OTIS vibration and acoustics testing | | Completed 3/2/17 |
| | 15 | Deliver observing proposal and planning subsystem software build that supports launch | | Completed 1/12/17 |
| | 16 | Complete electrical testing of the spacecraft at Northrop-Grumman | | Completed 3/7/17 |
| Feb-17 | 17 | Complete OTIS optical measurements after vibration and acoustic tests | | Completed 3/31/17 |
| | 18 | Deliver wavefront and control software that supports launch (controls telescope mirror shape) | | Completed 1/20/17 |
| | 19 | Deliver horizontal deployable radiators to Observatory I&T | | Delayed June for release testing |
| Mar-17 | 20 | Deliver OTIS to the Johnson Space Center | | Completed 5/7/17 |
| | 21 | Deliver the pre-launch Flight Operations System software build | | Completed 2/17/17 |
| | 22 | Delivery of sunshield extension boom #2 membrane attachment assembly to Observatory I&T | | Completed 4/13/17 |

Blue font(underline) denotes milestones accomplished ahead of schedule, orange font denotes milestones accomplished late. "•" denotes 2016 milestones carried forward.



Milestones: How the Project reports its progress monthly to Congress.

Key is constant & full communication, and always see problems coming.

# 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 | 24 | 11 | 17* | 3 | 1 |

*Late milestones have been completed late within the year or are forecast to complete late within the year. Deferred milestones are not included in the number-completed-late tally.

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

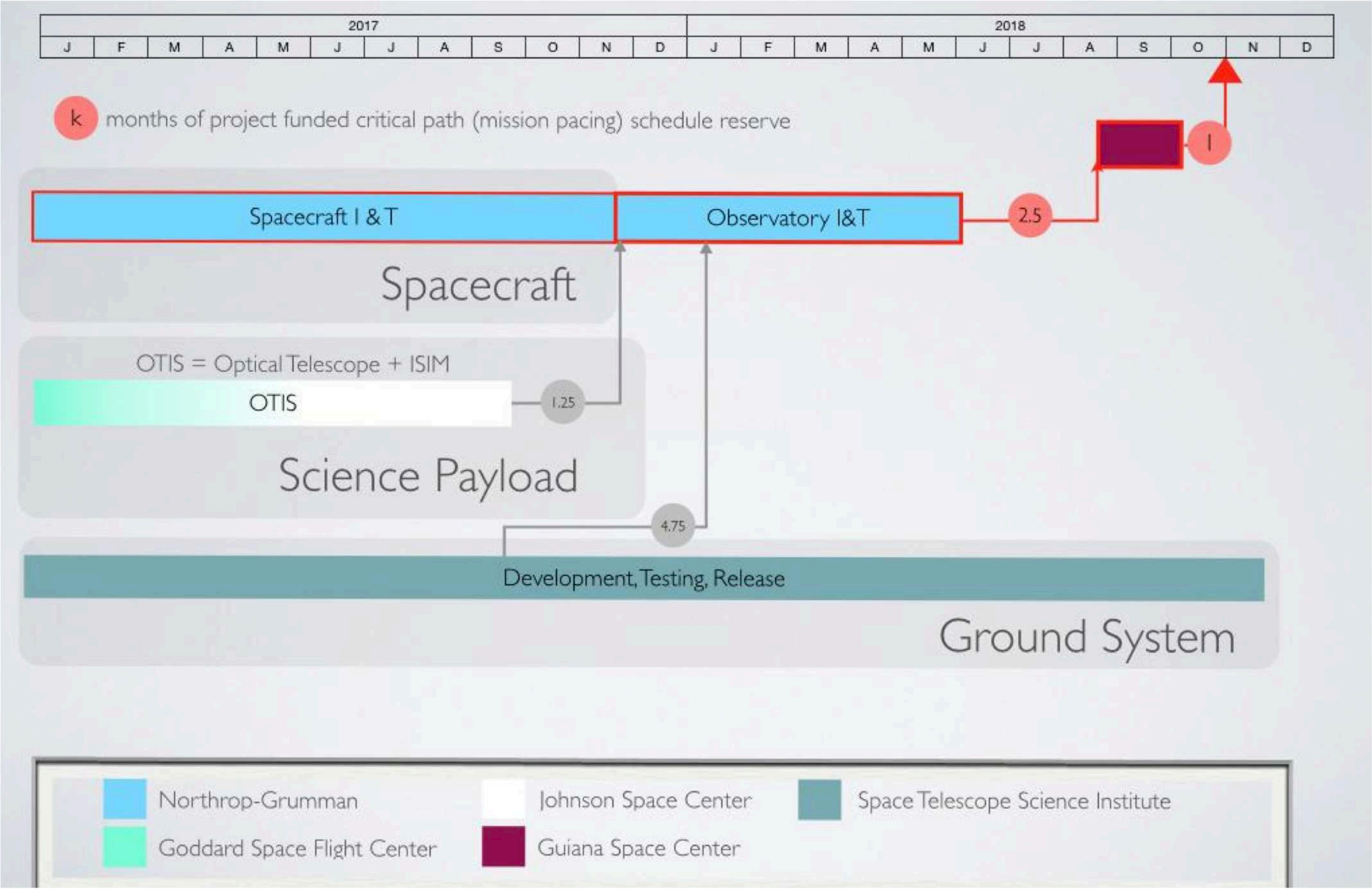


FY14: 8 milestones late by 1 month due to Oct 13 Government shutdown.

FY15, F16: Most "Lates" not on critical path, nor cause a launch delay.

FY17: Most "Lates" anticipated to finish with FY, not causing launch delay.

# Simplified Schedule




170612 JWST Monthly Telecon 5

Path forward to Launch (in Oct. 2021): $\lesssim$10 months schedule reserve.

Instruments+detectors & Optical Telescope Element remain on critical path.

## (C) Management/Budget/Schedule Lessons from JWST

For a Mega-project to succeed, make sure that you DO (cont):

- 6) Have great communication with all (sub-)contractors.
- 7) Put management pressure on contractors, when necessary.
- 8) Have best work-force from contractors for entire length of project.
- 9) Prioritize testing, and test extensively.
- 10) Carefully construct the incentives in your industrial contracts.

(Eric Smith: For-profit companies are very adept at insuring their teams win incentives. Hence, the Project contract needs to balance its incentives to get the best possible outcome in terms of both technical performance, cost *and* schedule).

# (C) Management/Budget/Schedule Lessons from JWST

For a Mega-project to succeed, make sure that you DON'T:

- 1) Advocate project with optimistic budget estimates.

(Lesson number 1 from HST: Don't buy in at bargain prices):

HST was 450 M$ in FY78. At its 1990 launch, it was 1.5 B$ *without* the Shuttle launch or servicing cost. Jean Oliver said: "When someone asks you: Can you build it for xx $, the answer is invariably "Yes", and then folks go about making that work" (see Robert Smith's book).

(John Mather: "Our job includes communicating progress, and being as open with the world as possible. Eric Smith: Everyone is trying their best to understand the costs of things that have never before been attempted.)"

- 2) Cut project contingency to below critical mass (*i.e.* $\lesssim$25-30%/FY).

When project contingency is cut to below $\lesssim$25-30%/FY, Project managers have no choice but to defer essential tasks to next FY's, which can ruin the Project's long-term budget plan very quickly.

- 3) Try (or allow Contractors to try) to save funds by cutting corners.

(Eric Smith: If jobs are not properly allocated, the work can't be done for any price. You need individual key people and organizations, and strong central oversight.)

## (C) Management/Budget/Schedule Lessons from JWST

For a Mega-project to succeed, make sure that you DON'T (cont):

- 4) Change science requirements after Phase A (unless essential to simplify, reduce risk and cost).

- 5) Allow contractors to change requirements, or have requirements jeopardize/delay project budget/schedule.

- 6) Change contract midstream, unless it is to reduce risk.

(Eric Smith: Sometimes it's is better to take the paperwork hit if it is technically required to change a requirement as you go).

- 7) Defer project component PDR's or CDR's to well after Mission PDR or CDR, resp.

- 8) Test items without a clearly defined decision path.

Mega-project needs heritage/links to technology from other parts of govt.

Mega-project needs strong technology benefits/lessons TO other parts of govt!

# (D) Political/Outreach Lessons from JWST

For a Mega-project to succeed, make sure that you DO:

- 1) Assemble, maintain and fully use a *strong Coalition* of supporters and advocates who will fight for the project, since there will be storms and budget cancellations (HST did so successfully, SSC did so too late).

(Robert Smith: JWST didn't have its full "Coalition" in place until it got into serious budget trouble in 2010/2011).

- 2) Understand & foresee full political landscape of contractor world.

- 3) Have strong multi-partisan & multi-national support for project.

- 4) Educate, educate, and re-educate government & general public about project's essence.

(Harley Thronson: "Strong support for and opposition to Mega-projects can be as much *emotional* as rational. Not only does it matter to Coalition stakeholders whether it can be built, my state gets dollars, it is affordable, the technology is ready, and whether its science is exciting and possible. Both support and opposition can be emotional (or non-rational): pride, ego, bragging rights, reaction to animations and visualizations, and to project appearance/home institution, etc, all do matter. A Mega-project must be mindful of the very real human characteristics involved as well.")

# (D) Political/Outreach Lessons from JWST

For a Mega-project to succeed, make sure that you DO (cont):

- 5) Strong heritage/links to technology *from* other parts of government.

(Eric Smith: "Unless an item is "build-to-print", the heritage benefit may not be great. We often have to modify items enough that we are making a new item effectively.")

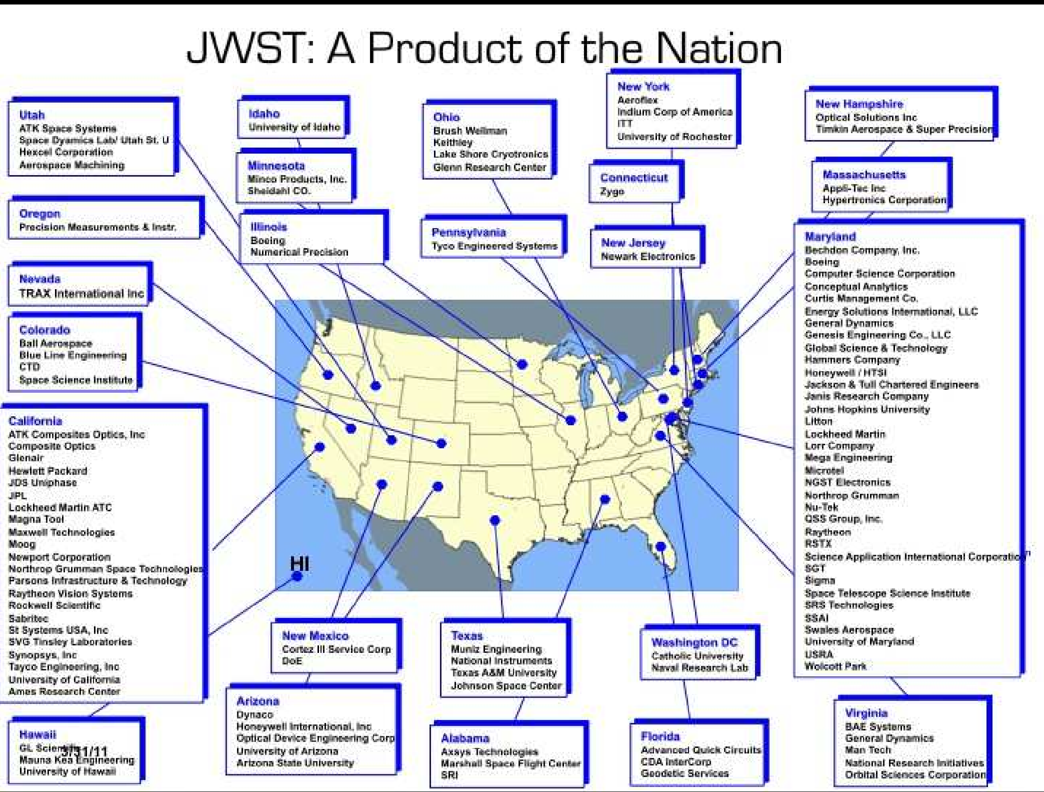
- 6) Strong technology benefits/lessons *TO* other parts of government.

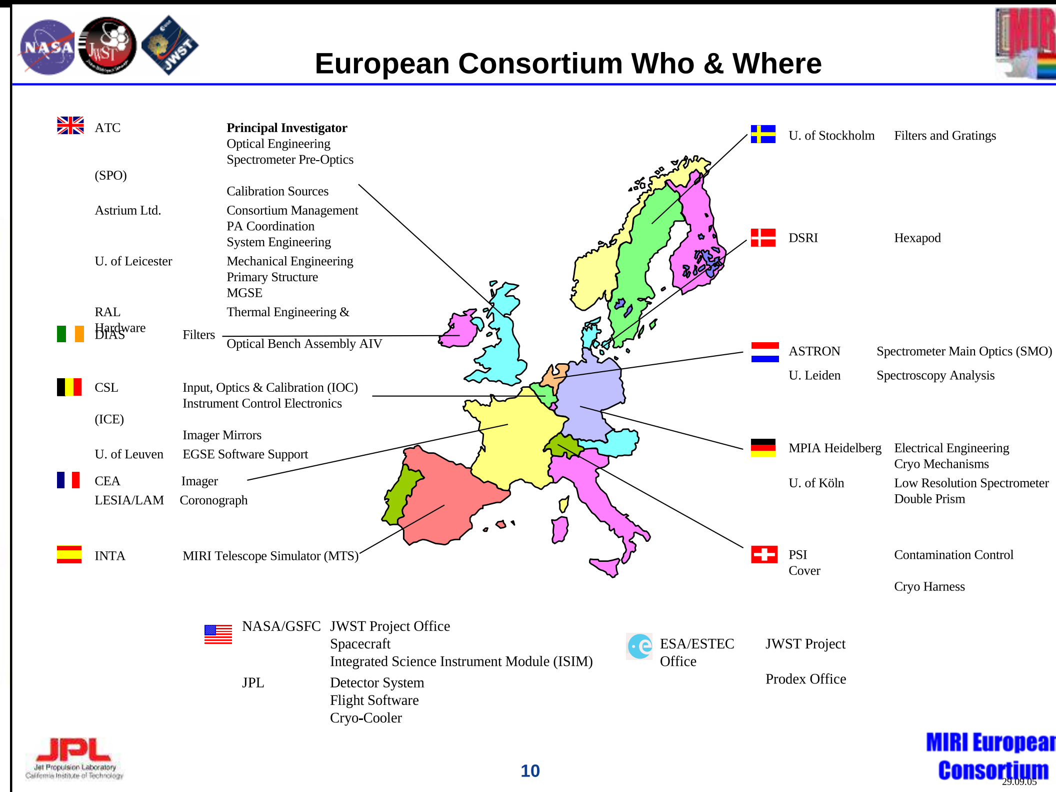
- 7) Strong, compelling benefits to society ("must-have" applications). (SSC could not explain to a broad audience: Why SSC?).

- 8) Know your (funding-) decision makers: what exactly makes them tick?

- 9) Have a last resort ("nuclear") option, but plan to never have to use it.

- 10) Expect the unexpected. This includes: be willing to do (legal and moral) things to help save a Mega-Project that may cost you your job.




- JWST hardware made in 27 US States, Canada, and 16 European countries.
- 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.

This nationwide + international coalition was critical for project survival!

# Keep all levels of government informed about your mission:

Annual Girl Scout Stargazing at the White House South lawn (July 2015).

Amber Straughn (right; ASU graduate, now at NASA GSFC working for Dr. John Mather) informs the Obama's about NASA and JWST.

# (D) Political/Outreach Lessons from JWST

For a Mega-project to succeed, make sure that you DON'T:

- 1) Have project politicized in the government (lesson from SSC).

(John Mather: Entire professional societies went to war to stop the Space Station. They didn't have to do that. This rubbed off negatively onto the SSC as well ... Astronomy has done well because our Decadal Survey sets priorities, which the community is willing to accept and abide by).

- 2) Assume your government understands or likes the project: Educate, educate, and re-educate.

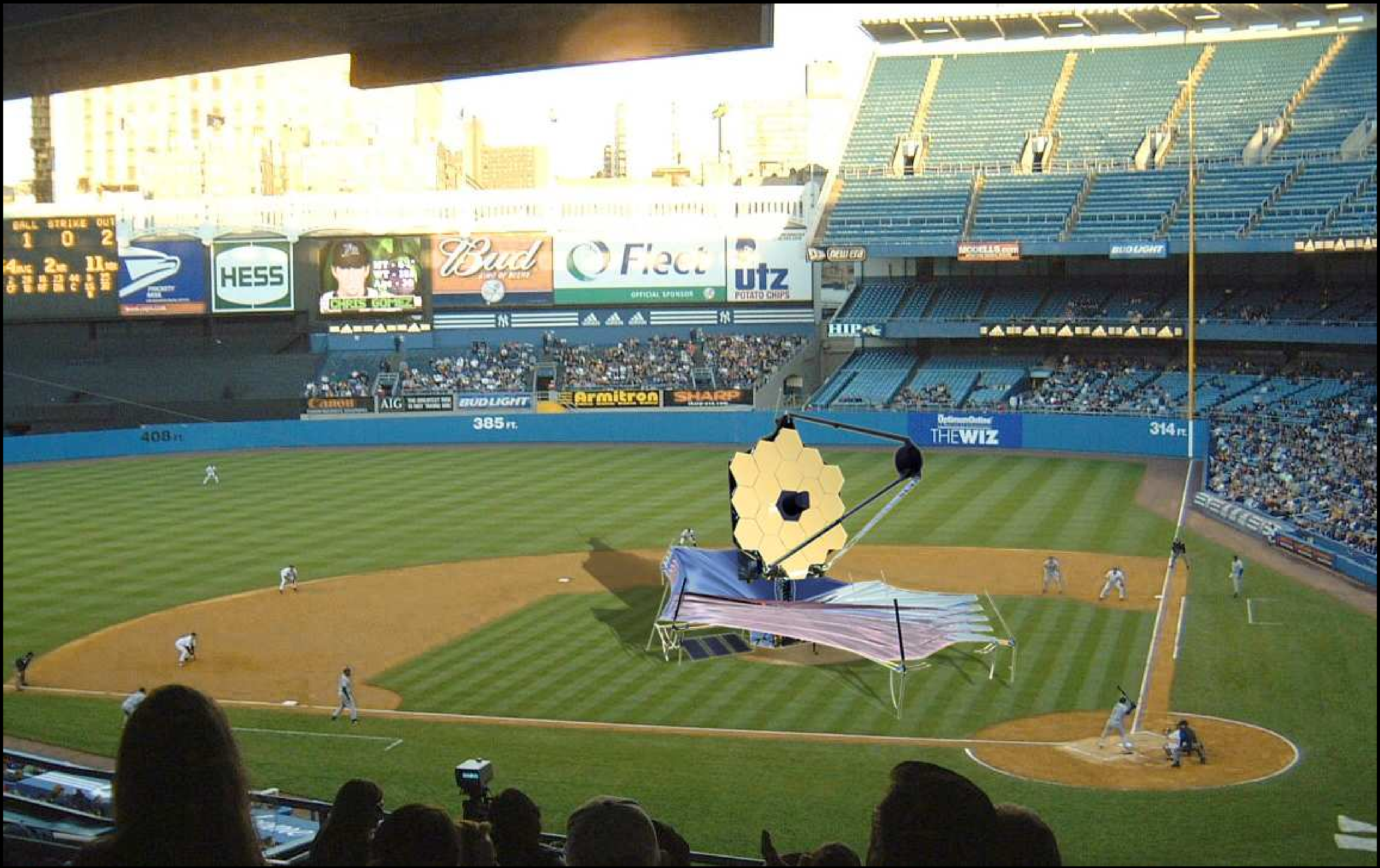
- 3) Have project become target of social media: Must continuously educate instead and reach out to opponents.

- 4) Have project too concentrated in one state (or nation): MUST distribute efforts and wealth.

- 5) Don't pick fights you cannot win.

- 6) Ever fall asleep, not until launch anyway ...

# Conclusion: How can we knock it out of the ball-park in the next 30 years?




ATLAST (& ground-based 20-40 m telescopes) will fill Yankee ballpark ...

- New paradigm: Too large for individual universities or countries to take on.
  - Countries must closely collaborate world-wide to make this happen.

# Some things are better left discussed during ...



Miller time!

Het Borrel uur!

# SPARE CHARTS

## Summary: Main Lessons from the JWST Project:

(1) Mega-projects demand new rules, in particular regarding building and keeping together a *strong Coalition* of project supporters and advocates:

(A) JWST Scientific/Astro-Community Lessons:

- 1) Project is a must-do scientifically and cannot be done any other way.
- 2) Keep advocating Mega-project to community until launch/first light.
- 3) Don't ignore importance of communication with patrons: Scientists, international partners, contractors, tax-payers, Congress, White House.
- 4) Don't have community infighting ("My mission is better than yours" — One key reason for Supercollider (SSC) demise).

(B) JWST Technical Lessons:

- 1) Use advanced technologies being developed elsewhere, if possible.
- 2) Know when not to select the most risky technologies.
- 3) Do your hardest technology development upfront. Have all critical components at TRL-6 before Mission Preliminary Design Review (PDR).

(C) JWST Management/Budget/Schedule Lessons:

- 1) Make conservative full end-to-end budget before Mission CDR.

- 2) Make sure budgets are externally reviewed, and at $\gtrsim$80% joint cost+ schedule confidence level. (Could not do $\lesssim$2010; Did so early 2011).

- 3) Plan *&* effectively use 25–30% ($+schedule!) contingency each FY.

(D) JWST Political/Outreach Lessons:

- 1) Assemble, maintain and fully use a broad Coalition of supporters and advocates who will fight for the project (SSC did so too late).

- 2) Have strong multi-partisan & multi-national support for project.

- 3) Strong technology benefits/lessons *TO* other parts of government.

- JWST *is* the telescope that the community asked for 17 years ago, and it is coming into being as we speak. The community should get ready to submit JWST proposals in less than 3.5 years from today!

OVERALL CONCLUSION: JWST is now on the right track, but we did have to learn our lessons.

DISCLAIMERS:

- (1) The materials below are our opinions only (Rogier Windhorst & Robert Smith's), not necessarily NASA's or our Universities' opinion.

- (2) When we get to *(D) Political Lessons* and suggest "One should", or "One should not", we do NOT imply to address civil servants. (I.e., only those individuals who are allowed to reach out to Congress should consider doing so, or should ever feel encouraged doing so).

- (3) No NASA funds or resources are used to reach out to Congress, nor are University funds or resources used to reach out to State legislators.

- (4) No ITAR sensitive materials are ever presented in outreach talks or activities for Mega-Projects, and certainly not in such talks given abroad.

- (5) We are not here to judge, but to learn.

# we do not want this to happen to U.S. astrophysics


Avoid ending up like SSC (left). Canceled project funds never returns!

# References and other sources of material shown:

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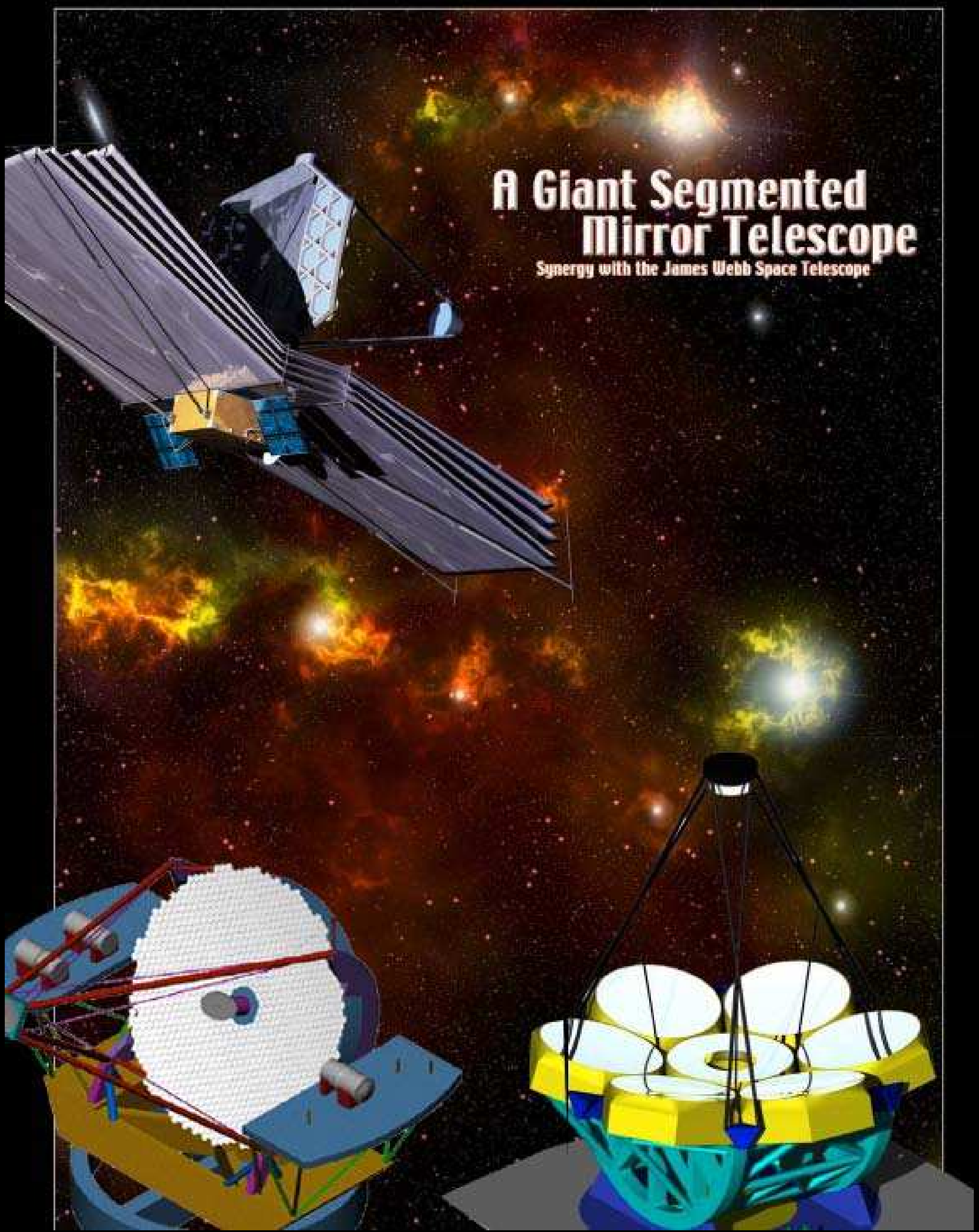
# SPARE CHARTS

(Appendix from Rogier Windhorst's talk on synergy between JWST and GMT/TMT)

Appendix: GMT/TMT/ELT and JWST Synergy: (Kudritzki, Frogel+ 2005):




- (1) Are the top two priority missions of the 2001 Decadal Survey in Astronomy & Astrophysics.

- (2) Each give orders of magnitude gain in sensitivity over existing ground and space telescopes, resp.

- (3) Have complementary capabilities that open a unique new era for cosmic and planetary discovery.

- (4) Maximize concurrent operation of GMT/TMT/E-ELT and JWST!

## (A) Unique Capabilities of the 6.5 meter JWST in L2

- (1) Full sky coverage & high observing efficiency.
- (2) Above the atmosphere, JWST will have:
- Continuous wavelength coverage for 0.6 $\lesssim \lambda \lesssim$28.5 $\mu$m.
- High precision and high time-resolution photometry and spectroscopy.

(3) JWST is a cold telescope ($\lesssim$40 K):

- Minimizes thermal background (for $\lambda \lesssim$10 $\mu$m, set by the Zodi: $10^3$–$10^4\times$ or 7–10 mag lower than ground-based sky!).
- Very high sensitivity for broad-band IR imaging ($\Leftarrow$ no atm OH-lines).

(4) Diffraction limited for $\lambda \gtrsim$2.0 $\mu$m over a wide FOV ($\gtrsim$5$'$ ), hence:

- PSF nearly constant across the FOV.
- PSF stable with time — WFS updates on time-scales of ($\sim$10) days.
- Very high dynamic range.

GMT/TMT/E-ELT lessons: JWST provides a critical *concurrent* complement to GMT/TMT/E-ELT: Panchromatic near–mid-IR imaging & spectral follow-up of GMT/TMT/E-ELT discoveries.

## (B) Unique Capabilities of the GMT/TMT/E-ELT

(1) Sensitivity 25× greater than JWST in accessible spectral regions.

- Very high optical sensitivity (0.32–1.0 $\mu$m) over a wide FOV ($\gtrsim$10$'$ ).

(2) Very high spatial resolution, diffraction-limited imaging in mid- and near-IR — with AO can get PSF 4–6× better than JWST.

- High sensitivity for non-background limited IR imaging and high-resolution spectroscopy (between OH-lines).

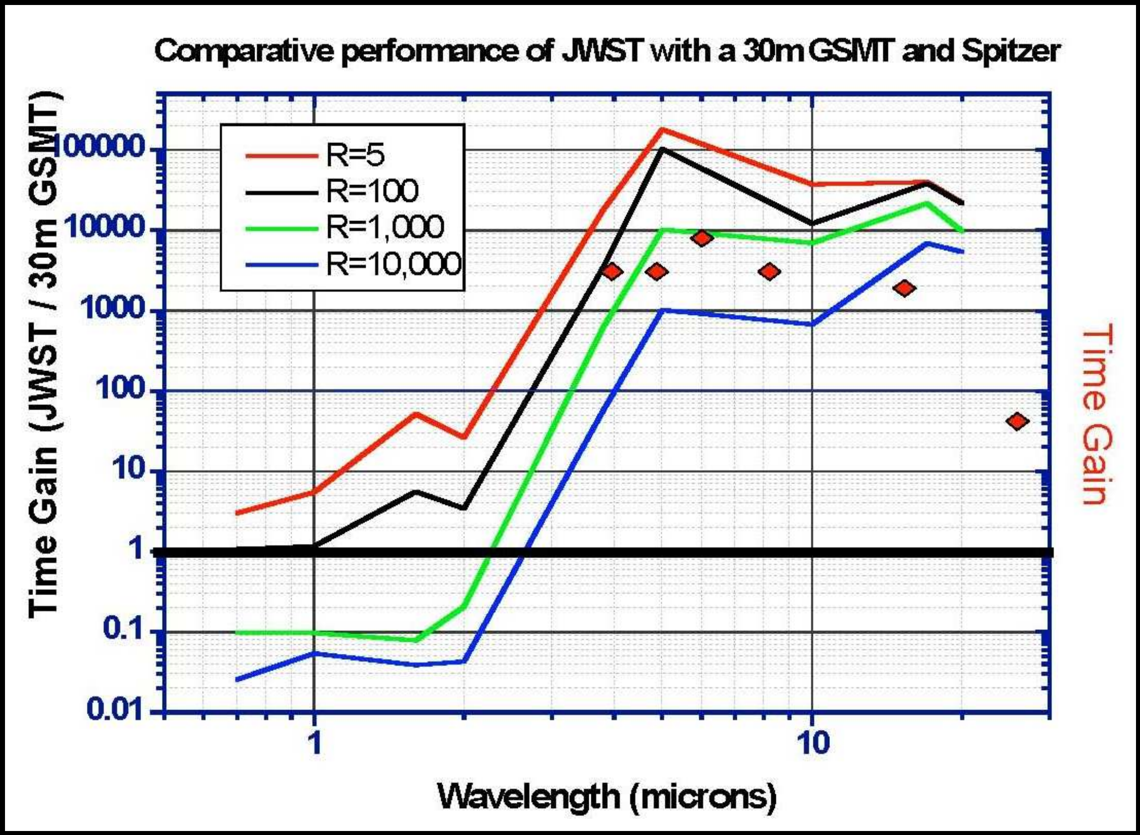
(3) Very high resolution spectroscopy — (R $\gtrsim$10$^{5}$) in optical–mid-IR.

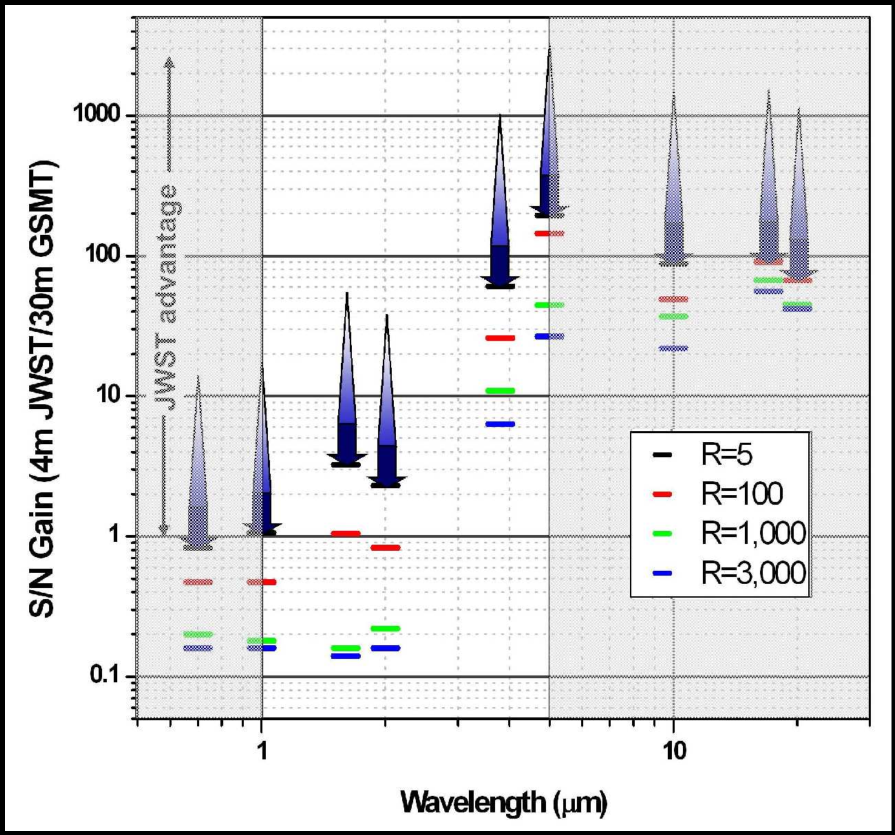
(4) Short response times — few minutes for TOO's.

(5) Flexible and upgradable — take advantage of new developments in instrumentation in the next decades.

- Expect to need JWST for the unexpected GMT/TMT/E-ELT discoveries !

# (C) Synergy between the GMT/TMT/E-ELT and JWST




LEFT: Time-gain($\lambda$) of JWST compared to GMT/TMT/E-ELT and Spitzer.
GMT/TMT-AO competition is why JWST no longer has specs at $\lambda \lesssim 1.7 \mu$m.

RIGHT: S/N-gain($\lambda$) of JWST compared to ground-based:

- Top of arrows: 6m JWST/Keck; Middle: 6m JWST/TMT; Bottom: 4m JWST/TMT.

# (D) Comparison of GMT/TMT/E-ELT and JWST — areas of unique strength

| *Instrument Capabilty* | *Uniqueness* |
|---|---|
| Imaging 0.7-1.7 microns | 20-30m MCAO will be comparable |
| Imaging 1.7 - 5.0 microns | JWST Unique |
| Imaging 5-28 microns | JWST Unique |
| Coronagraphy 0.7 - 2.3 microns | Extreme AO on 8-10m superior |
| Coronagraphy 2.4 - 5 microns | JWST Unique |
| Coronagraphy 5 - 28 microns | JWST in principle unique |
| Tunable filter 1.0 - 2.0 microns | 8-10m AO & narrow band filters comparable |
| Tunable filter 2.4 - 5 microns | JWST in principle unique |
| Slit Spectroscopy 0.7-1.7 microns | 20-30m MCAO superior |
| Slit Spectroscopy 1.6 - 5 microns | JWST Unique |
| MOS spectroscopy 0.7- 1.7 microns | 20-30m MCAO superior |
| MOS spectroscopy 1.7 - 5 microns | JWST Unique |
| IFU spectroscopy 1.0- 1.7 microns | 20-30m MCAO superior |
| IFU spectroscopy 1.7 - 5 microns | JWST Unique |
| (IFU) spectroscopy 5-28 microns | JWST Unique |

JWST: diffraction limited wide-FOV imaging and low-res spectra at $\gtrsim 2\mu$m.

GMT/TMT: high-res imaging, coronagraphy, TF-imaging & IFU spectra at $\lesssim 1.7\mu$m, and high-res spectroscopy at $\lesssim 2\ \mu$m (with AO beyond).