space science & the space economy

https://www.sciencedirect.com/science/article/pii/S0265964625000372

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www.lascienzainutile.it

will it be possible in the future to realize large, complex, basic science missions like HST, Chandra and JWST? If yes, How?

space-related investments have grown exponentially in recent years, exceeding $0.5 trillion in 2023, when private investment surpassed government investment for the first time

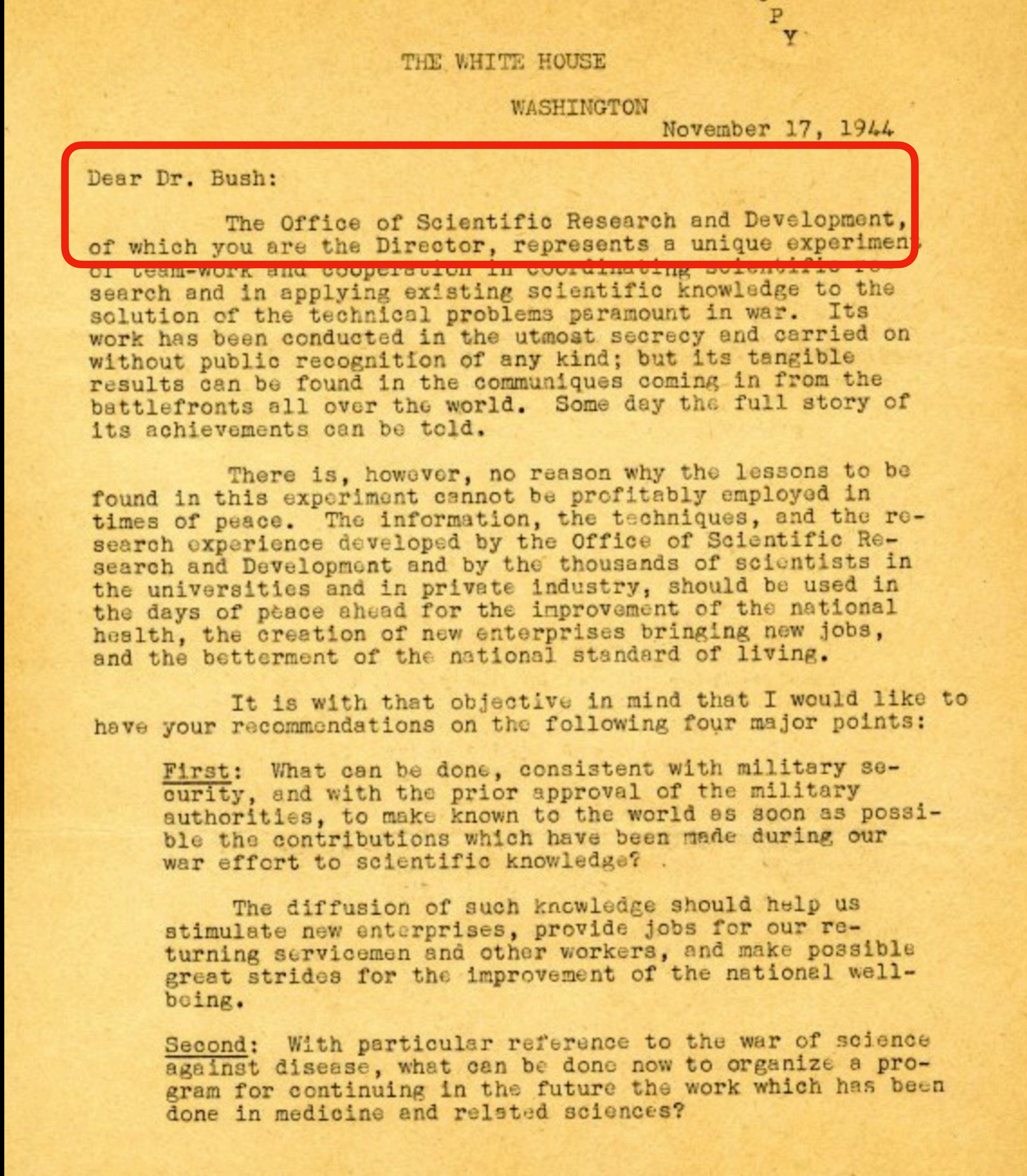
can space science take advantage of the benefits of the *new space economy* to reduce cost and development time and at the same time succeed in producing powerful missions in basic science?

NASA cuts

	FY2024 Enacted	FY2027 President budget	FY2026 Senate CJS Report	FY House CJS Report	House report change from FY2024
Science total	7300	3907	7300	6000	-18%
Astrophysics	1530	523	1605	1485	-3%
Planetary science	2717	1891	2552	2500	-8%
Heliophysics	805	433	887	625	-22%
Earth science	2195	1036	2166	1325	-40%
STEM	143	0	148	0	-100%

science the endless frontier

the birth of the American scientific vision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THE WHITE HOUSE

WASHINGTON

November 17, 1944

Dear Dr. Bush:

The Office of Scientific Research and Development, of which you are the Director, represents a unique experiment of team-work and cooperation in coordinating scientific research and in applying existing scientific knowledge to the solution of the technical problems paramount in war. Its work has been conducted in the utmost secrecy and carried on without public recognition of any kind; but its tangible results can be found in the communiques coming in from the battlefronts all over the world. Some day the full story of its achievements can be told.

There is, however, no reason why the lessons to be found in this experiment cannot be profitably employed in times of peace. The information, the techniques, and the research experience developed by the Office of Scientific Research and Development and by the thousands of scientists in the universities and in private industry, should be used in the days of peace ahead for the improvement of the national health, the creation of new enterprises bringing new jobs, and the betterment of the national standard of living.

It is with that objective in mind that I would like to have your recommendations on the following four major points:

First: What can be done, consistent with military security, and with the prior approval of the military authorities, to make known to the world as soon as possible the contributions which have been made during our war effort to scientific knowledge?

The diffusion of such knowledge should help us stimulate new enterprises, provide jobs for our returning servicemen and other workers, and make possible great strides for the improvement of the national well-being.

Second: With particular reference to the war of science against disease, what can be done now to organize a program for continuing in the future the work which has been done in medicine and related sciences?

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The fact that the annual deaths in this country from one or two diseases alone are far in excess of the total number of lives lost by us in battle during this war should make us conscious of the duty we owe future generations.

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Third: What can the Government do now and in the future to aid research activities by public and private organizations? The proper roles of public and of private research, and their interrelation, should be carefully considered.

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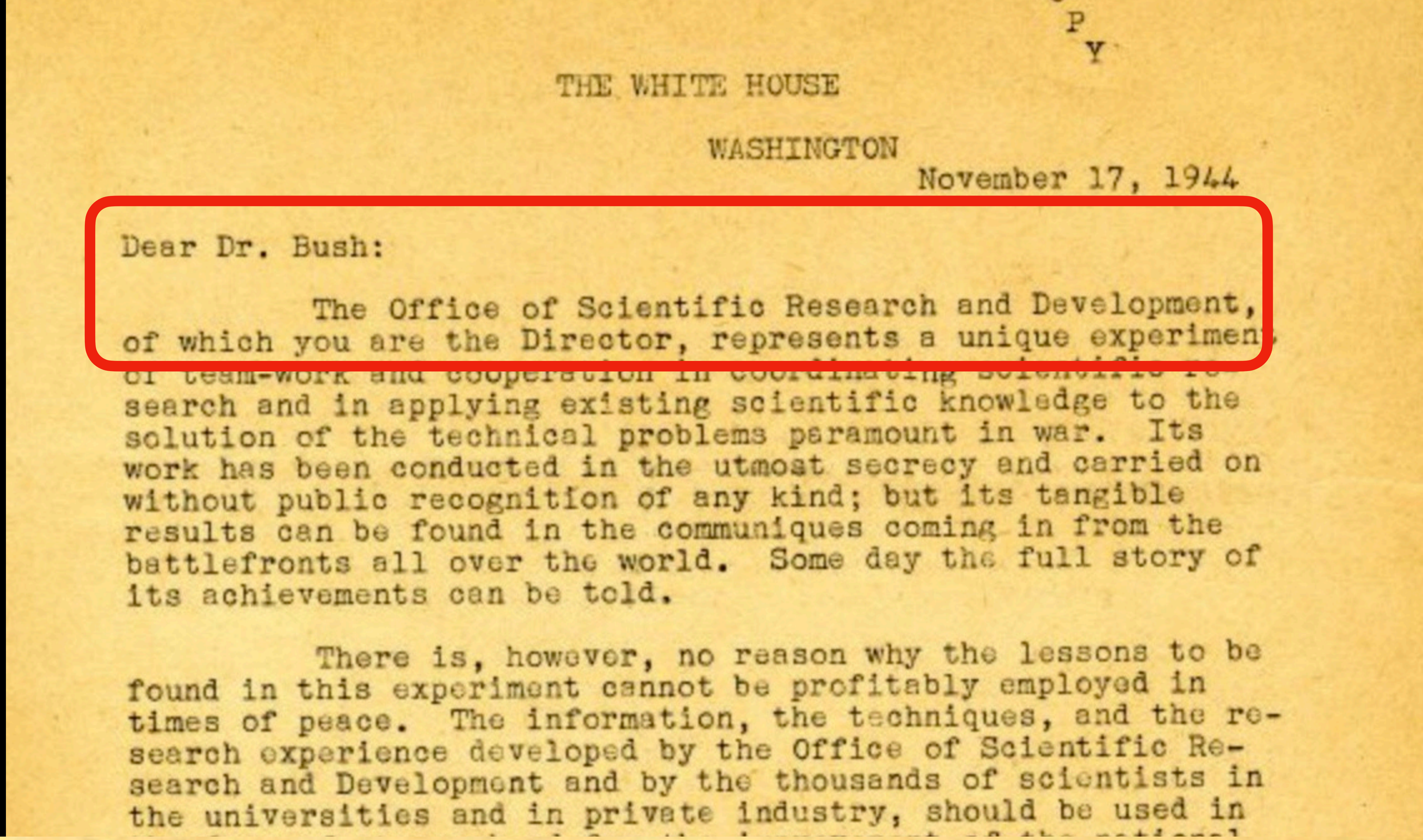

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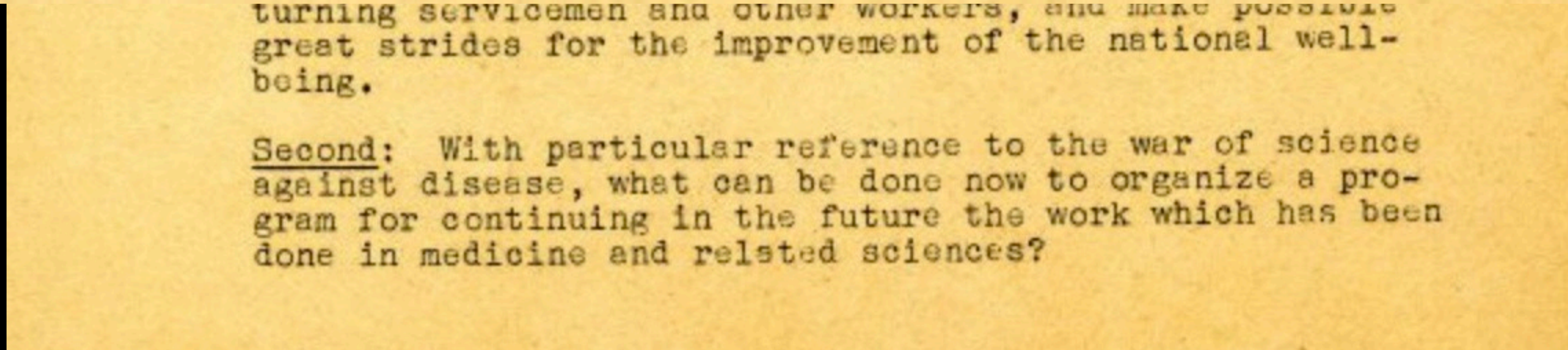
Fourth: Can an effective program be proposed for dis- covering and developing scientific talent in American youth so that the continuing future of scientific research in this country may be assured on a level comparable to what has been done during the war?



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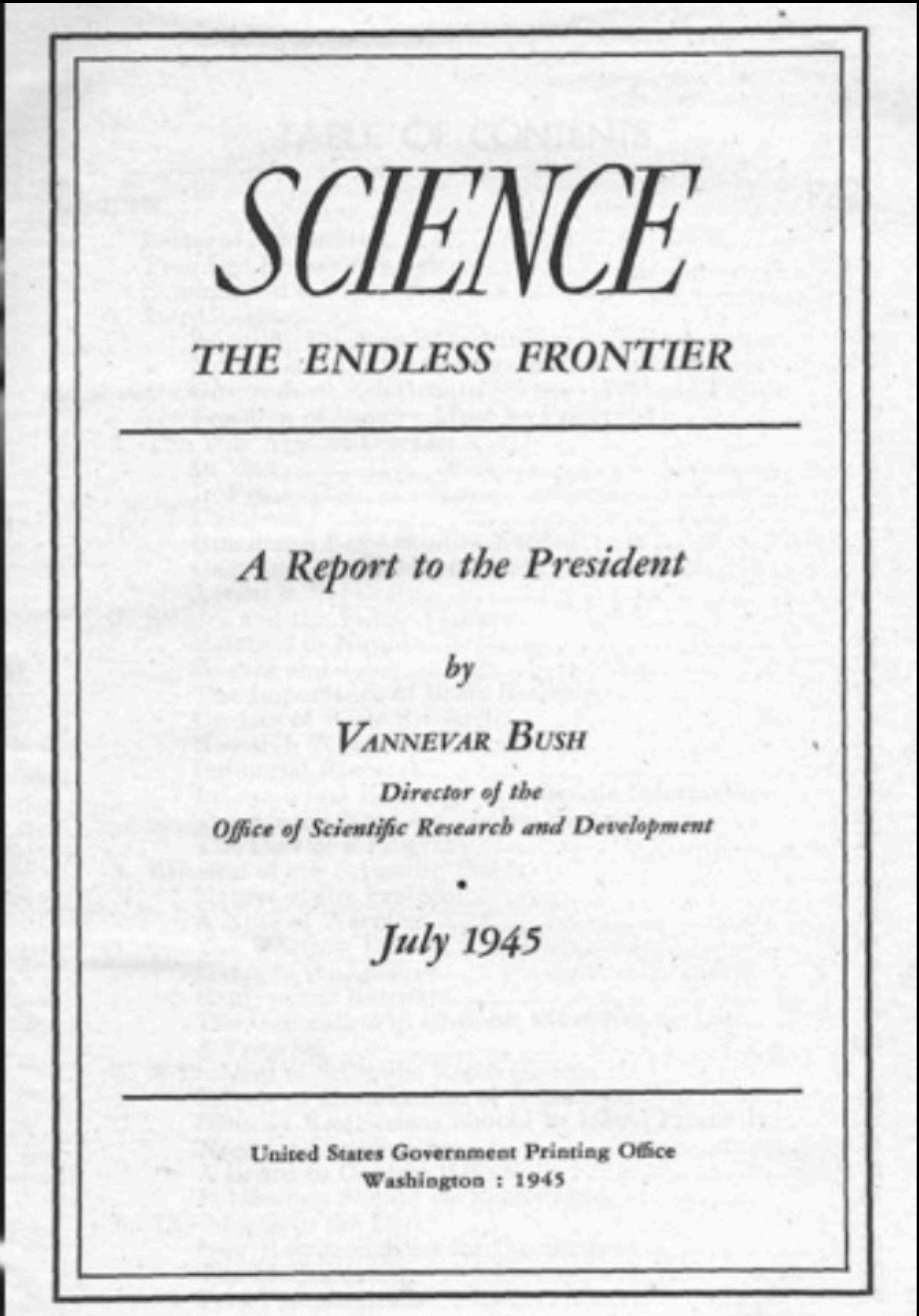

SCIENCE
THE ENDLESS FRONTIER

A Report to the President

by

VANNEVAR BUSH

Director of the
Office of Scientific Research and Development

July 1945

United States Government Printing Office
Washington : 1945

science the endless frontier
the birth of the American scientific vision

- Vannevar Bush, director of the Office of Scientific Research and Development (OSRD) the organization that managed all research and development activities during the war, including the Manhattan Project and the invention of radar
- the starting poing of the report: SCIENTIFIC PROGRESS IS ESSENTIAL (capital letters)
- ..progress in the fight against disease depends on the flow of new scientific knowledge. Responsibility for medical research, which is fundamental in the fight against disease, lies with medical schools and universities, which must be financed for the most part directly by the government
- ..full employment can be achieved through the creation of many new businesses, but these must be based on new principles and new concepts, which in turn derive from basic scientific research

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- ..basic research is scientific “capital.” The real reservoir for the production of new scientific knowledge … is the number of trained scientists available
- ..establish a new “agency” to achieve all these goals. The new agency should have stable funding so that long-term programs can be undertaken. The agency must recognize the importance of preserving freedom of research. Government funding of basic research is the “pacemaker” of technological progress
- the report led to the creation of the National Science Fundation in 1950. The latest budget (2025) was 8 billion $ for basic research (e.g. LIGO, Vera Rubin, Gemini, Kitt Peak, NRAO (JVLA, ALMA…) etc. etc.
- https://www.nsf.gov/about/history/vbush1945.htm
- 2025: Trump administration proposes to cut this budget in half (nearly zeroed astrophysics)

outline

- basic science from space
- the new space economy
- public funding: pros and cons for large missions, metrics for science mission success
- toward a new generation of ambitious and affordable space science missions
- conclusions

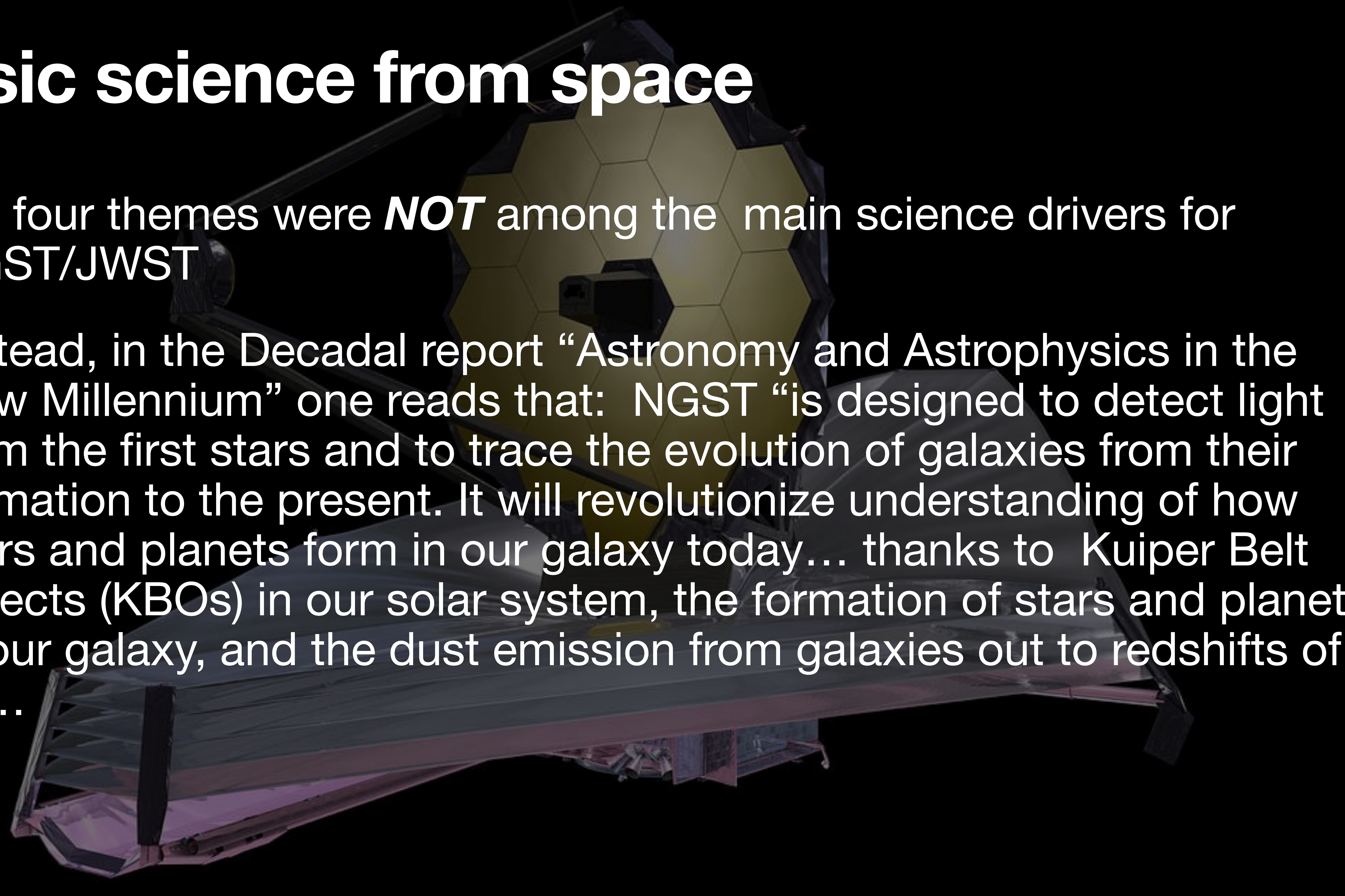
basic science from space

main astrophysics themes emerged in the past 25 years

- exoplanets
- black holes - galaxy scaling relations - black hole direct imaging
- the accelerated expansion of the Universe
- multimessenger astrophysics

- 11 Nobel Prizes in the past 14 years: S. Perlmutter, B. Schmidt, A. Riess, R. Weiss, B. Barish, K.Thorne, M. Mayor, D. Queloz, R. Penrose, R. Genzel, A. Ghez

basic science from space

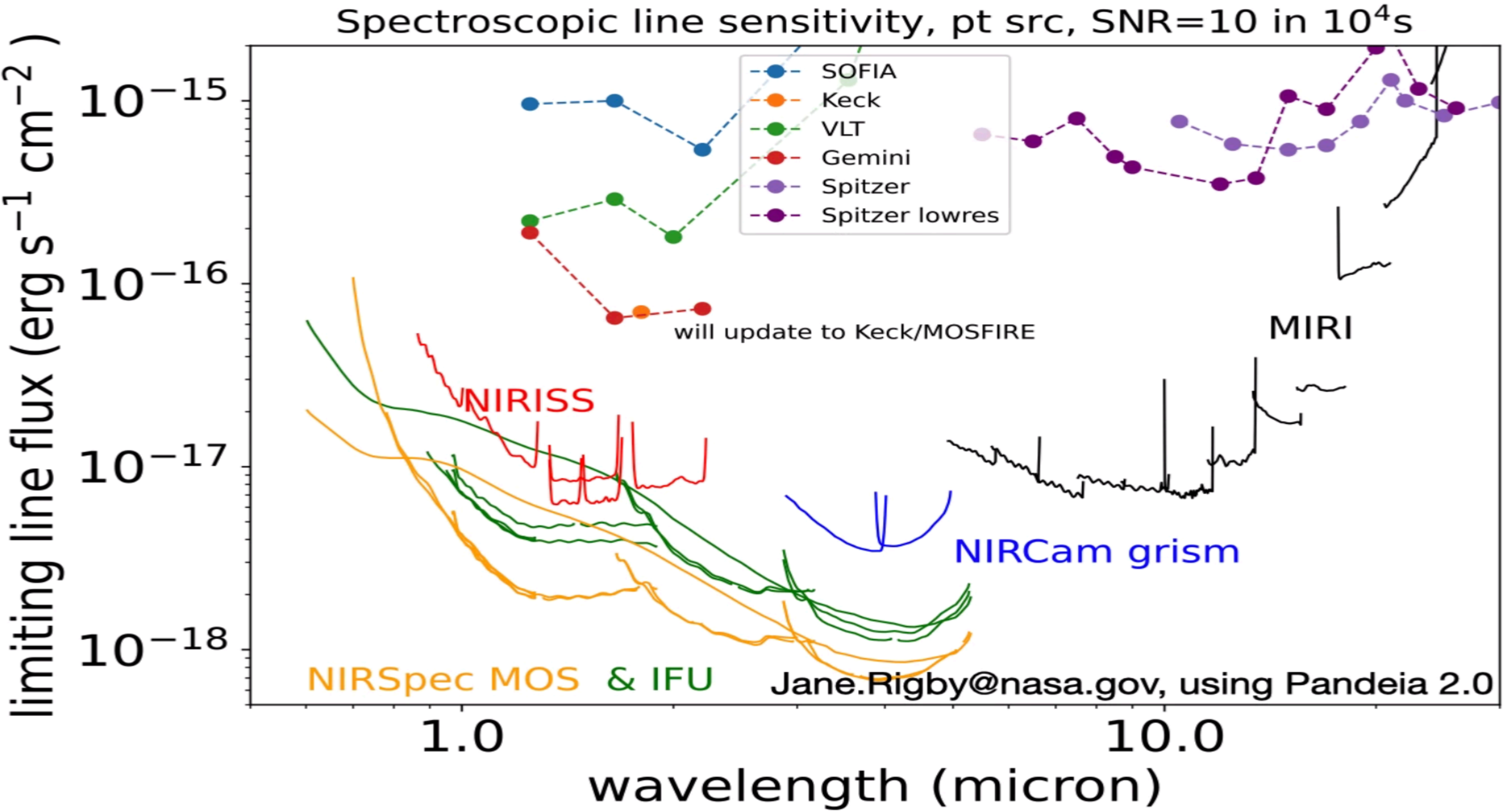


- the four themes were ***NOT*** among the main science drivers for NGST/JWST
- instead, in the Decadal report “Astronomy and Astrophysics in the New Millennium” one reads that: NGST “is designed to detect light from the first stars and to trace the evolution of galaxies from their formation to the present. It will revolutionize understanding of how stars and planets form in our galaxy today… thanks to Kuiper Belt objects (KBOs) in our solar system, the formation of stars and planets in our galaxy, and the dust emission from galaxies out to redshifts of 3”…

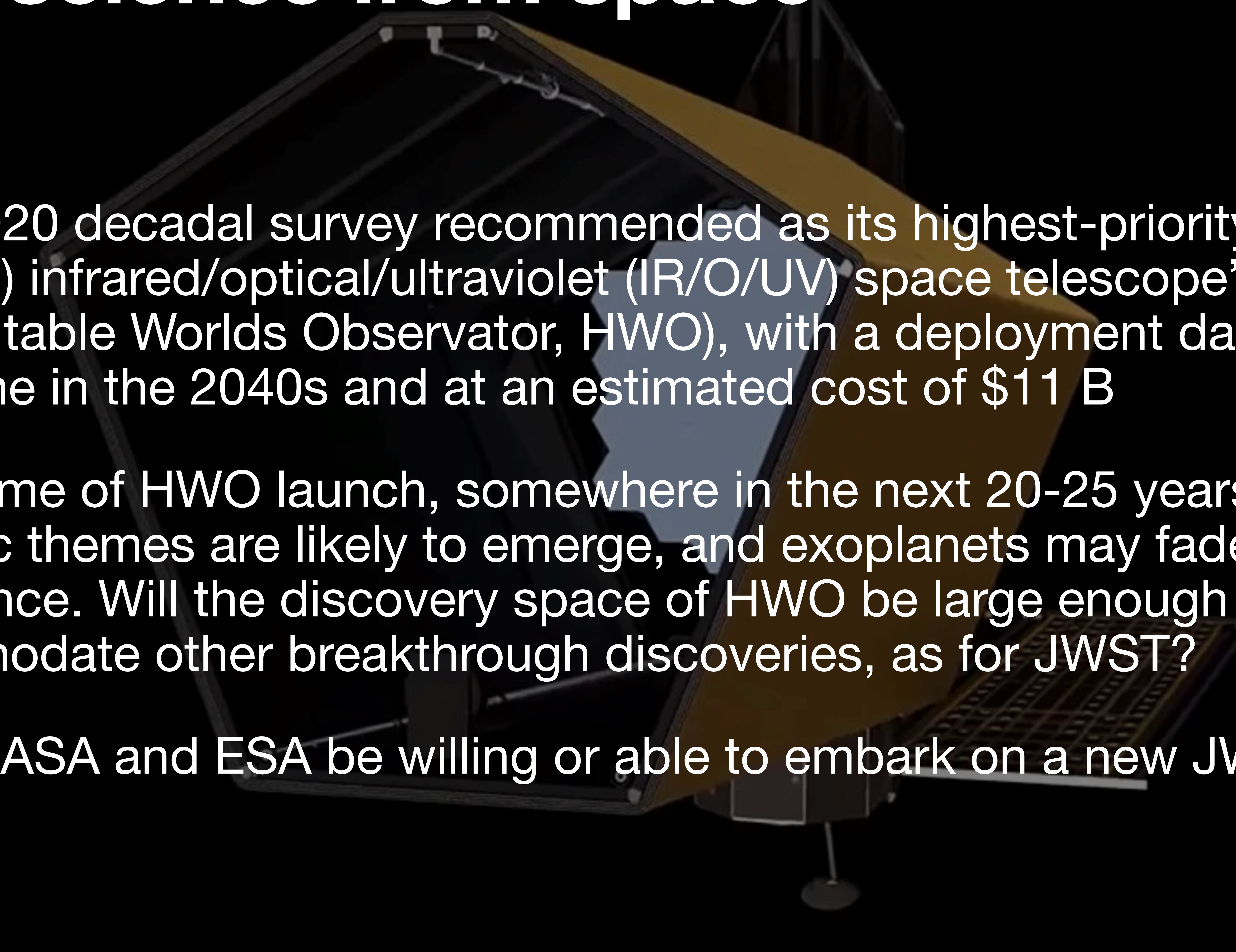
basic science from space

- JWST is doing a great job on all 4 main themes! it was designed to be a multipurpose observatory that pushes the sensitivity by orders of magnitude with respect to previous or contemporary facilities, opening up new “discovery space”
- this did not come for free:
  - cost: $10 b (cannibalization of other astrophysical programs, e.g. BE)
  - develpment time: 23 years
  - complexity/risk

Actual spectroscopic sensitivity (line flux)



basic science from space

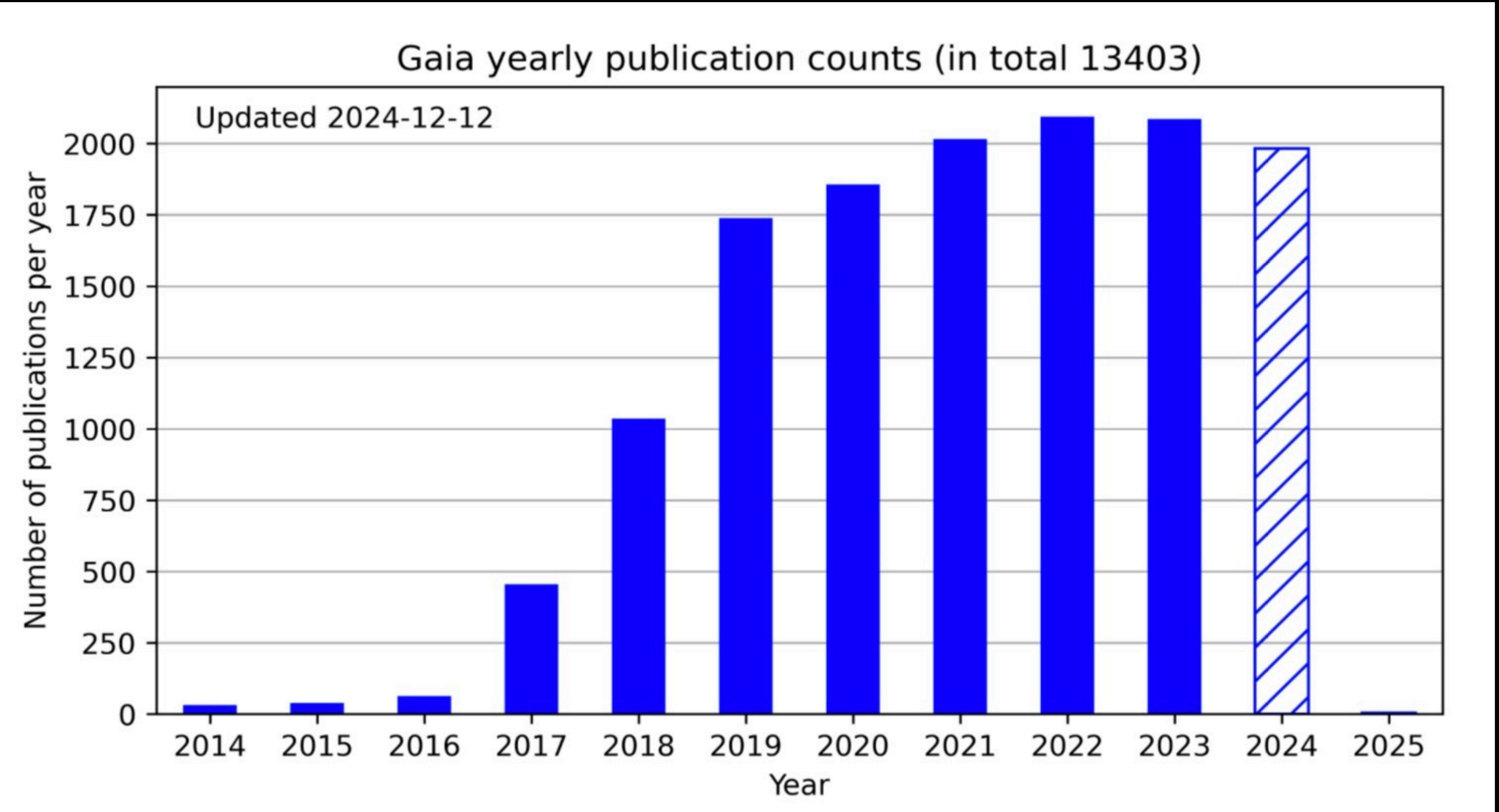


- Astro 2020 decadal survey recommended as its highest-priority a “large (~6 m aperture) infrared/optical/ultraviolet (IR/O/UV) space telescope” (now called the Habitable Worlds Observator, HWO), with a deployment date slated for sometime in the 2040s and at an estimated cost of $11 B
- by the time of HWO launch, somewhere in the next 20-25 years, new scientific themes are likely to emerge, and exoplanets may fade in relative importance. Will the discovery space of HWO be large enough to accommodate other breakthrough discoveries, as for JWST?
- would NASA and ESA be willing or able to embark on a new JWST-scale project?

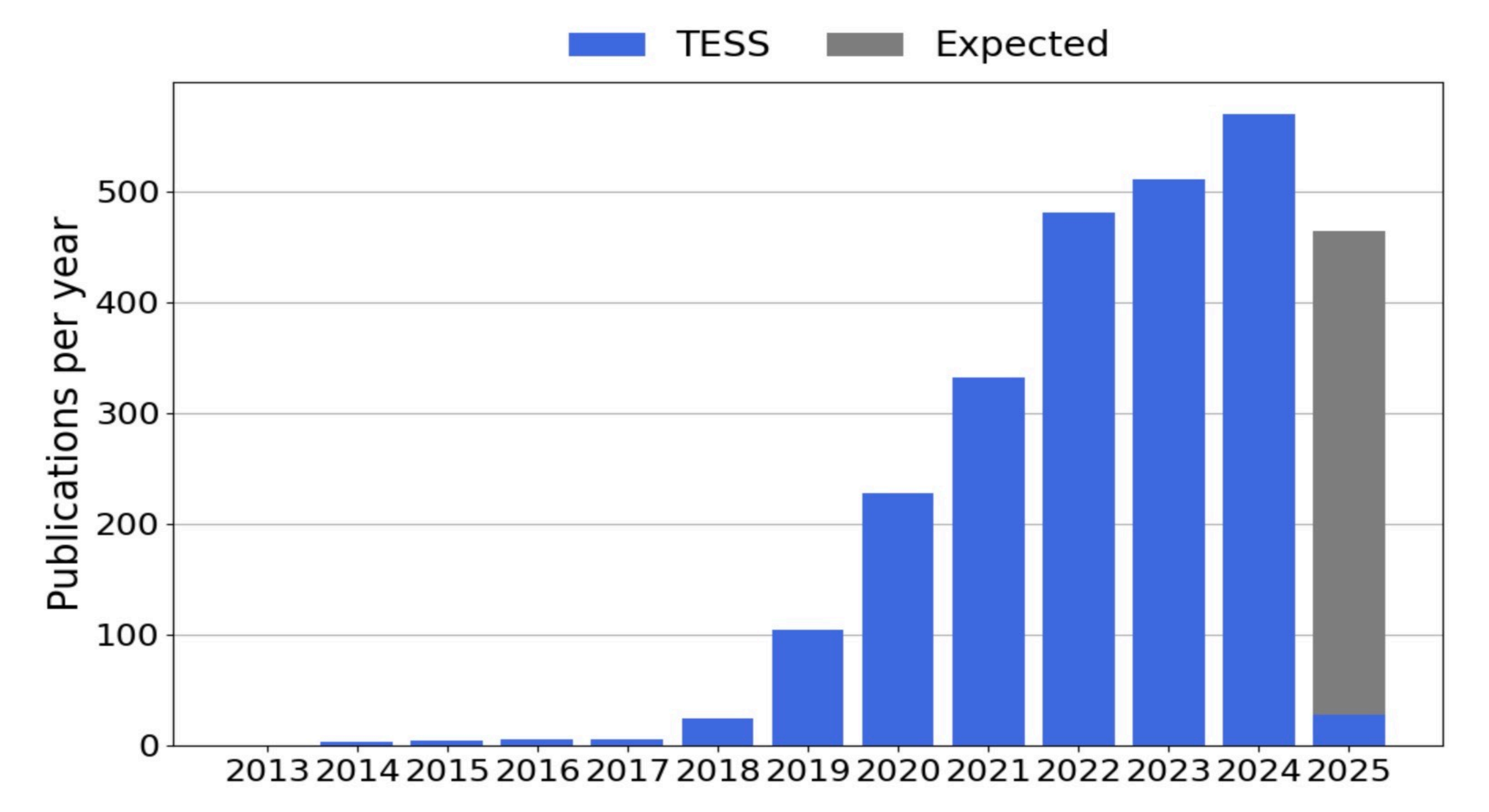
basic science from space

- in April 2024 NASA paused the original JPL-led Mars Sample Return project
- in July 2024 NASA ended the Moon VIPER rover project
- Can HWO and Artemis (and MSR) coexist?
- One alternative to expensive, multipurpose observatories is to have multiple dedicated missions:
  - ESA Gaia, Euclid, NASA Probes, Explorer program

dedicated science missions



dedicated science missions



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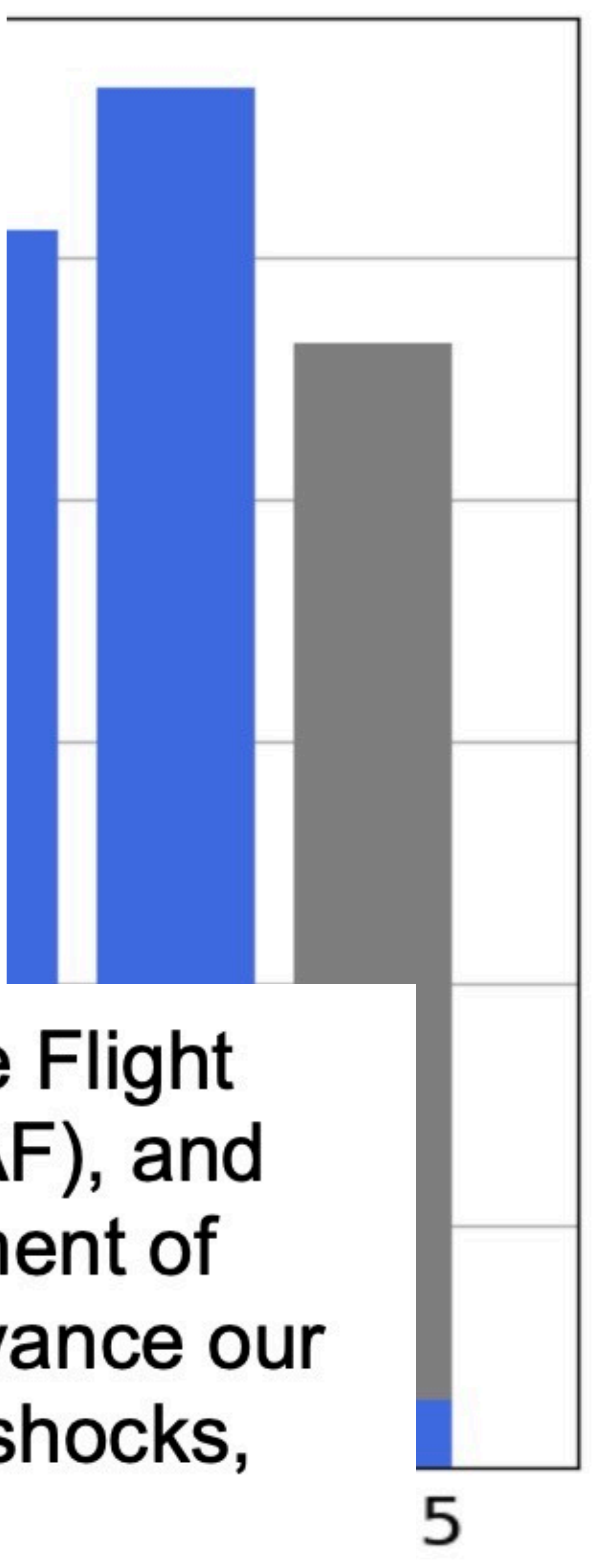
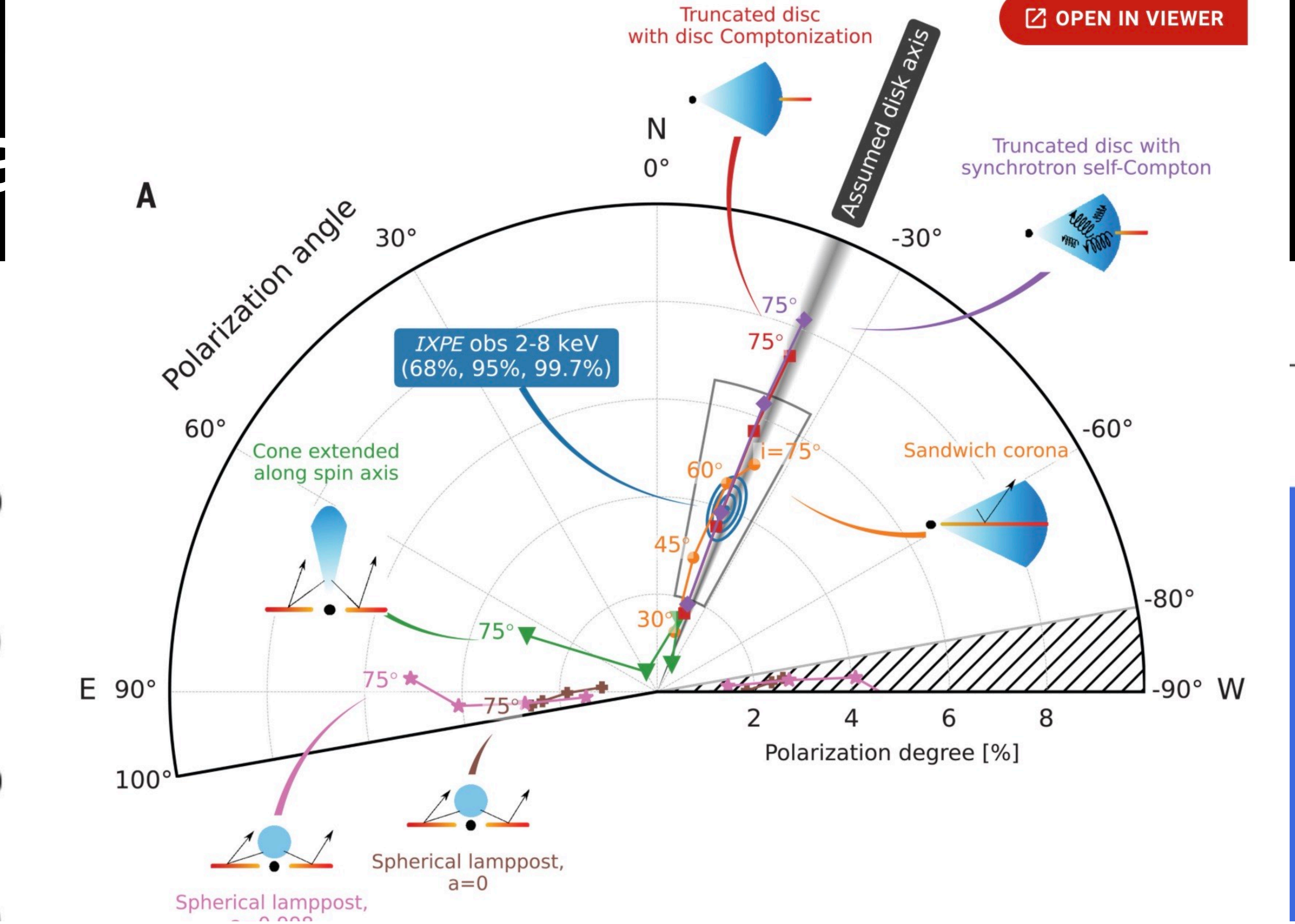
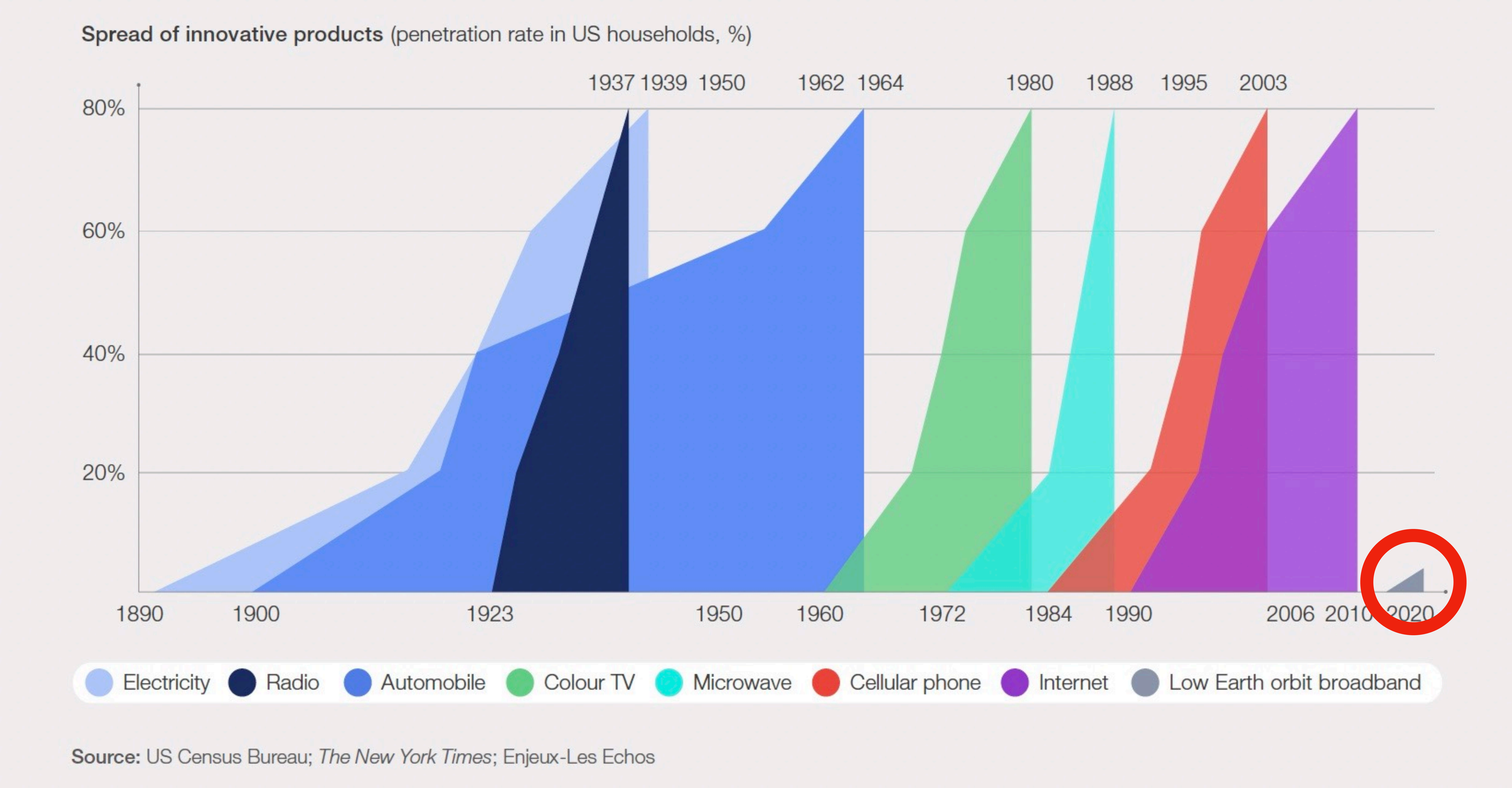




This year's Rossi Prize names Martin Weisskopf (NASA Marshall Space Flight Center), Paolo Soffitta (National Institute for Astrophysics in Italy, or INAF), and the IXPE team. It says the Rossi Prize is being given "for their development of the Imaging X-ray Polarimetry Explorer whose novel measurements advance our understanding of particle acceleration and emission from astrophysical shocks, black holes and neutron stars."

the new space economy



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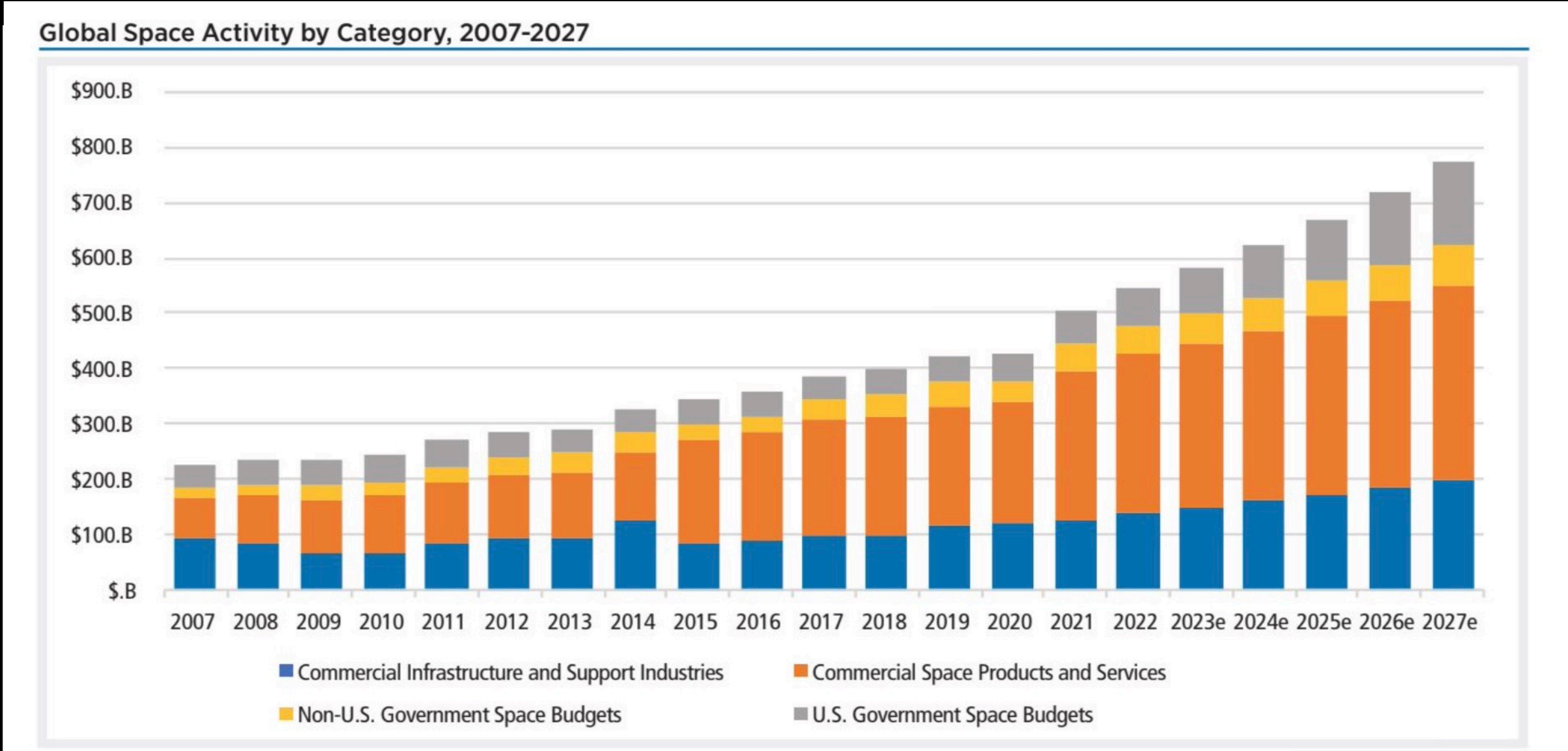
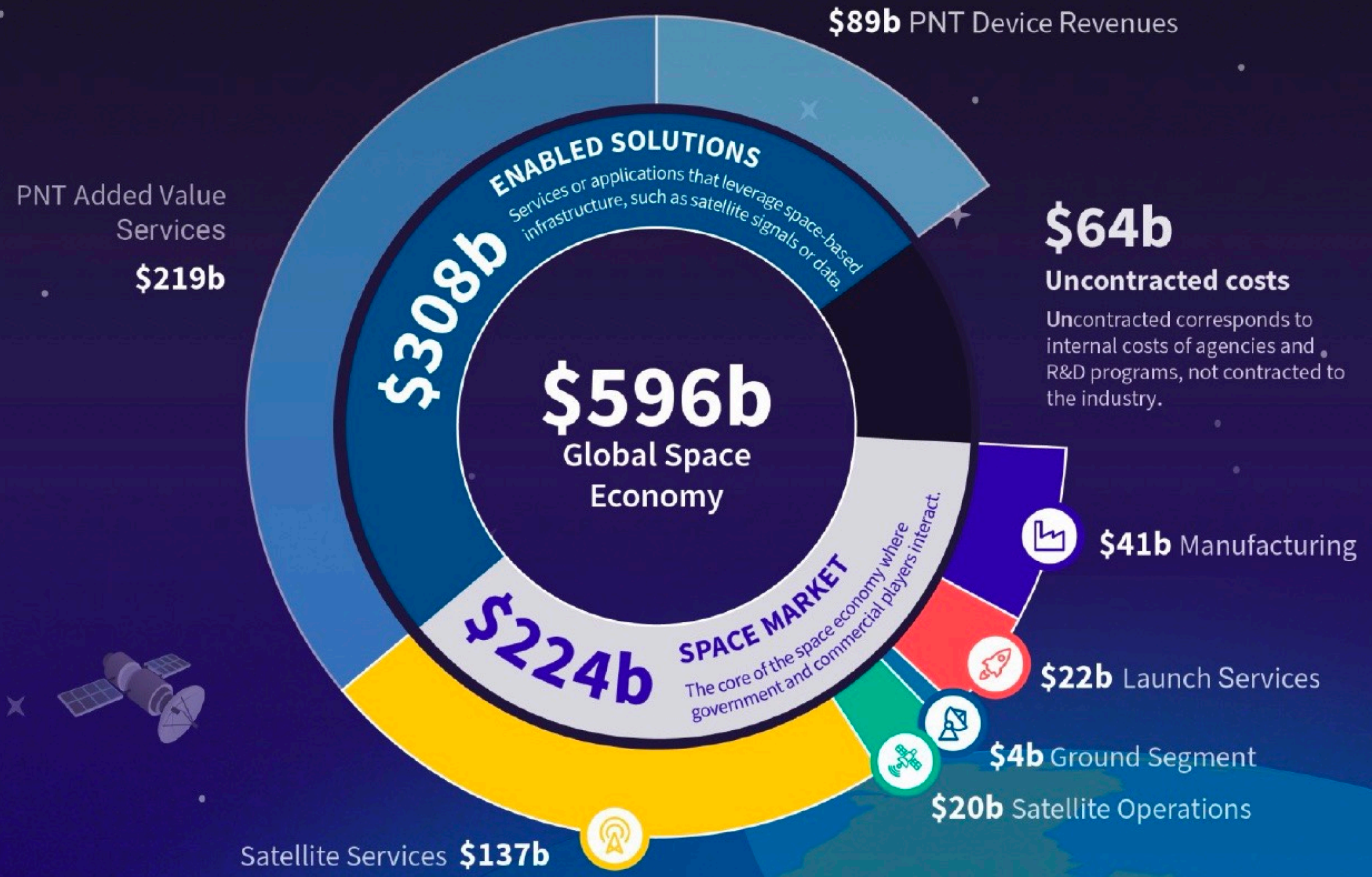


Graphic: The Space Foundation

2024 Space Economy Valuation

in USD



Space Market by Application

Space Market by Region

Regional segmentation is excluding ground segment market value

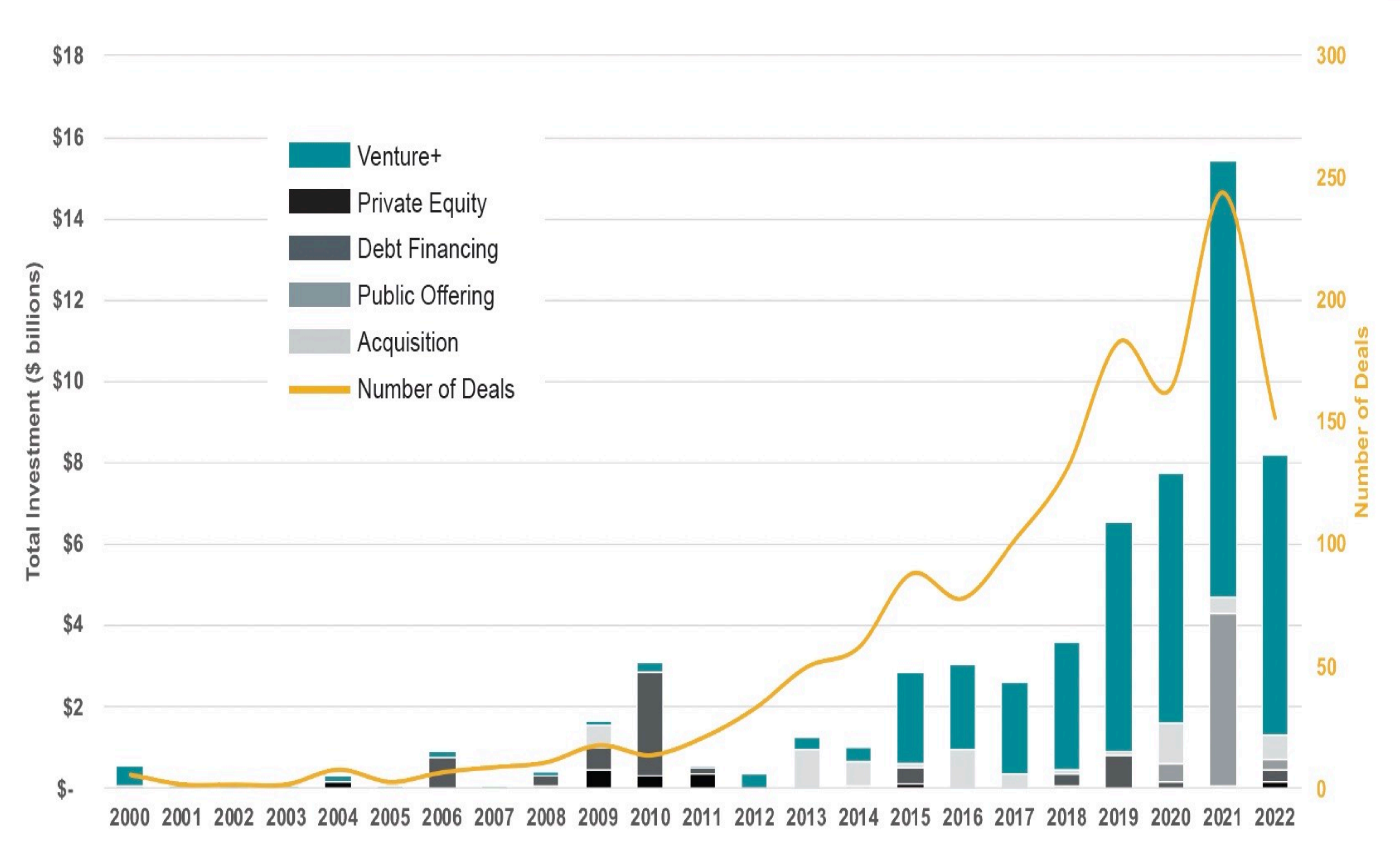
NOVASPACE

Source: Novaspace, Space Economy Report, 2024

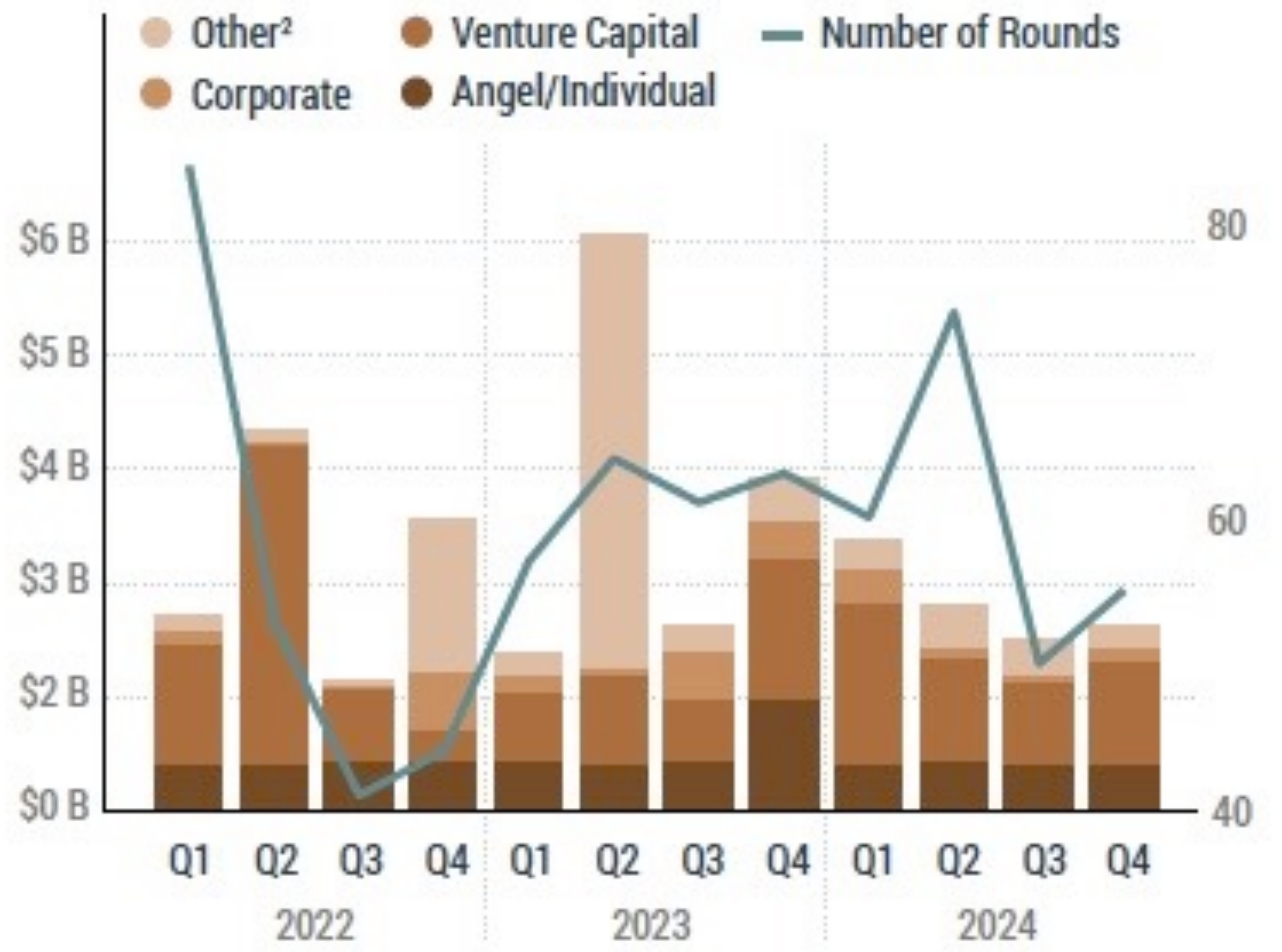

Space economy 2025-2035
Global space economy
630→1790
Backbone
330→755
Reach
300→1035
Commercial
205→435
Services and end user equipment
183→356
Infrastructure and support
22→79
State-sponsored
125→320
Civil
59→140
Defence
66→180
Communications 133→218
PNT 47→120
Space-based Earth observation (EO) 2→9
Others¹ 1→9
Vehicles and satellite manufacturing 17→44
Launch sites and operations 2→3
Ground hardware and operations 2→11
Others² 1→21
Communications 4→8
Basic sciences, technology and research 8→12
Space-based Earth observation 14→32
Space exploration 15→39
Space observation 3→5
Launch systems and operations 5→11
Others³ 10→24
Command, control and communications 4→16
Space sensing 7→22
PNT 4→10
Space domain awareness and combat power 1→4
Launch systems and operations 5→12
Classified defence and intelligence 37→91
Others³ 8→25
Enabled by communications →133
Enabled by PNT 196→799
Enabled by EO 2→10
Enabled by others 4→16
Enabled by civil 3→6
Enabled by defence 28→71

the new space economy

Figure 1. $8 billion invested in 2022 across 154 deals.



QUARTERLY INVESTMENT SOURCE



Q4 Infrastructure investment reached $2.0B, up 7% QoQ but 28% below the three-year average of $2.8B. While lower, funding shows signs of stabilization, consistently hovering around $2.0B, with rounds near the quarterly average of 58. The continued demand for innovative, resilient infrastructure drives investor and government interest, with VCs contributing 56% of Q4 capital, exceeding the 44% average.

business in space is enabled by resources

Standard, literature scheme:

- location is a key resource, today by far the most important
- solar light is a second obvious resource
- materials will (may)be important resources on mid/long timescales

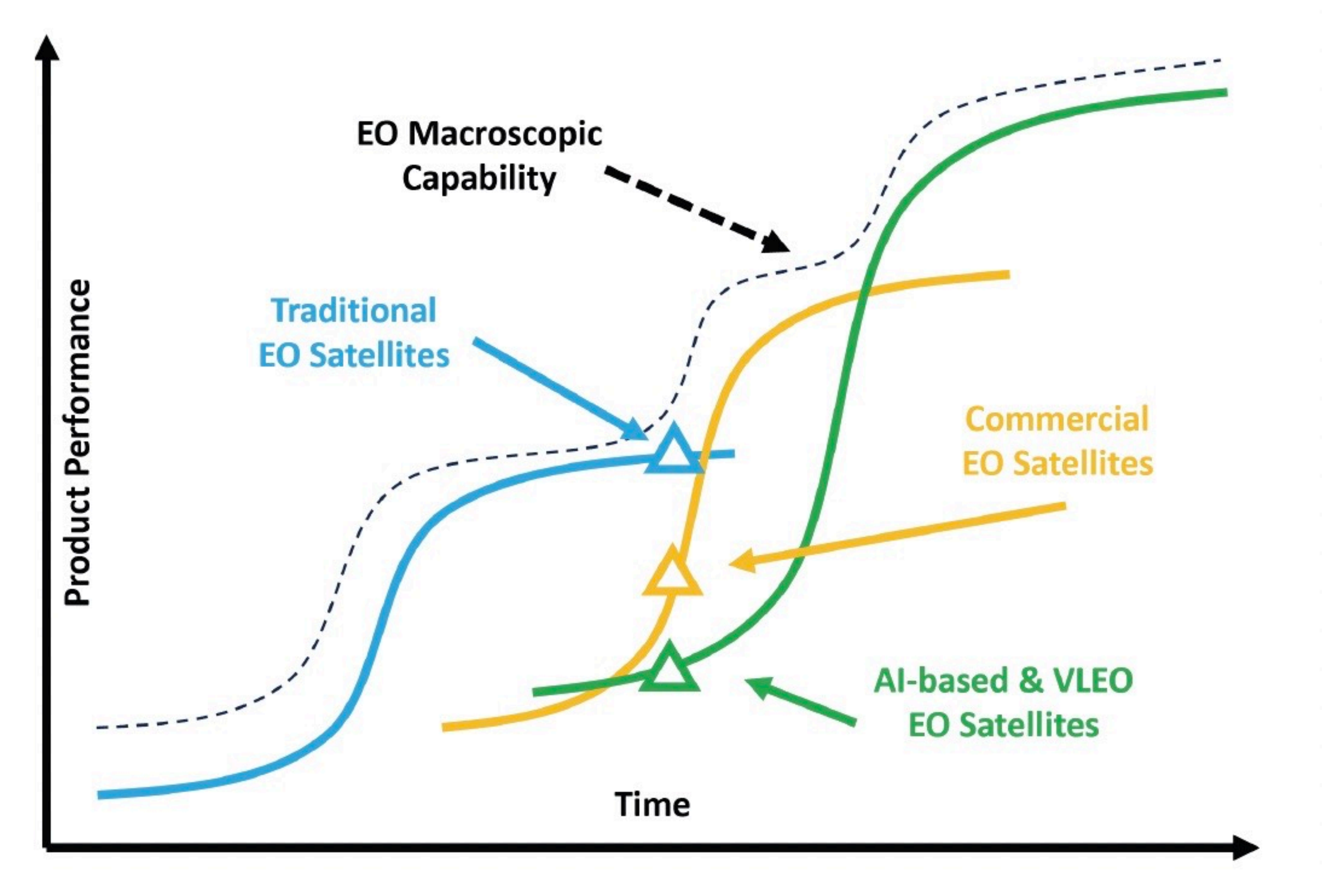
This misses a crucial point!

- *knowledge* enables harvesting all other resources!!!

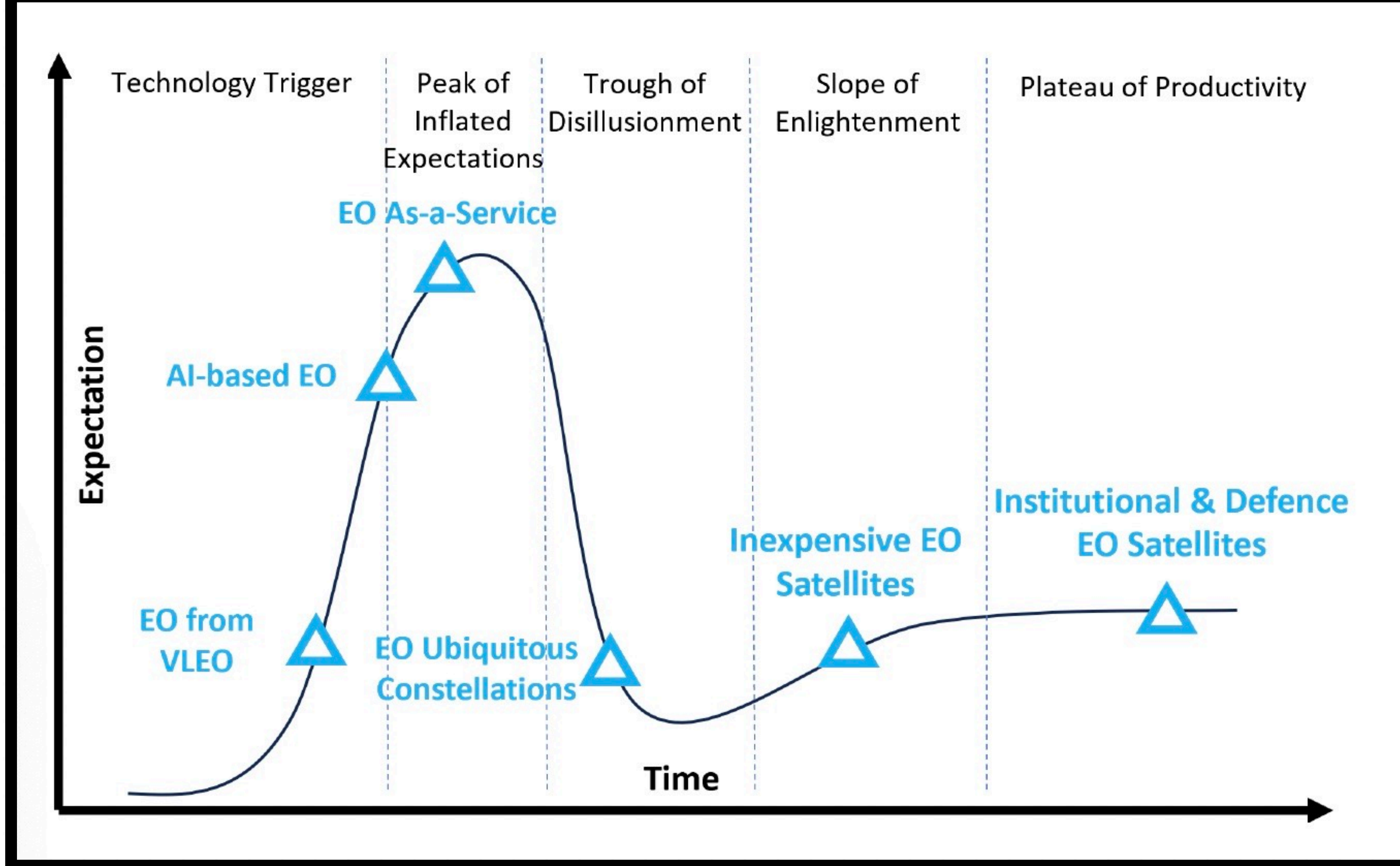
… and basic science researchers are the best suited to produce knowledge useful for space enterprises

innovation paradigm: three main pillars

- technology innovation, proceeding through both disruptive innovation and incremental innovation



Gartner hype cycle



innovation paradigm: three main pillars

- technology innovation, proceeding through both disruptive innovation and incremental innovation
- business innovation, defined as vertical integration, scale production and service oriented business model
- cultural innovation. Startups must have a bold-risk culture, which manifests in risk openness project management models, for example the Agile methodology, which breaks projects into several “sprints” and delivers a Minimum Viable Product (MVP) at the end of each sprint

strategic vs commercial paradigm

geopolitical influence, no risk, no incentive to bring down cost	make money, low cost, risk openess
military advantage	quality of life, wellness, proportional to innovation
need new invention	allow new invention
Technological development is pushed	Technological development is pulled
single missions but distributed procurement, artisanal production	constellation, vertical integration, scale production
timing is not a driver	time is money, fast deliver is mandatory

strategic vs commercial paradigm

- most space astrophysics has been funded so far by Governments under the strategic paradigm with clear connection/synergies with military programs. many examples:
  - HST shares common design with NRO KH-11 Kennen
  - Roman uses a 2.4 primary mirror donated by NRO
  - NIR/IR detector developer for military purposes
  - Swift fast repointing developed by military
  - JWST segmented berillum primary mirror developed jointly by NASA & DoD: Advanced Mirror System Demonstrator (AMSD) program

Feature	JWST Implementation	Military Synergies	Examples/Impacts
Lightweight Beryllium Mirrors	Gold-plated segments for $25.4\ m^2$ collecting area; stable at cryogenic temps.	Enables compact, high-performance optics in drones, satellites, and aircraft; X-ray transparency aids secure comms.	Used in EO/IR sensors for UAVs (e.g., Predator drones); DoD satellites for missile warning. Enhances stealth via lighter designs.
Cryogenic Stability	Maintains shape at 30–50 K; low thermal distortion for precise alignment.	Critical for high-altitude or space-based IR sensors detecting heat signatures in extreme environments.	Missile seekers (e.g., AIM-9X Sidewinder); space-based infrared systems (SBIRS) for ballistic missile defense. Improves reliability in hypersonic scenarios.
Segmented/ Deployable Design	18 segments with actuators for on-orbit phasing; survives launch vibrations.	Supports scalable, foldable optics for small satellites or deployable arrays in contested orbits.	Adaptive optics in military telescopes (e.g., ground-based laser systems); future deployable surveillance sats..
Precision Actuation & Alignment	132 actuators total; aligns to <25 nm rms surface error post-deployment.	Enables real-time wavefront correction in dynamic environments like airborne targeting.	Laser weapon systems (e.g., HELIOS); gimbal-stabilized EO/IR turrets on ships/aircraft. Boosts accuracy in electronic warfare.

Feature	JWST Implementation	Military Synergies	Examples/Impacts
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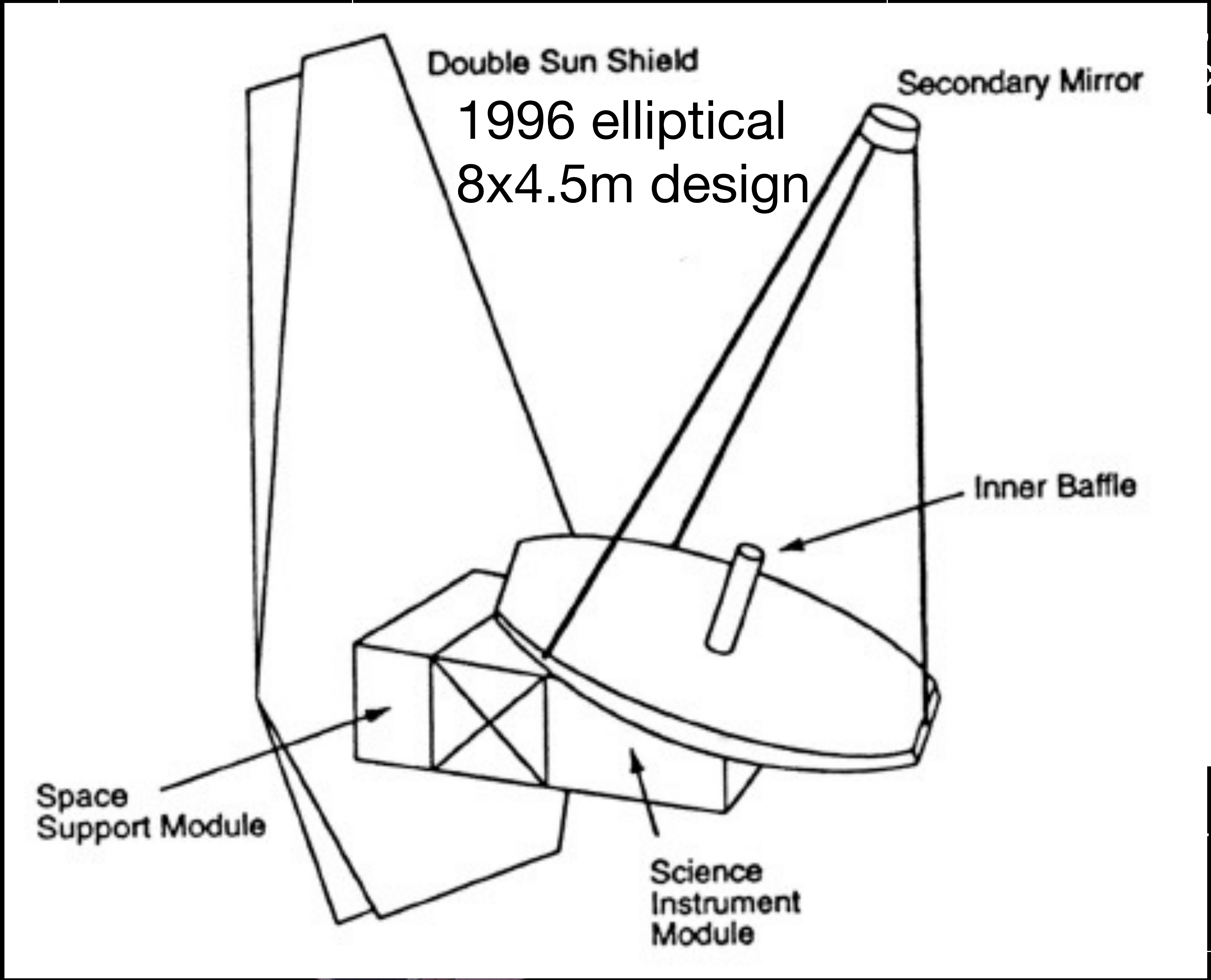
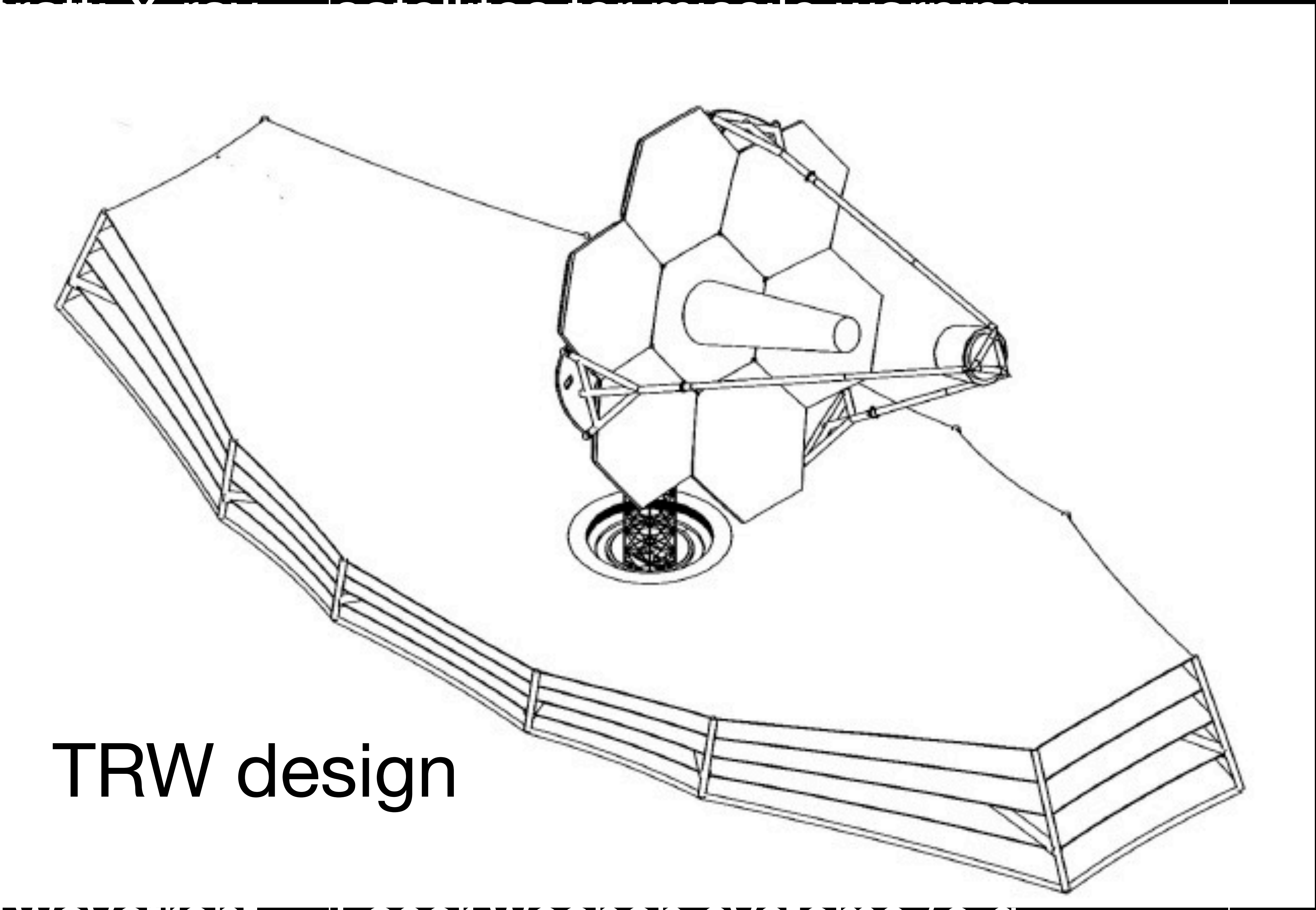
		wavefront mic airborne	Laser weapon systems (e.g., HELIOS); gimbal-stabilized EO/IR turrets on ships/aircraft. Boosts accuracy in electronic warfare.





strategic vs **commercial** paradigm

Geology

- large energy oil and gas companies have financed most of the extensive and costly drilling in the US (>4millions oil wells, >10trillion$)
- data (drill bits, logs etc.) public >2-5yr from drilling
- often “in-kind” to balance the exchange: public entities offer free expertise in exchange for data. This reduces costs for private entities (~20-30% in R&D) and accelerates research
- crucial subsurface data for understanding the structure and geological history of the continent: plate tectonics, mapping structures such as faults and sedimentary basins

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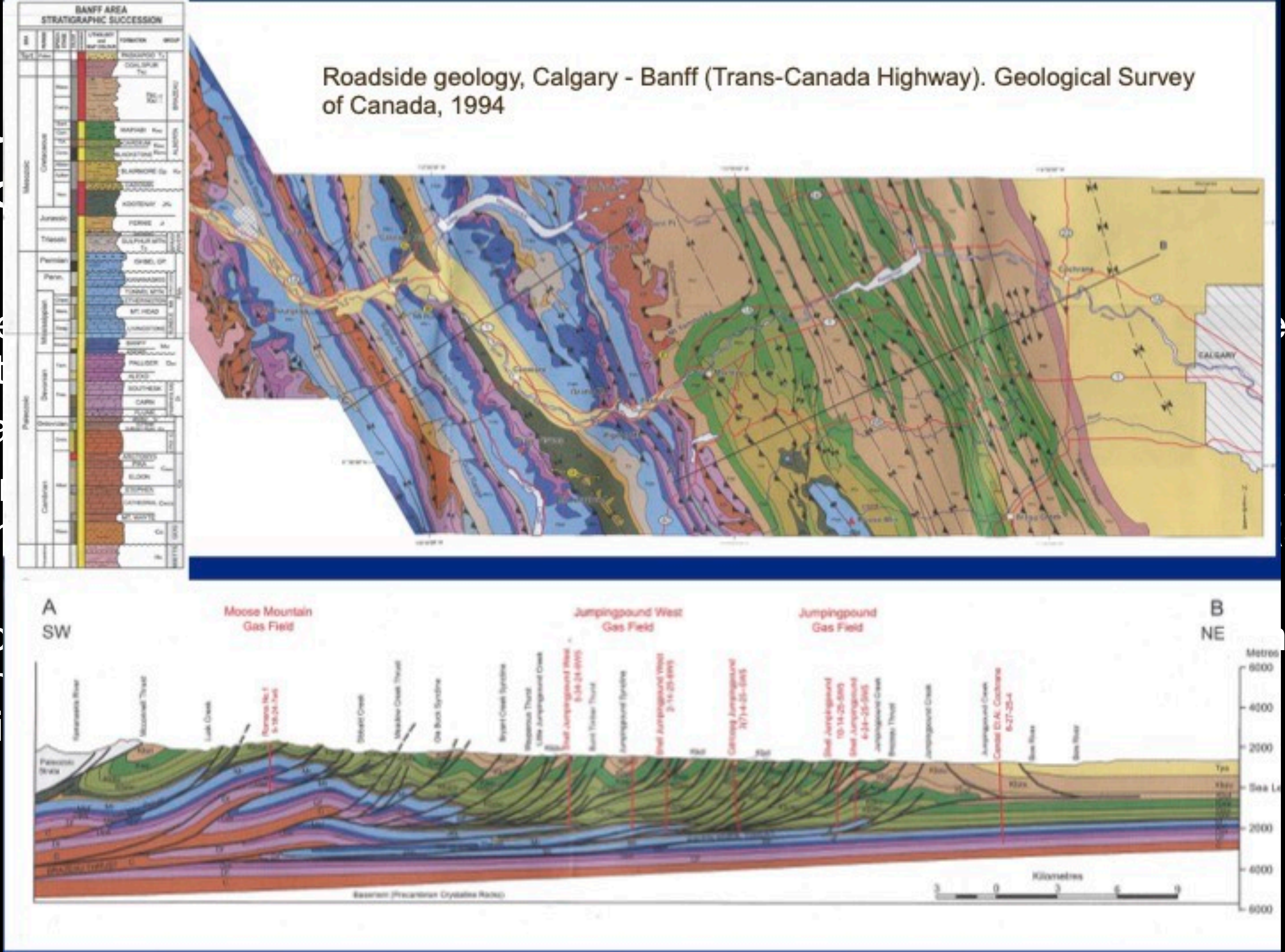


Jumpingpound West
Gas Field
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Gas Field
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5-34-24-6W5
Burnt Timber Thrust
Jumpingpound Syncline
Shell Jumpingpound West
2-14-25-6W5
Cdr/copg Jumpingpound
3(7)-4-25--5W5
Shell Jumpingpound
10-14-25-5W5
Shell Jumpingpound
4-24--25-5W5
Jumpingpound Creek
Brazeau Thrust
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Candel Et Al. Cochrane
6-27-25-4
Bow River
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Jr
RAVEN RIVER THRUST
Mr
Mr
Mbr
Dpa
Df
Kilometres
3
0
3

launch cost


$51,200
$25,600
$12,800
$6,400
$3,200
$1,600
$800
$400
$200
$100
$ per kg (log scale)
1960
1970
1980
1990
2000
2010
2020
2030
1 Soyuz
2 Saturn V
3 Space Shuttle
4 Long March 3b
5 Delta Heavy
6 Angara
7 Falcon 1
8 Falcon 9
9 Falcon Heavy
10 Starship (estimate)
SpaceX
Today, launching a spacecraft is 10x cheaper than it was a decade ago.
1ton=200k$ 10ton=2M$!!!!!

launch cost

- the starship revolution will not be limited to cost to orbit. Starship performance will make it unnecessary to spend time and resources to minimize mass and size, which will change the way not only how the satellites will be built but, more importantly, how the missions are architected.

satellite cost

Satellite	Multi	Weight kg	Cost M$	Cost M$/kg
JWST	1	6500	9000	1.4
Europa clipper	1	6000	5200	0.9
Euclid	1	2000	1510[a]	0.76[a]
IXPE (SMEX)	1	330	138	0.42
HERMES-PF 3U	6	6	0.86[a]	0.144[a]
Standard 3U CubeSat		5	0.1-0.4	0.02-0.08
Planet Lab 3U	100	5.2	~0.1-0.4*	0.02-0.08
Skysat	10	110	~3.5*	~0.032
Starlink1	1000	260	~0.25*	~0.001
Starlink 2 mini	1000	730	~0.8*	~0.0011
Starlink 2	1000	1500	~1.2*	~0.0008

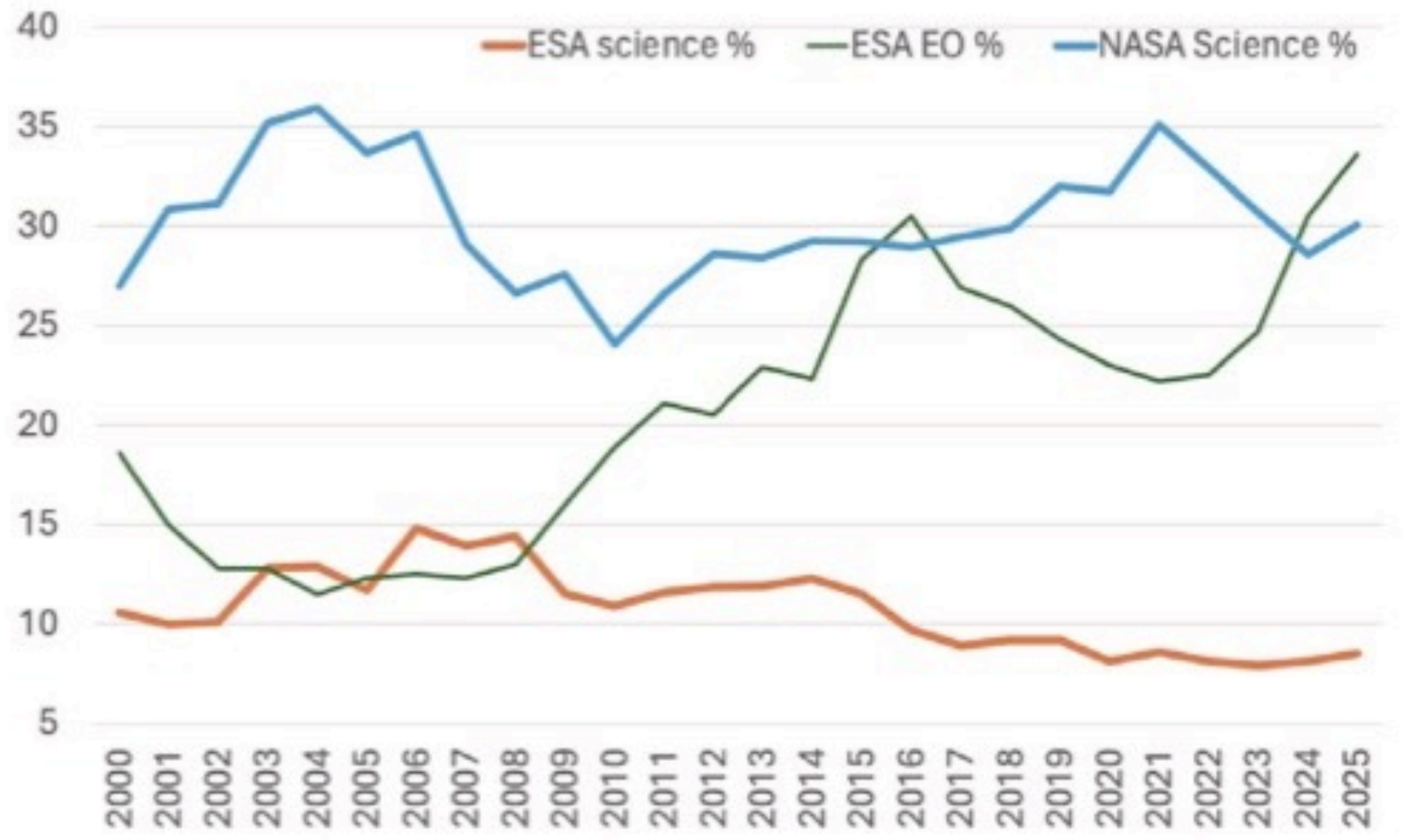
public funding pros & cons

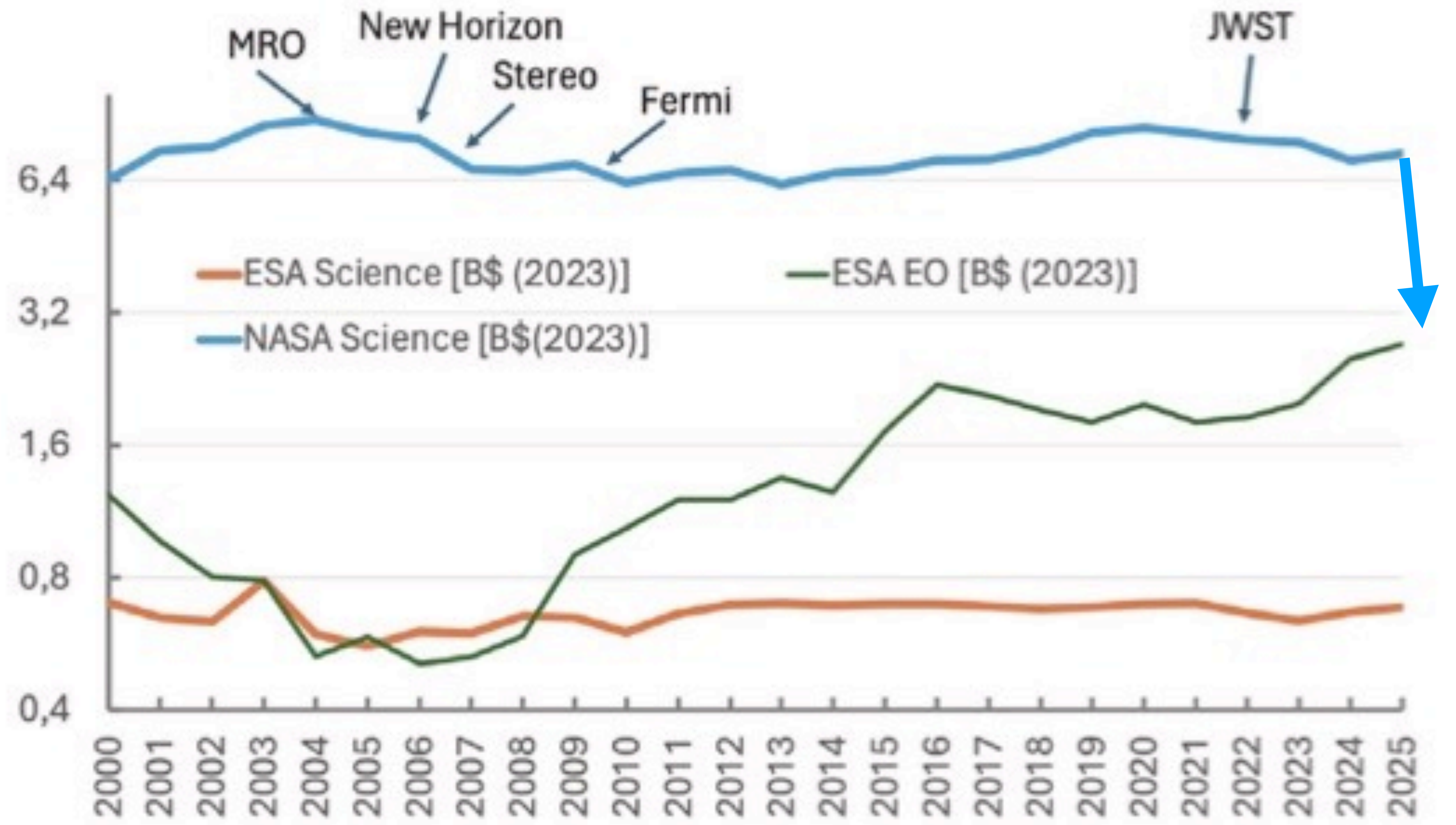
basic science missions are possible	single missions, sometime high risk
funding more stable than in private sector	intrinsically limited funding: ESA-NASA budgets
spin-off possible	limited incentives for spin-off, reduced efficiency in innovation, difficulty in hiring best personnel, hierarchical organization of research teams, complexity of administrative procedures
possibility to exploit synergies with strategic programs, military	

public funding pros & cons

basic science missions are possible

single missions, sometime high risk





strategic programs, military

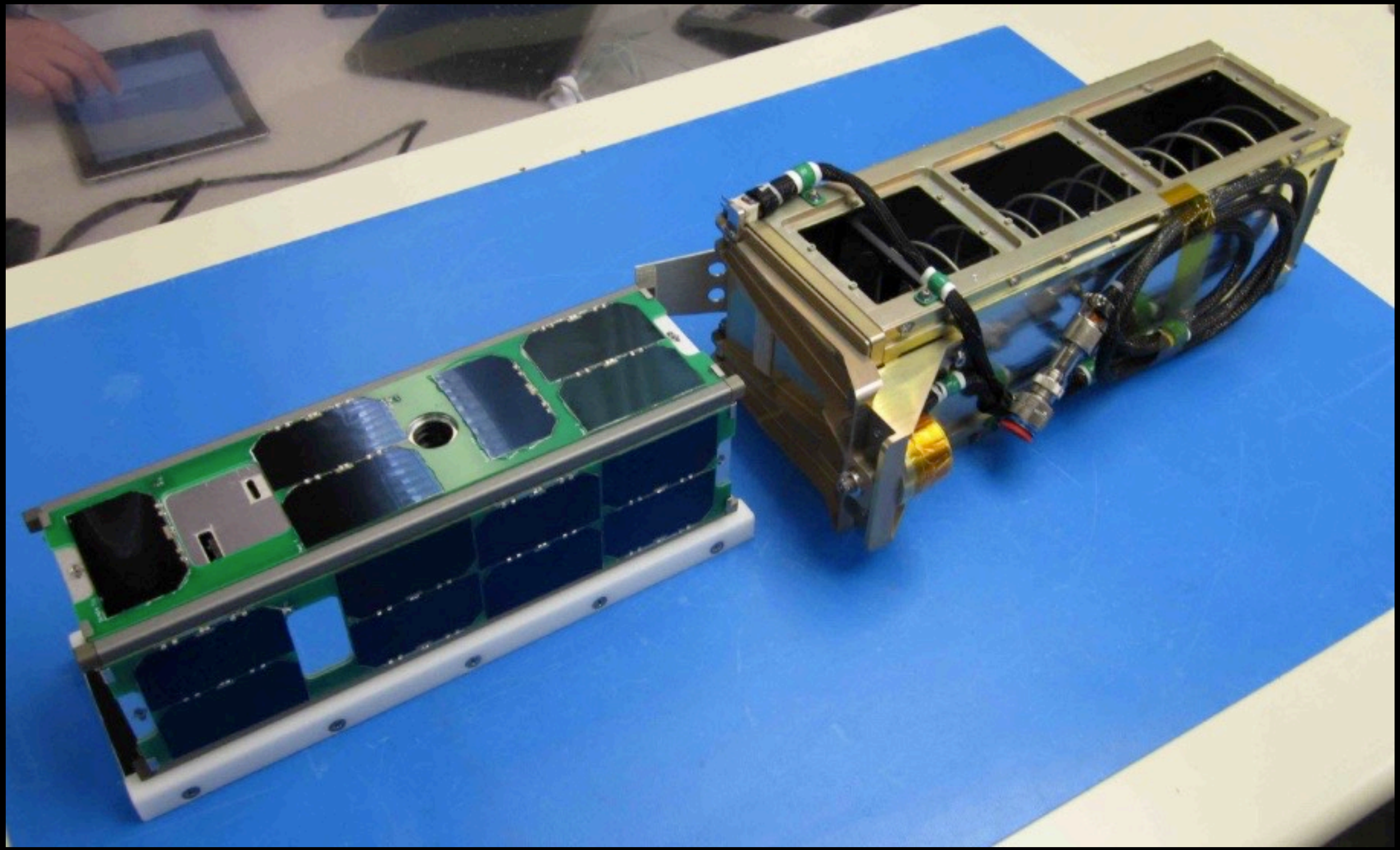
standard science mission cost driven by

- pushing scientific requirements to extremes with little regard for engineering realities
- minimizing launch mass and volume because of high launch costs and limited fairing volumes produces more complex engineering solutions, i.e. JWST's "origami" unfolding
- use of space qualified parts
- *failure is not an option* leads to large numbers of quality control procedures to reduce the risk of failure. ESA ECSS foresees >15000 requirements for standard missions, mostly on quality standards
- quasi-monopoly suppliers

the cubesat example

CSWWE 2012

- miniaturization
- standardization of hardware components, using COTS components, use of flight proven EEE instead of radhard EEE.
- reduced cost of manpower in Universities and research institutes
- less demanding quality control procedures



so far CubeSats have not been able to take advantage of two key elements of cost reduction: production at scale and vertical integration

toward new ambitious but affordable science missions

applying the CubeSat & Explorer approaches to larger spacecraft

two main steps:

- a broader funding base
- innovation

broadening the funding base

- private investors:
  - advertising their activities;
  - profit opportunities in activities such as planetary protection, or exploration of Moon, Mars and Asteroids for resource prospecting, or using science mission to test advanced technologies;
  - buy knowledge
- philanthropic foundations
- public-private partnerships as in e.g. NASA Commercial Orbital Transportation Services (COTS) and Commercial Lunar Payload Services (CLIPS)
- inter-governmental organizations like the European Commission

innovation

- make the requirements smart, where you end is not where you start. iterative approach to achieve the main science goal, during which the science requirements are continually challenged and questioned, with rapid iteration at each step of the development process
- before looking for complex technical solutions we must be sure they are really necessary to reach our main scientific objectives
- exploit as much as possible vertical integration and scale production, commercial buses:
  - starshield
  - https://www.k2space.com/
  - https://www.apexspace.com/

Approaches to lowering the cost of large space telescopes

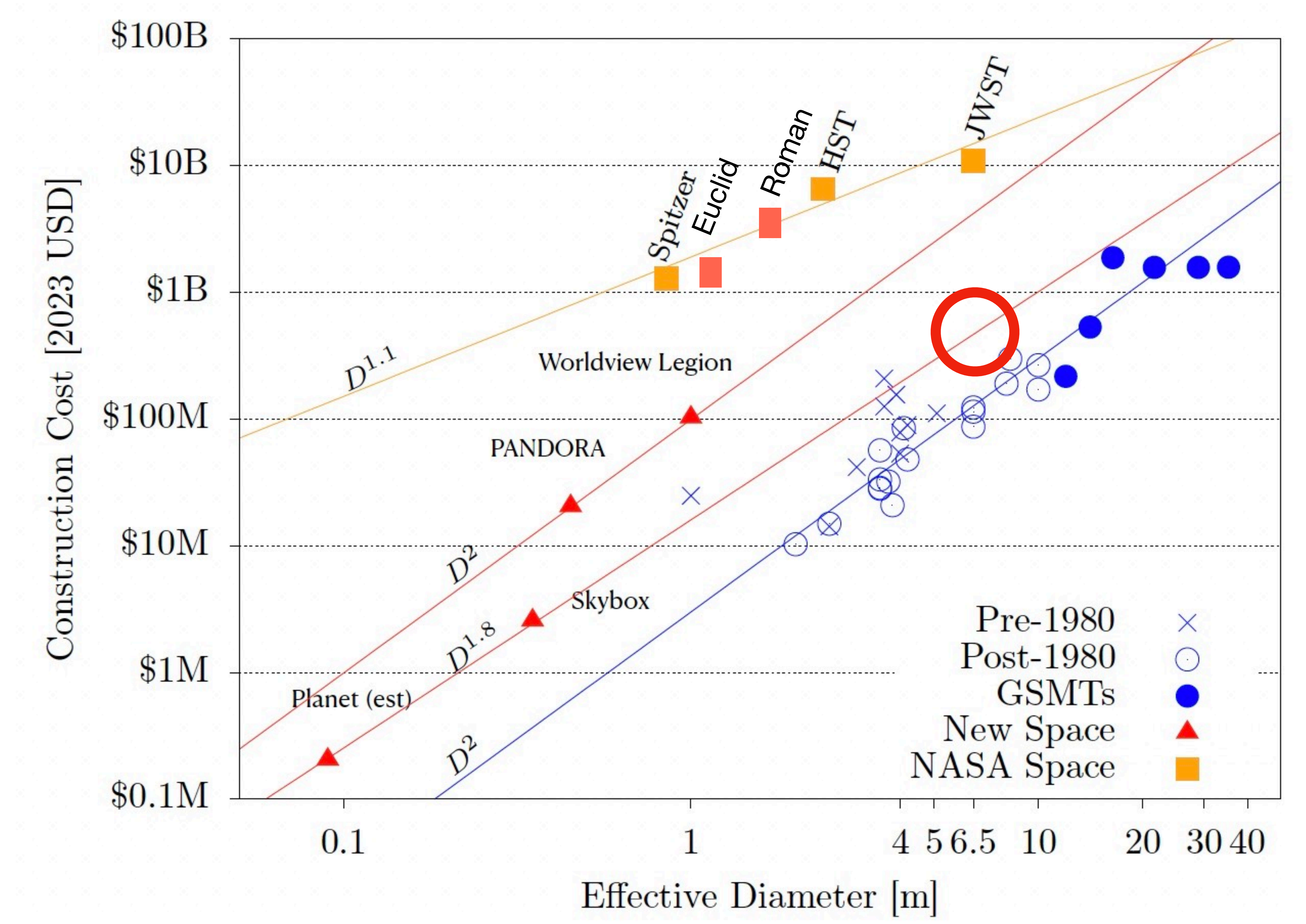
Ewan S Douglas[a], Greg Aldering[b], Greg W. Allan[c], Ramya Anche[a], Roger Angel[a], Cameron C. Ard[a], Supriya Chakrabarti[d], Laird M. Close[a], Kevin Derby[a], Jerry Edelstein[e], John Ford[a], Jessica Gersh-Range[f], Sebastiaan Y. Haffert[a], Patrick J. Ingraham[a], Hyukmo Kang[a], Douglas M. Kelly[a], Daewook Kim[a], Michael Lesser[a], Jarron M. Leisenring[a], Yu-Chia Lin[a], Jared R. Males[a], Buddy Martin[a], Bianca Alondra Payan[a], Sai Krishanth P.M.[a], David Rubin[g], Sanford Selznick[h], Kyle Van Gorkom[a], Buell T. Jannuzi[a], and Saul Perlmutter[b,e,i]

science goals:

- spectrophotometry of type1a SN
- high contrast imaging of sub-neptune planets around nearby stars

engeeniring constraints

- use fairing of Starship, 6.5m
- use Mirror Lab 6.5m light-weighted
- borosilicate honeycomb mirror
- adapt smallsat concepts to enable larger satellites

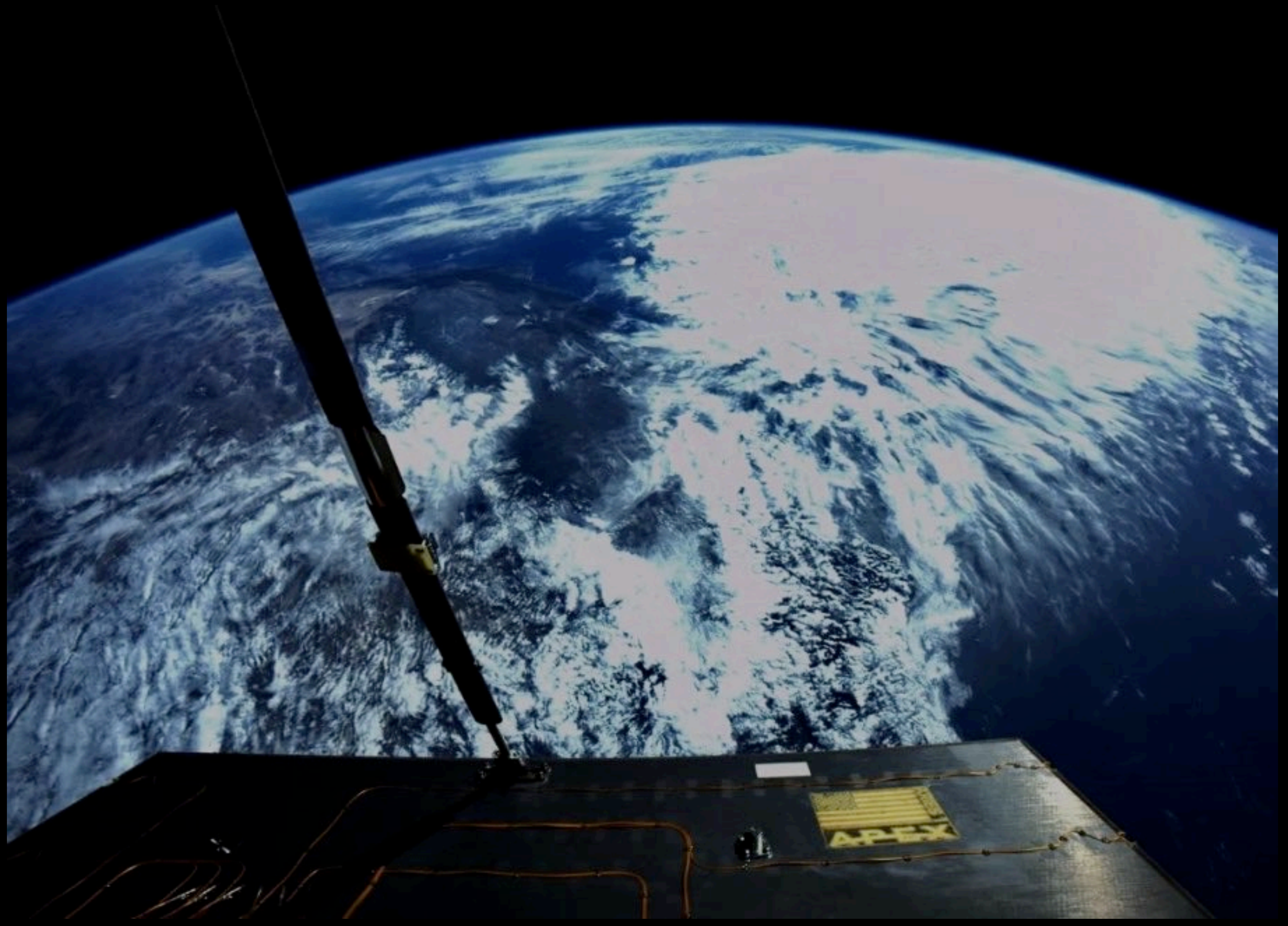


adapt smallsat (cubesat, explorer missions) to enable large basic science missions

- bus ~10MEur

https://www.apexspace.com/order-now

- P/L up to 150kg ~10MEur
- system engineering & system AIT ~10MEur
- launch ~10MEur
- precursos, GS, operations and margings ~10MEur
- Total 50MEur



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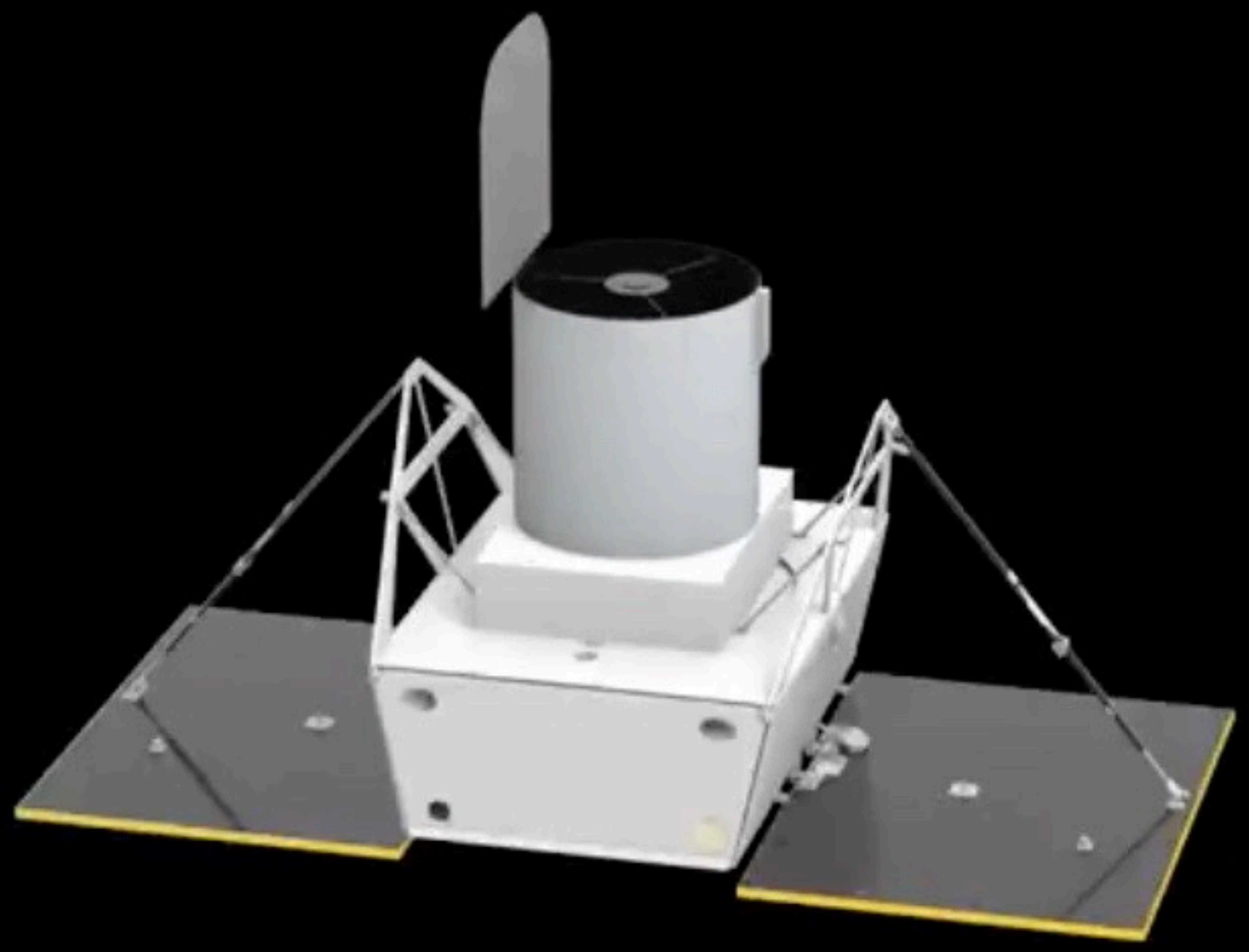

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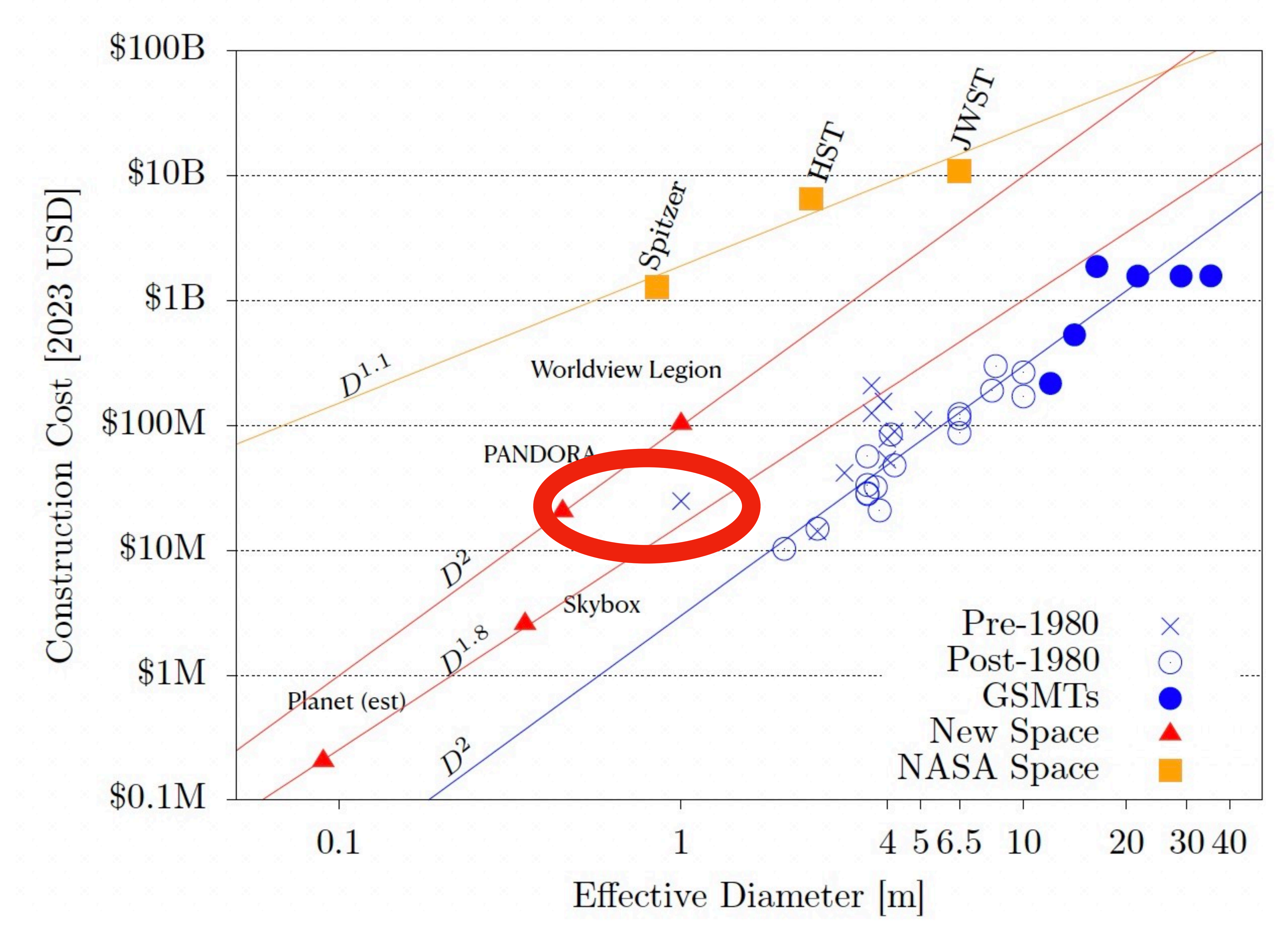

adapt smallsat (cubesat, explorer missions) to enable large basic science missions

Pioneer program: enabling cost-effective, but impactful, science missions.

0.45m ONIR telescope for simultaneous photometric & spectroscopic observations - ~20M$

adapt smallsat (cubesat, explorer missions) to enable large basic science missions

2 spacecrafts to be operated in Mars orbit manufactured by Rocket Lab: <80M$

where to start? back to the Moon!

- 130 missions so far, 13 currently operational, >40 in the next 5-10 years
- public-private engagement
- global interest: Artemis, ILRS but also India, Japan, Korea, UAE, Australia, Israel, Brazil, SA etc..
- Lunar economy moves $8-10B/year CSIS report 2024

https://csis-website-prod.s3.amazonaws.com/s3fs-public/2024-10/241021_Swope_Swimmimg_Upstream_0.pdf

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Moon Mine

Lunar environment has a lot to offer

Earth Use

Light Rare Earth Metals

57	58	59	60	62
La	Ce	Pr	Nd	Sm
Lanthanum	Cerium	Praseodymium	Neodymium	Samarium
138.905	140.116	140.908	144.243	150.36

Current and Potential Use
Catalysts, lasers, electrodes, cancer treatment, magnets, nuclear shielding

Platinum Group

44	45	46	76	77	78
Ru	Rh	Pd	Os	Ir	Pt
Ruthenium	Rhodium	Palladium	Osmium	Iridium	Platinum
101.07	102.906	106.42	190.23	192.217	195.085

Current and Potential Use
Catalytic converters, catalysts, jewelry, radiation shielding, corrosion-resistant metals, alloy strengtheners

Heavy Rare Earth Metals

21	39	64	65	66	68
Sc	Y	Gd	Tb	Dy	Er
Scadium	Yttrium	Gadolinium	Terbium	Dysprosium	Erbium
44.956	88.906	157.25	158.925	162.500	167.259

Current and Potential Use
Radiation shielding, electronic components, lasers, super conductors, dental applications

Pathway
Develop and demonstrate technologies to support efficient prospecting, extracting and delineation

In-Space Use

H_2O

Water
Potential Use
Environmental Control Life Support System necessity

H_2O_2

Hydrogen Peroxide
Potential Use
Monopropellant

1 H Hydrogen 1.008

Hydrogen
Potential Use
Propellant production

8 O Oxygen 15.999

Oxygen
Potential Use
Propellant production

Pathway
- Develop and demonstrate technologies to support efficient prospecting, extracting, processing and delineation
- Support frequent revision of planned architectures to leverage in situ resource utilization (ISRU) developments
- Support exploration architectures that rely on ISRU
- Develop and mature systems and technologies to utilize resources capable of supporting multiple critical aspects of potential architecture

^3He

Helium-3
Potential Use
Fusion fuel

Pathway
Develop/support development of power-generating He-3 fusion reactor

13 Al Aluminum 26.982

Aluminum
Potential Use
- Electronic components
- Solid rocket fuel

Pathway
Develop and demonstrate extraction technology

26 Fe Iron 55.845

Iron
Potential Use
- Tools/structures
- Additive manufacturing

Pathway
Support development of energy-efficient additive manufacturing

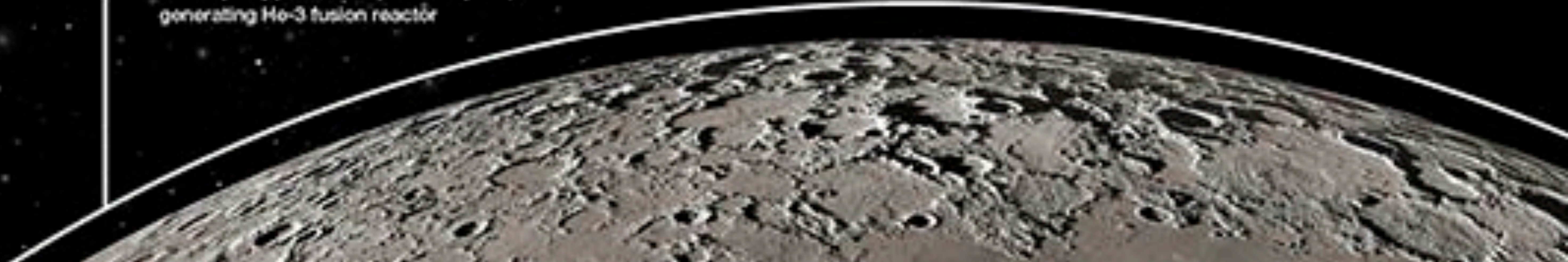
14 Si Silicon 28.086

Silicon
Potential Use
Component of solar arrays, glass, ceramics

Pathway
Develop/support development of systems for in situ purification and manufacturing

Lunar Regolith
Potential Use
Construction material

Pathway
- Develop/support development of systems for in situ processing and use
- Support use in exploration architectures



Of the Moon	On the Moon	From the Moon
Bombardment	Habitability of the Earth through time	Radio astronomy
Structure from core to crust	Life in the Universe	Optical and infrared astronomy
Rock diversity and distribution	Survivability in space	Cosmic ray astronomy
Polar volatiles (e.g. ice)	Physiology and medicine	
Volcanism	Fundamental physics	
Impact processes	Space physics	
Regolith	History of the Sun and Solar System	
Atmosphere, plasma and dust	Impact rate	
Tectonics	Earth-Moon formation	

references

- https://nap.nationalacademies.org/catalog/9839/astronomy-and-astrophysics-in-the-new-millennium
- https://nap.nationalacademies.org/read/12006/chapter/1#
- https://nap.nationalacademies.org/catalog/26141/pathways-to-discovery-in-astronomy-and-astrophysics-for-the-2020s
- https://www.nasa.gov/news-release/nasa-sets-path-to-return-mars-samples-seeks-innovative-designs/
- https://www.nasa.gov/news-release/nasa-exploring-alternative-mars-sample-return-methods/
- https://www.nasa.gov/news-release/nasa-ends-viper-project-continues-moon-exploration/
- https://arxiv.org/pdf/0911.3383
- https://www.spacefoundation.org/2024/07/18/the-space-report-2024-q2/
- https://www3.weforum.org/docs/WEF_Space_2024.pdf
- https://brycetech.com/reports
- MacDonald, A. “The Long Space Age”, Yale Univ Press

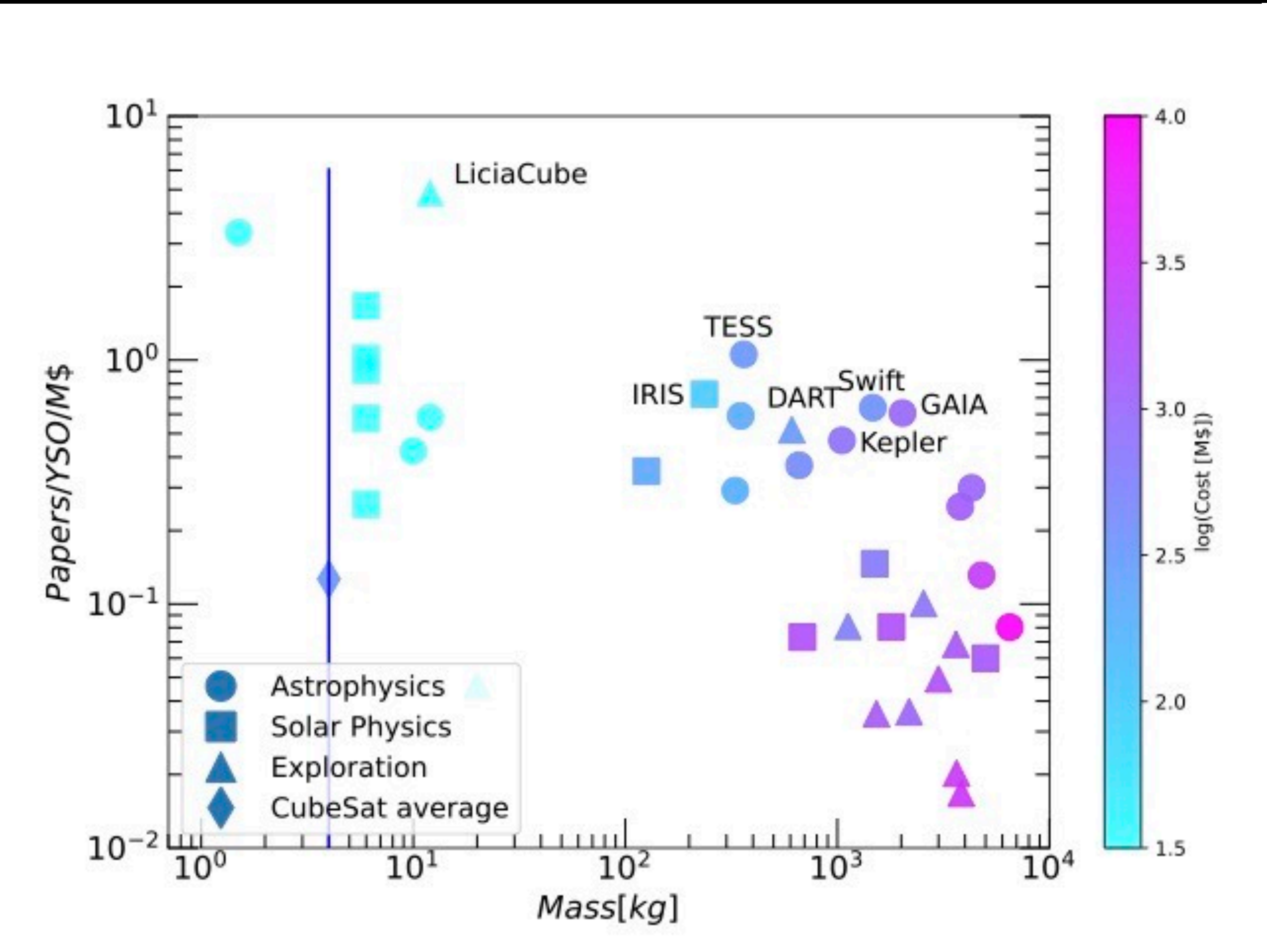
references

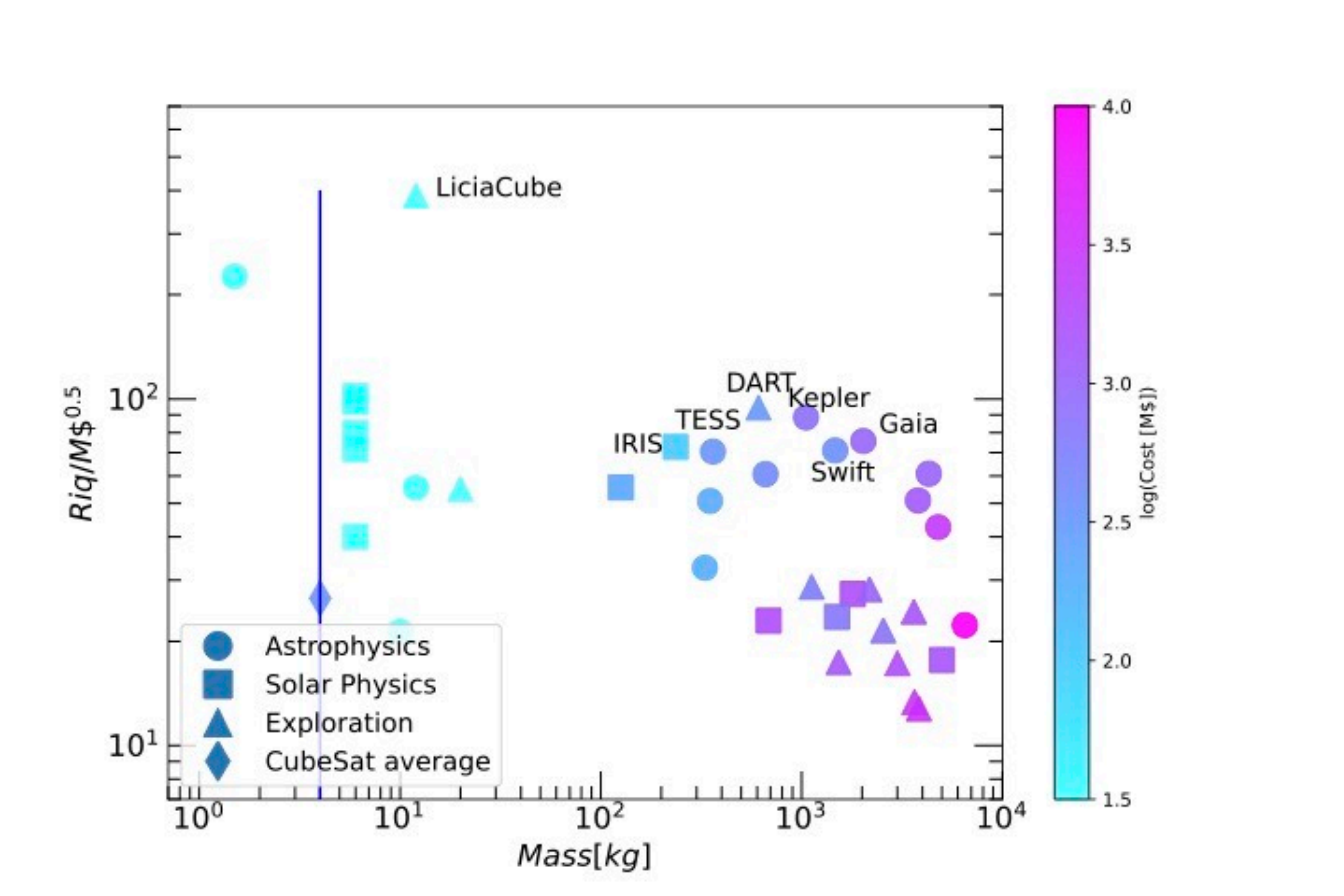
- https://chooser.crossref.org/?doi=10.12987/9780300258387
- McLeod, C.L., and Krekeler, P.S., Resources 2017, 6, 40
- https://pubs.aip.org/physicstoday/article/76/2/40/2869438/Accelerating-astrophysics-with-the-SpaceX
- Heldmann, J.L et al. 2021, Planetary Science and Astrobiology Decadal Survey 2023-2032 white paper e-id. 518
- Douglas, E.S. et al. 2023, arXiv:2309.04934
- https://www.nanosats.eu/tables#keywords
- Fiore et al. 2020 https://doi.org/10.1117/12.2560680
- Fiore et al. 2021 https://doi.org/10.3390/galaxies9040120
- Bloser et al. 2022, arXiv:2212.11414
- McCurdy, H.E., “Faster, Better, Cheaper” 2001, Johns Hopkins Press. ISBN 0-8018-6720-7
- Spence, H. E. et al, 2022, Space Weather Journal, volume 20, issue 7

references

- https://spacenews.com/starlink-soars-spacexs-satellite-internet-surprises-analysts-with-6-6-billion-revenue-projection/
- https://spacenews.com/heavier-smallsats-weigh-down-market-forecasts/
- https://www.k2space.com/
- https://www.apexspace.com/
- https://arstechnica.com/space/2024/04/spacex-working-with-northrop-grumman-on-spy-satellites-for-us-government/
- Garver, L. “Escape Gravity” Diversion Books
- Silk, J. Crawford, I., Elvis, M., Zarnecki, J. 2023, Nature Astronomy, 7. 648
- Pepe, A. & Kurz M.J., 2012, PLOS ONE 7(11): e46428.
- Bely, P. et al. 2025, JATIS, 11 (3) Genesis of the James Webb Space Telescope architecture: the designers’ story

metrics for science mission success





$$tori = \sum_n 1/ar$$

$$riq = \sqrt{tori/yso}$$

a is the number of authors of each citing paper and r is the number of references of the citing paper