The Event Horizon Explorer mission concept

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Chief Scientist of Cosmic Origins
National Aeronautics and Space Administration
October 18, 2022

*views expressed here are my own and do not reflect the views of the Cosmic Origins Program or NASA

Mission concept study team

45 Individuals representing 19 institutions in 5 countries

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18 Institute for Advanced Study, 1 Einstein Drive, Princeton, NJ 08540, USA
19 Princeton Gravity Initiative, Princeton University, Princeton, NJ 08544

Related presentations at this workshop

Presenter	Day/Time	Title
Peter Galison	Tues 9:30 – 9:50	What is detection? Hunting the black hole photon ring
Freek Roelofs	Tues 9:50 – 10:10	Simulating the future of black hole imaging with space VLBI
Lindy Blackburn	Tues 11:00 – 11:30	ngEHT and its potential spaceborne extension
Peter Kurczynski	**this presentation**	**The Event Horizon Explorer mission concept**
Daniel D'Orazio	Tues 12:00 – 12:20	The Event Horizon Explorer: more than two, the black hole demography science goal
TK Sridharan	Weds 9:30 – 9:50	Precision timing for mm/submm space VLBI
Jade Wang	Weds 10:10 – 10:30	Optical communications for the Event Horizon Explorer mission concept

Black holes capture …

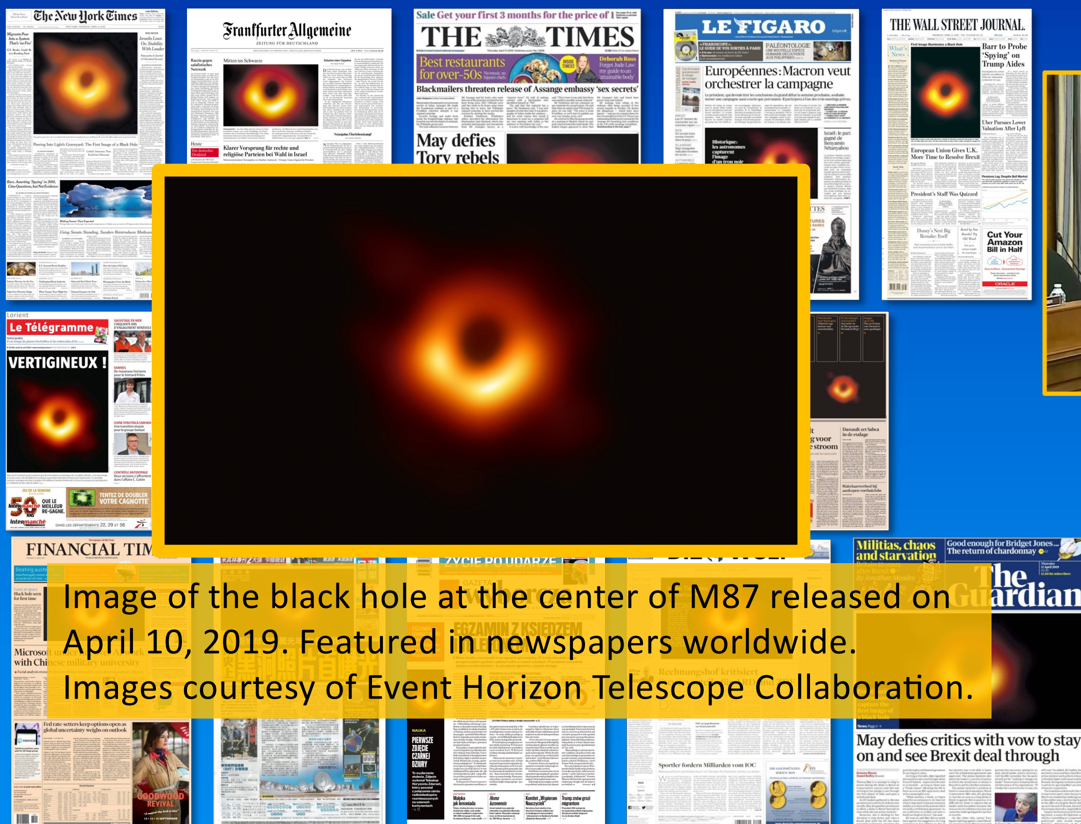
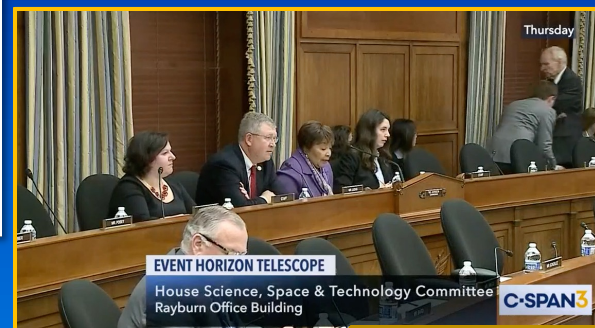
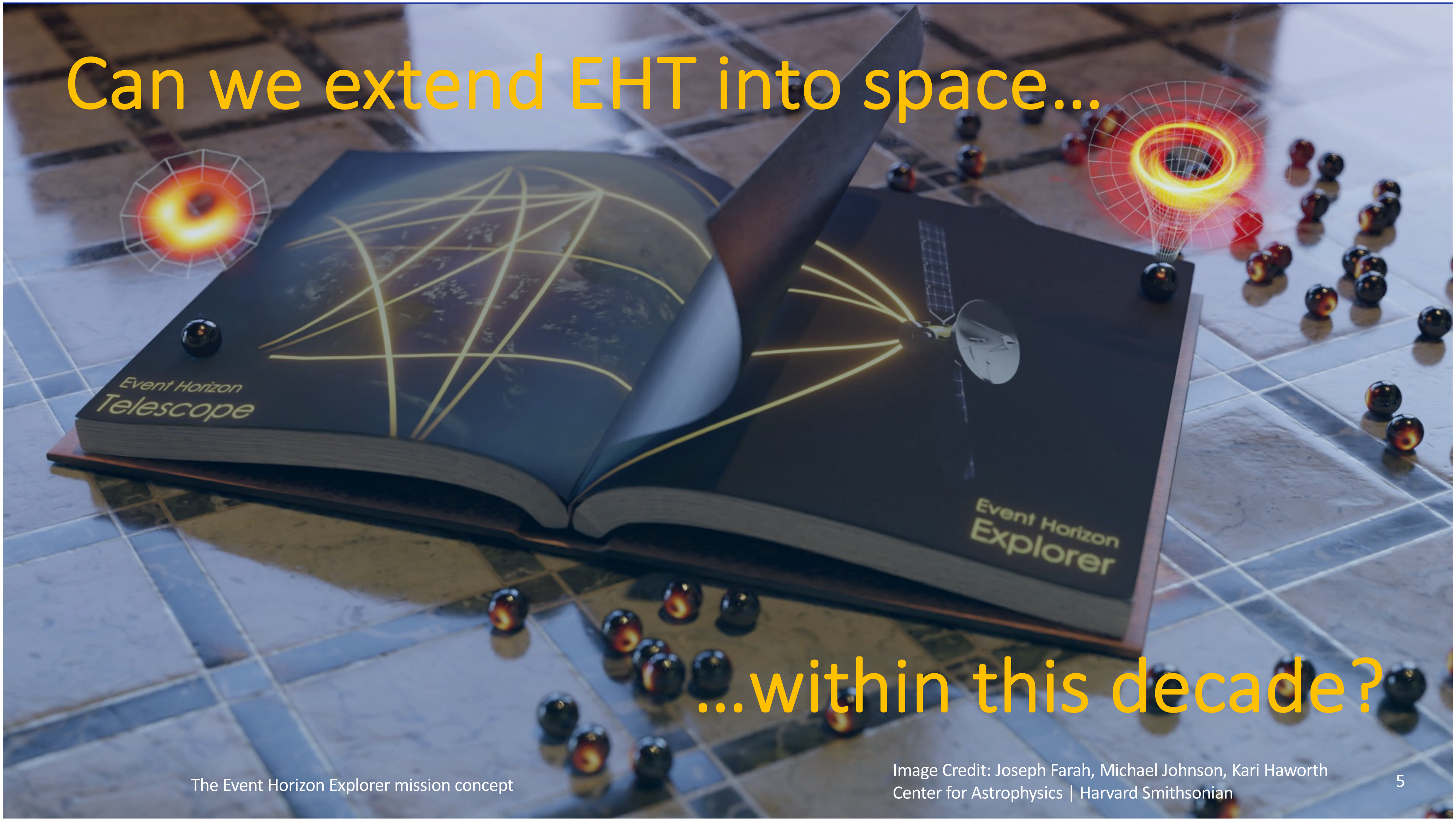


Image of the black hole at the center of M87 released on April 10, 2019. Featured in newspapers worldwide.
Images courtesy of Event Horizon Telescope Collaboration.



… our imagination

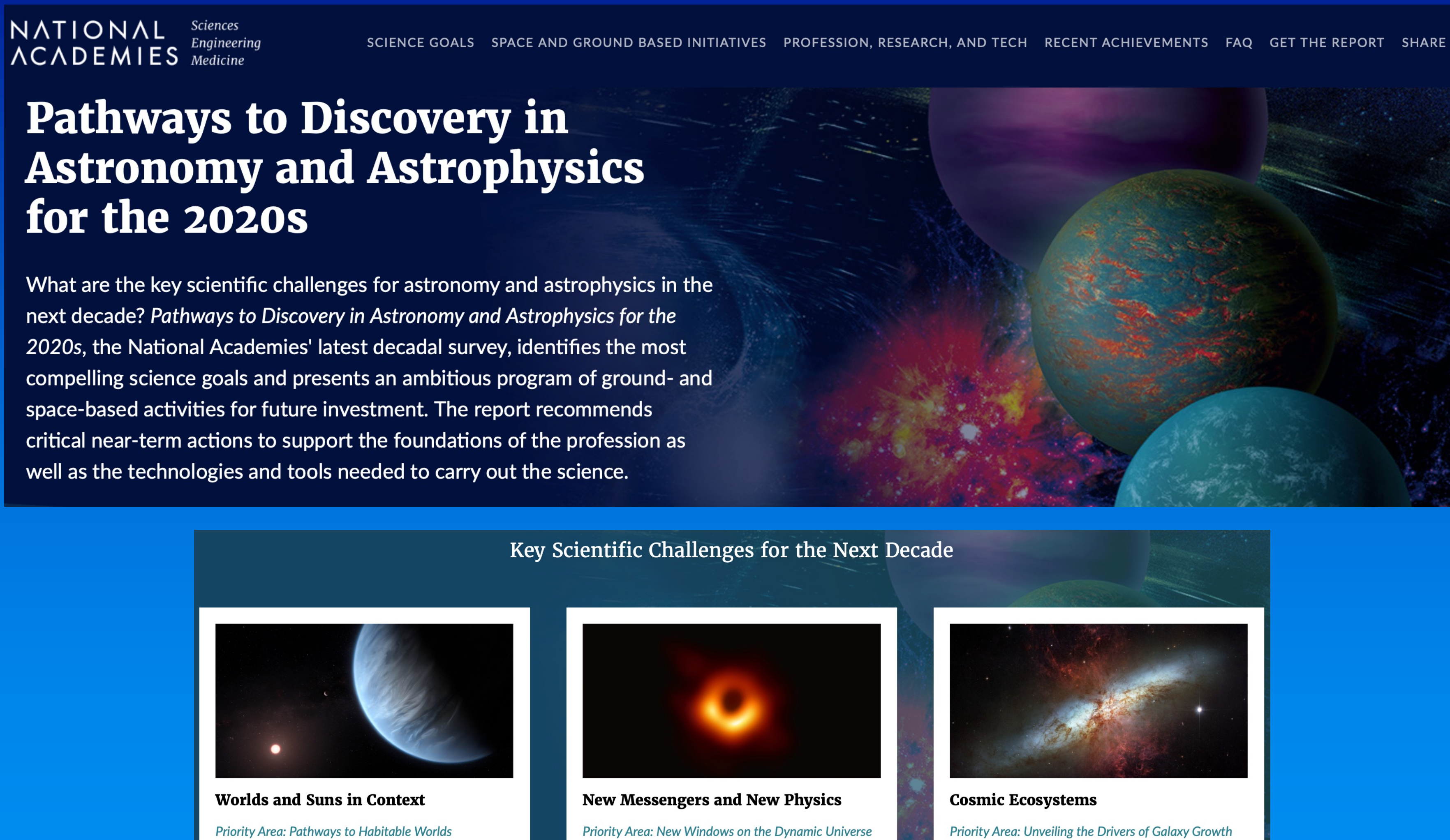
Can we extend EHT into space…



…within this decade?

The Event Horizon Explorer mission concept

Image Credit: Joseph Farah, Michael Johnson, Kari Haworth
Center for Astrophysics | Harvard Smithsonian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Pathways to Discovery in Astronomy and Astrophysics for the 2020s
What are the key scientific challenges for astronomy and astrophysics in the next decade? *Pathways to Discovery in Astronomy and Astrophysics for the 2020s*, the National Academies' latest decadal survey, identifies the most compelling science goals and presents an ambitious program of ground- and space-based activities for future investment. The report recommends critical near-term actions to support the foundations of the profession as well as the technologies and tools needed to carry out the science.
Key Scientific Challenges for the Next Decade
Worlds and Suns in Context
Priority Area: Pathways to Habitable Worlds
New Messengers and New Physics
Priority Area: New Windows on the Dynamic Universe
Cosmic Ecosystems
Priority Area: Unveiling the Drivers of Galaxy Growth

NASA astrophysics strategy: set by Decadal Survey recommendations

Astro2020 recommends the following strategic space observatories:

- A 6m-class IR/Optical/UV observatory to be launched during the first half of the 2040s;
- A Far-IR Flagship to be launched later than the 2040s;
- An X-ray Flagship, also later than the 2040s (before, after, or in parallel to the Far-IR Flagship);
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Image: 2022 Astrophysics Biennial Technology Report, https://apd440.gsfc.nasa.gov/technology.html

NASA Astrophysics Flight Programs

Program	Cost (~$)	Examples	Mitigating Factors (?) = intuition
Flagship	$10B	Hubble, JWST	Must be DS top recommendation
Probe	$1B	NEW!	DS recommendation: FIR/X-ray ; broad community-wide support; risk averse (?)
Explorer - MIDEX	**$300M**	**Swift, TESS**	**1 “new” technology (?); 100x ground-based capability (?)**
Explorer - SMEX	$165M	IXPE, COSI (Dev), GALEX, SWAS	1 “new” technology (?); 100x ground-based capability (?)
Pioneers	$20M	Smallsat, Balloon, ISS payload	Too small for transformative VLBI science (?)

MIDEX means transformative science…

A representative table of recent MIDEX mission characteristics

Name	Science	Mass (kg)	Power (W)	Orbit (km)	Cost ($M)	Launch (Year)
SPHEREx	IR all-sky survey, spectroscopy	178	N/A	700	250	2024
TESS	All-sky survey, 1000's of exoplanets!	362	530	375,000	200	2018
Swift	γ-ray bursts: counterparts, origins	1470	1040	600	163	2004
WMAP	Precision cosmology	835	419	L2	150	2001
RXTE	Neutron stars, millisecond timing	3200	800	409	350	1995
IMP-8	Solar wind	410	800	35 R_E	N/A	1973

MIDEX Announcement of Opportunity: 4-year cadence. Delayed for budgetary reasons in 2021. Next MIDEX AO: 2026 (?)

Mission concept study format

1 **Science study**

Science goals and objectives. Science Traceability Matrix for the relevant Science cases. Science report.

2 **External review**

External panel review. Review criteria based on NASA Explorers Program review

3 **Engineering study**

Establishing core engineering requirements, TRL assessments, technology development paths

4 **Mission architecture study**

Establishing Initial viable configuration, power, mass etc.

1 Science study

Science goals and objectives. Science Traceability Matrix for the relevant Science cases. Science report.

- **Precision black hole measurements**
- Black hole accretion and jets
- Black hole formation and demographics

1

Science study

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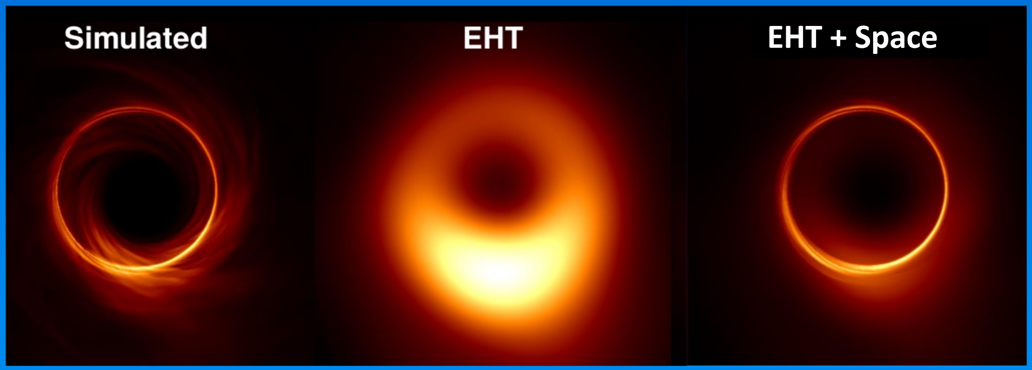
Presentations by
Peter Galison & Freek
Roelofs

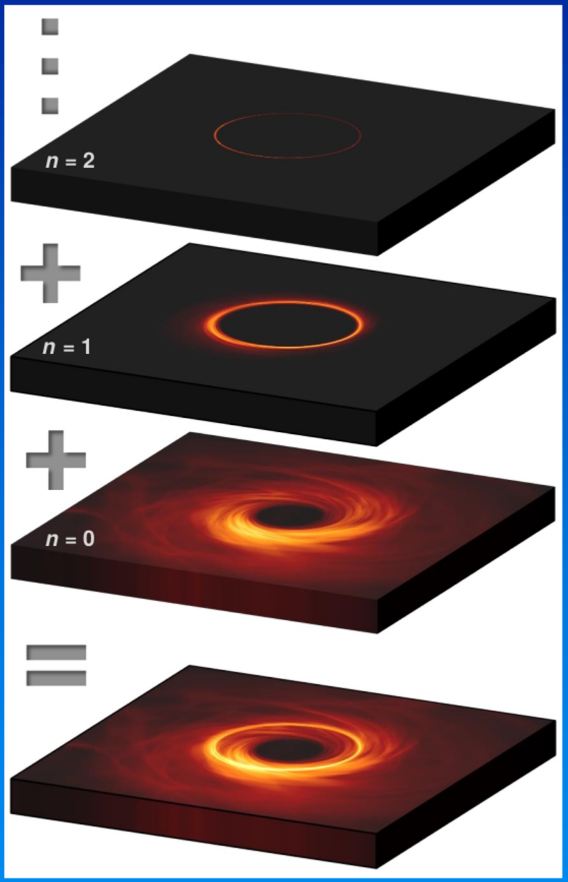
Precision black hole measurements

Space-VLBI can observe a black hole's photon ring, giving precise information about the unstable orbits of light in the photon shell

Opportunity to measure a black hole's mass and spin and to derive model-independent tests of general relativity



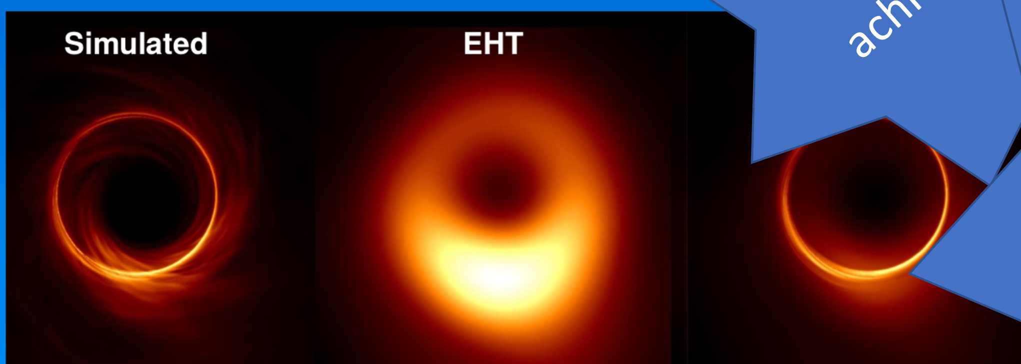
Credit: Michael Johnson (CfA)



Credit: George Wong & Michael Johnson

2 External review

- Great!
- Amazing!
- Not enough



Credit: Michael Johnson (CfA)

(spin) “profound achievement”

“strongest part of the motivation for EHE”

Will “blow away” the public

“spin measurements are interesting…but needs more than n=1 to sell it…”

“I’m not very interested in checking up n Einstein… ”

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1 Science study

Science goals and objectives. Science Traceability Matrix for the relevant Science cases. Science report.

- Precision black hole measurements
- Black hole accretion and jets
- **Black hole formation and demographics**

Presentation by Daniel D'Orazio coming up next!

1 More science to come?

- How do black holes shine?
- Do wormholes exist?
- Are black holes holographic?*
- Other questions?

Insert your testable hypotheses here!

*eg see Dennis Overbye, New York Times, October 10, 2022

3

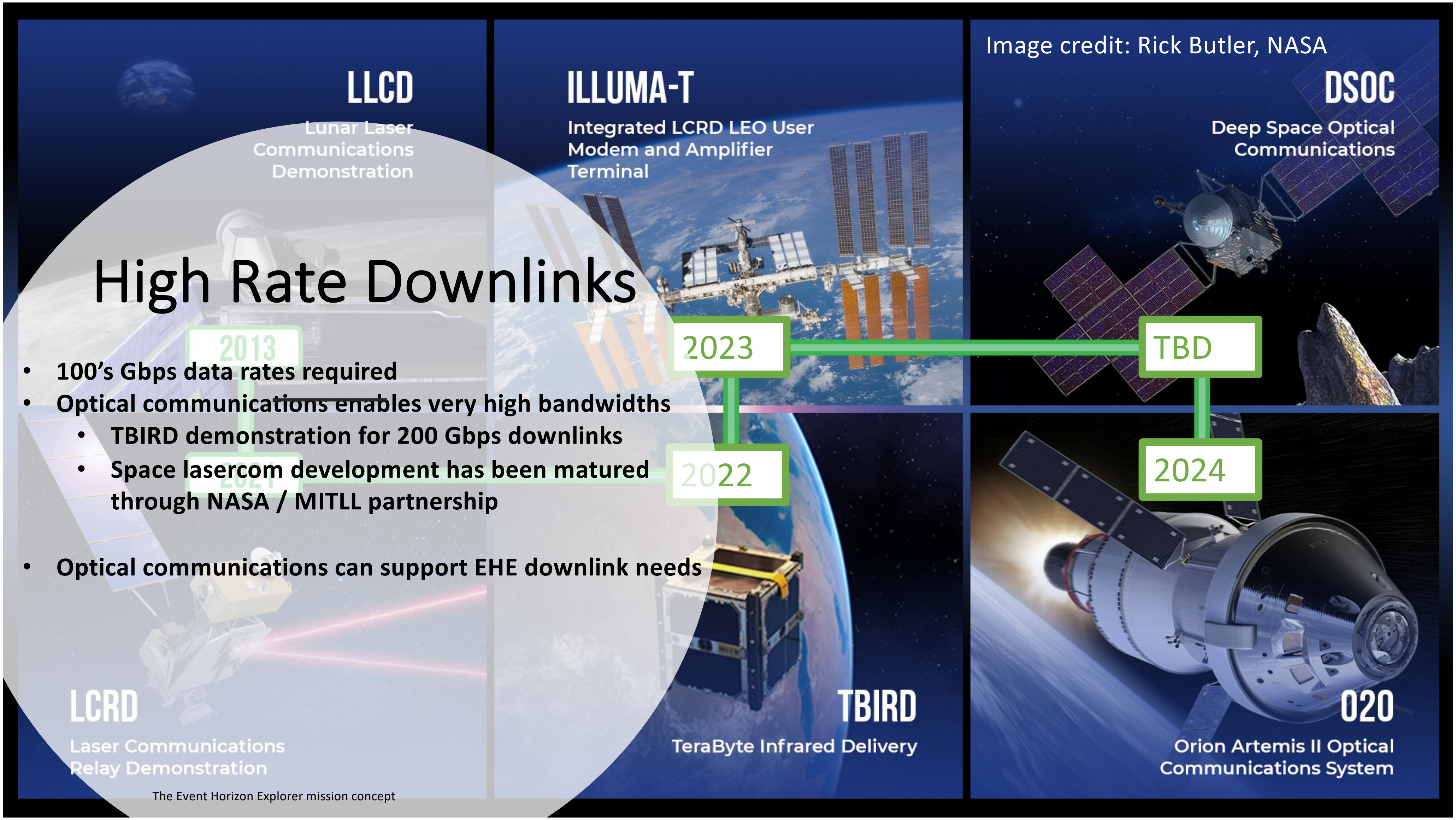
Engineering Study

Establishing core engineering requirements, TRL assessments, technology development paths

- **Assess key technologies**
- Inform mission architecture trades

High Rate Downlinks

- 100’s Gbps data rates required
- Optical communications enables very high bandwidths
  - TBIRD demonstration for 200 Gbps downlinks
  - Space lasercom development has been matured through NASA / MITLL partnership
- Optical communications can support EHE downlink needs



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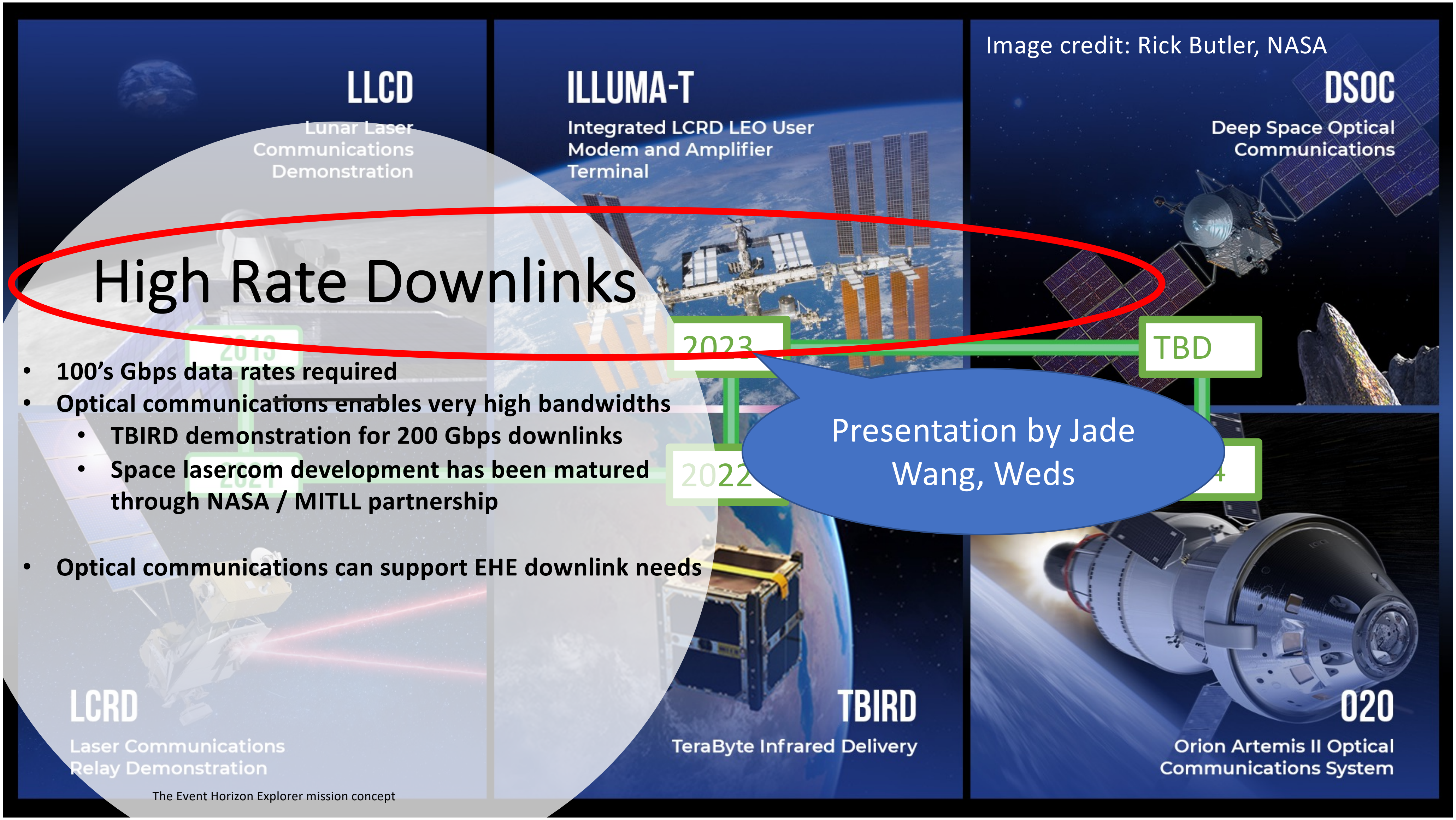
Presentation by Jade Wang, Weds



The Event Horizon Explorer mission concept

Precision timing: space qualified clocks

- Needs better than one part per trillion (10^{-14}) relative stability over short time intervals of 1 to 100 seconds
- upcoming missions require an order of magnitude improvement
- Fortunately, timing and clock reference standards have progressed, which achieved frequency precision of $2.5*10^{-19}$
- Understanding the space qualification and SWaP of these clocks is needed

Other applications of next-gen precision timing in space

- GPS, deep space probes
- Geodesy (cm)
- Gravity sensor (eg Volcanos' subterranean magma chambers)
- Dark matter searches
- Gravitational wave detection
- Tests of variation of fundamental constants (new physics)
- SI definition of the second

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Presentation by TK Sridharan, Weds

Antennas

Technology	TRL	Limiting Factor
Monolithic, carbon fiber (eg BLAST TNG)	6	Small aperture (< 3m); has not launched in environment of EHE
Mesh	7	Not proven to work reliably in required frequency range
Unfurlable Mesh	5	Needs development to work in required frequency range
Inflatable	3	Potentially transformative; early technology development

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See presentation by Dan Marrone, Weds

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Being delivered to NASA/GSFC for optical testing

3 Engineering: Next Steps

Establishing core engineering requirements, TRL assessments, technology development paths

- Assess key technologies
- **Inform mission architecture trades**

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$$\text{Science} = f(Engineering)$$

3 Engineering: Next Steps

Establishing core engineering requirements, TRL assessments, technology development paths

$$\text{Science} = f(Engineering)$$

e.g. Sensitivity

e.g. Antenna, downlink rate, timing…

3 Engineering: Next Steps

Establishing core engineering requirements, TRL assessments, technology development paths

$$d\ Science = \frac{\partial f}{\partial E_1} dE_1 + \frac{\partial f}{\partial E_2} dE_2 + \ldots$$

3 Engineering: Next Steps

Establishing core engineering requirements, TRL assessments, technology development paths

$$d\ Science = \frac{\partial f}{\partial E_1} dE_1 + \frac{\partial f}{\partial E_2} dE_2 + \ldots$$

Enables architecture trades

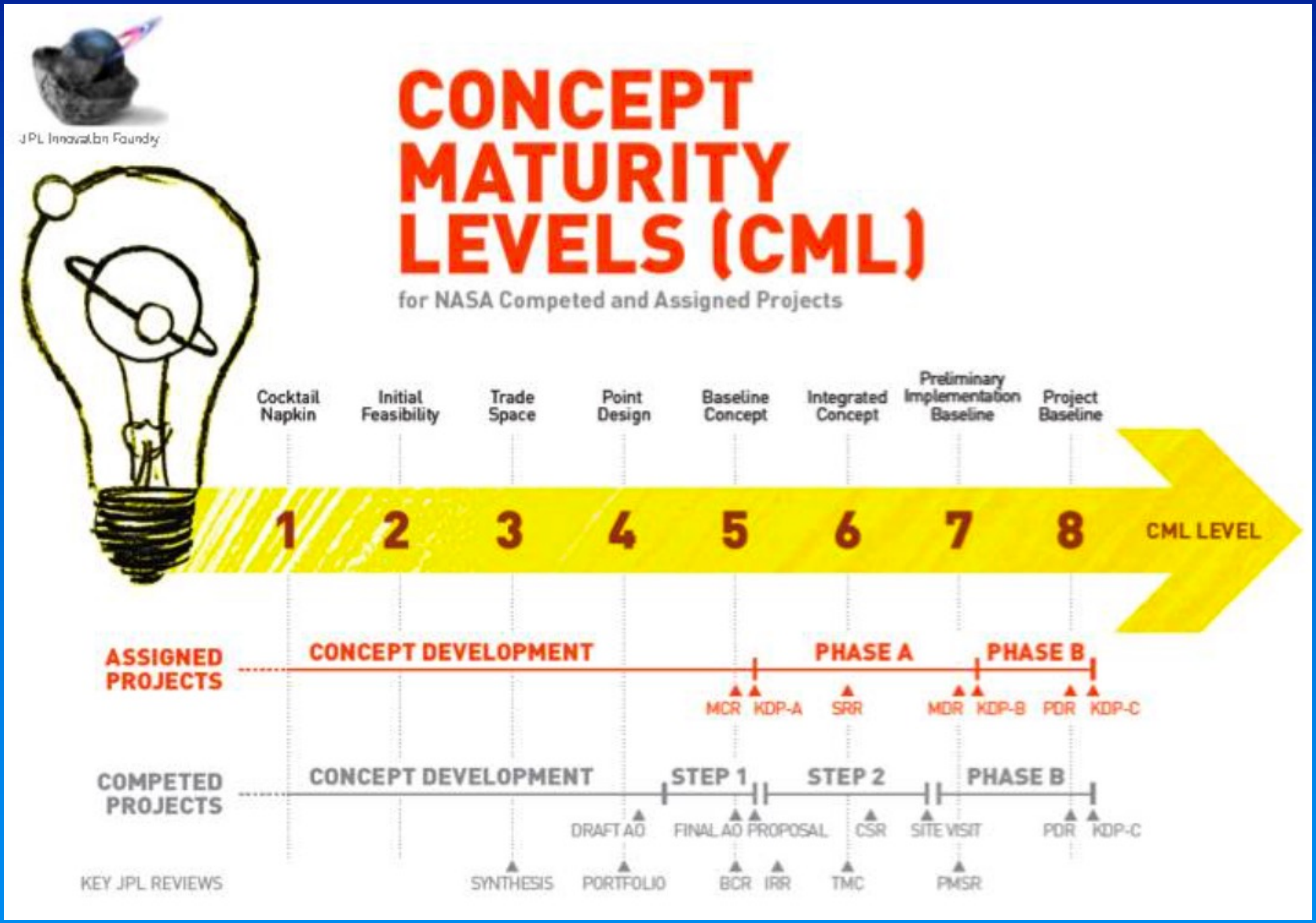
3 Engineering: Next Steps

Establishing core engineering requirements, TRL assessments, technology development paths

"all too often mission concepts move forward without understanding the science partials, which is how science return changes as a function of some mission parameter …

… trade space exploration is a key part of concept maturation (in order to find) a global optimum in the design of a viable concept"

Wessen, R. et al. 2013, Space Mission Concept Development Using Concept Maturity Levels, AIAA



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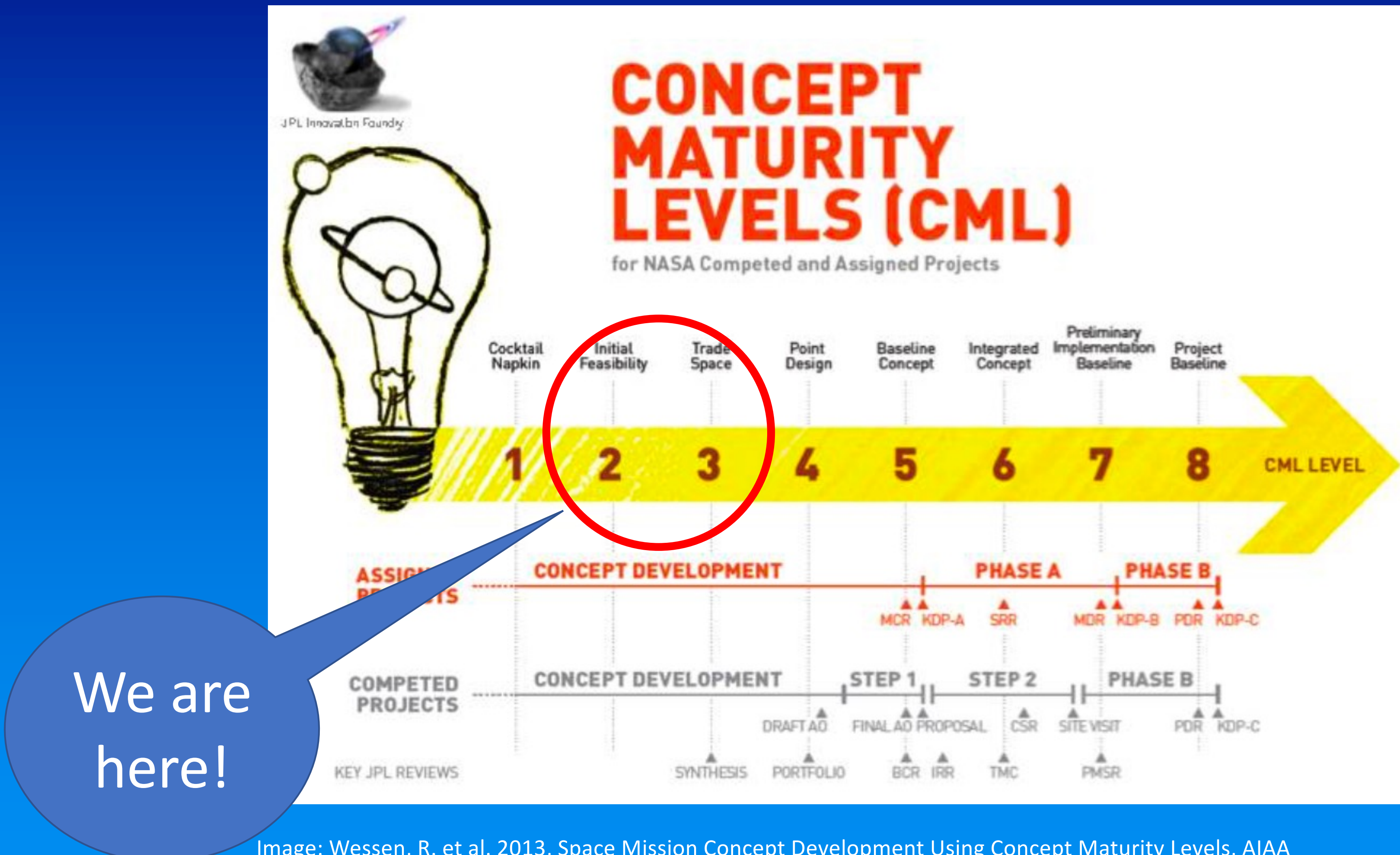

Image: Wessen, R. et al. 2013, Space Mission Concept Development Using Concept Maturity Levels, AIAA

What VLBI community can do

Align with (and influence) NASA strategic technology development plan

Tier 1 Technology Gaps

- Advanced Cryocoolers
- Coronagraph Contrast and Efficiency
- Coronagraph Stability
- Cryogenic Readouts for Large-Format Far-IR Detectors
- Heterodyne Far-IR Detector Systems
- High-Performance, Sub-Kelvin Coolers
- High-Reflectivity Broadband Far-UV-to-Near-IR Mirror Coatings
- High-Resolution, Large-Area, Lightweight X-ray Optics
- High-Throughput Bandpass Selection for UV/VIS
- High-Throughput, Large-Format Object Selection Technologies for Multi-Object and Integral Field Spectroscopy
- Large Cryogenic Optics for the Mid IR to Far IR
- Large-Format, High-Resolution Focal Plane Arrays
- Large-Format, Low-Darkrate, High-Efficiency, Photon-Counting, Solar-blind, Far- and Near-UV Detectors
- Large-Format, Low-Noise and Ultralow-Noise Far-IR Direct Detectors
- Long-Wavelength-Blocking Filters for X-ray Micro-Calorimeters
- Low-Stress, High-Stability, X-ray Reflective Coatings
- Mirror Technologies for High Angular Resolution (UV/Vis/Near IR)
- Stellar Reflex Motion Sensitivity – Astrometry
- Stellar Reflex Motion Sensitivity – Extreme Precision Radial Velocity
- Vis/Near-IR Detection Sensitivity

Tier 2 Technology Gaps

- Broadband X-ray Detectors
- Compact, Integrated Spectrometers for 100 to 1000 μm
- Far-IR Imaging Interferometer for High-Resolution Spectroscopy
- Far-IR Spatio-Spectral Interferometry
- Fast, Low-Noise, Megapixel X-ray Imaging Arrays with Moderate Spectral Resolution
- High-Efficiency X-ray Grating Arrays for High-Resolution Spectroscopy
- High-Resolution, Direct-Detection Spectrometers for Far-IR Wavelengths
- Improving the Calibration of Far-IR Heterodyne Measurements
- Large-Aperture Deployable Antennas for Far-IR/THz/sub-mm Astronomy for Frequencies over 100 GHz
- Large-Format, High-Spectral-Resolution, Small-Pixel X-ray Focal-Plane Arrays
- Polarization-Preserving Millimeter-Wave Optical Elements
- Precision Timing for Space-Based Astrophysics
- Rapid Readout Electronics for X-ray Detectors
- Starshade Deployment and Shape Stability
- Starshade Starlight Suppression and Model Validation
- UV Detection Sensitivity

NASA Astrophysics Strategic Technology Gaps, from 2022 Astrophysics Biennial Technology Report, https://apd440.gsfc.nasa.gov/technology.html

NASA astrophysics strategy:
set by Decadal Survey recommendations

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Image: 2022 Astrophysics Biennial Technology Report, https://apd440.gsfc.nasa.gov/technology.html

VLBI can align with (much larger) IR astronomy community!

Conclusions: Initial feasibility study

- Photon ring is key science; additional science is needed
- Antenna, downlink, timing - under development
- Next steps: mission architecture trades

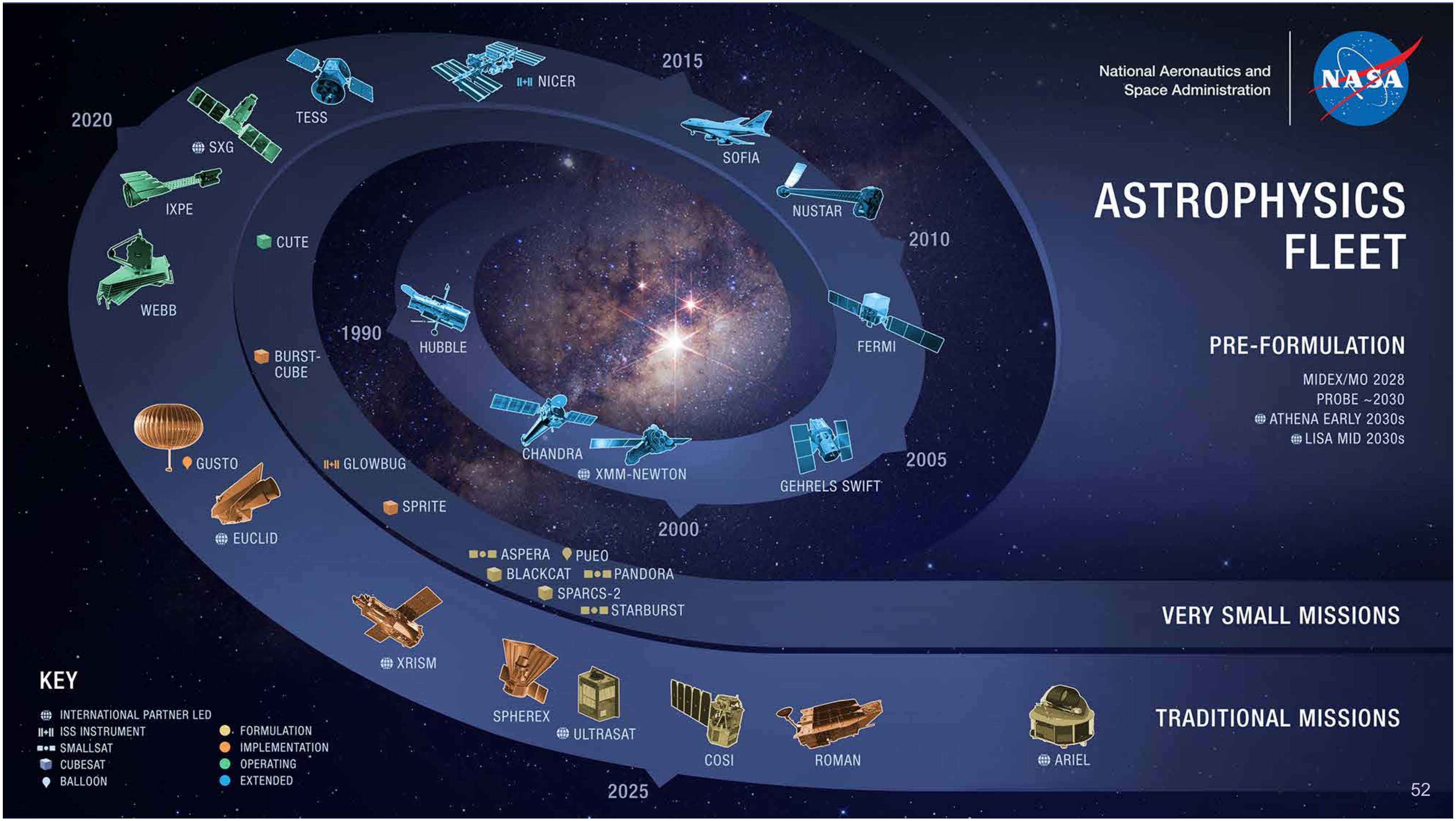
Acknowledgement: This research was supported by the NASA GSFC Internal Research and Development Program

Conclusions: VLBI community

- VLBI is transformational science and technology!
- Engage with IR community for flagship/probes
- Engage with NASA technology development

Join the Cosmic Origins Program Analysis Group!
https://cor.gsfc.nasa.gov

Extra slides


National Aeronautics and Space Administration
NASA
ASTROPHYSICS FLEET
PRE-FORMULATION
MIDEX/MO 2028
PROBE ~2030
ATHENA EARLY 2030s
LISA MID 2030s
VERY SMALL MISSIONS
TRADITIONAL MISSIONS
1990
2000
2005
2010
2015
2020
2025
HUBBLE
CHANDRA
XMM-NEWTON
GEHRELS SWIFT
FERMI
NUSTAR
SOFIA
NICER
TESS
SXG
IXPE
WEBB
CUTE
BURST-CUBE
GUSTO
GLOWBUG
SPRITE
EUCLID
ASPERA
PUEO
BLACKCAT
PANDORA
SPARCS-2
STARBURST
XRISM
SPHEREX
ULTRASAT
COSI
ROMAN
ARIEL
KEY
INTERNATIONAL PARTNER LED
ISS INSTRUMENT
SMALLSAT
CUBESAT
BALLOON
FORMULATION
IMPLEMENTATION
OPERATING
EXTENDED

Technology Readiness Levels (TRL)

Appendix C: TRL Assessment information

TRL	Description
1	Basic scientific principles on which the project will rely have been noted.
2	Technological implementation has been formulated.
3	Specific functions of the project have been evaluated.
4	A low-fidelity model of the project has been tested in a laboratory.
5	A medium-fidelity model of the project has been tested in a simulation of the environment in which it will be used.
6	A high-fidelity model of the project has been tested in a simulation of the environment in which it will be used, and demonstrates that it can operate as expected.
7	A high-fidelity prototype of the project has been tested in a simulation of the environment in which it will be used, and demonstrates that it can perform as expected.
8	The final build of the project has been tested and has demonstrated that it is qualified to fly.
9	The final build of the project has proven itself to be qualified through its successful performance in an actual mission.

Table 5 A general description of each Technology Readiness Level (TRL).[27]

Peretz, E. et al, 2022 Event Horizon Explorer Astrophysics Mission Concept Engineering Study Report, unpublished