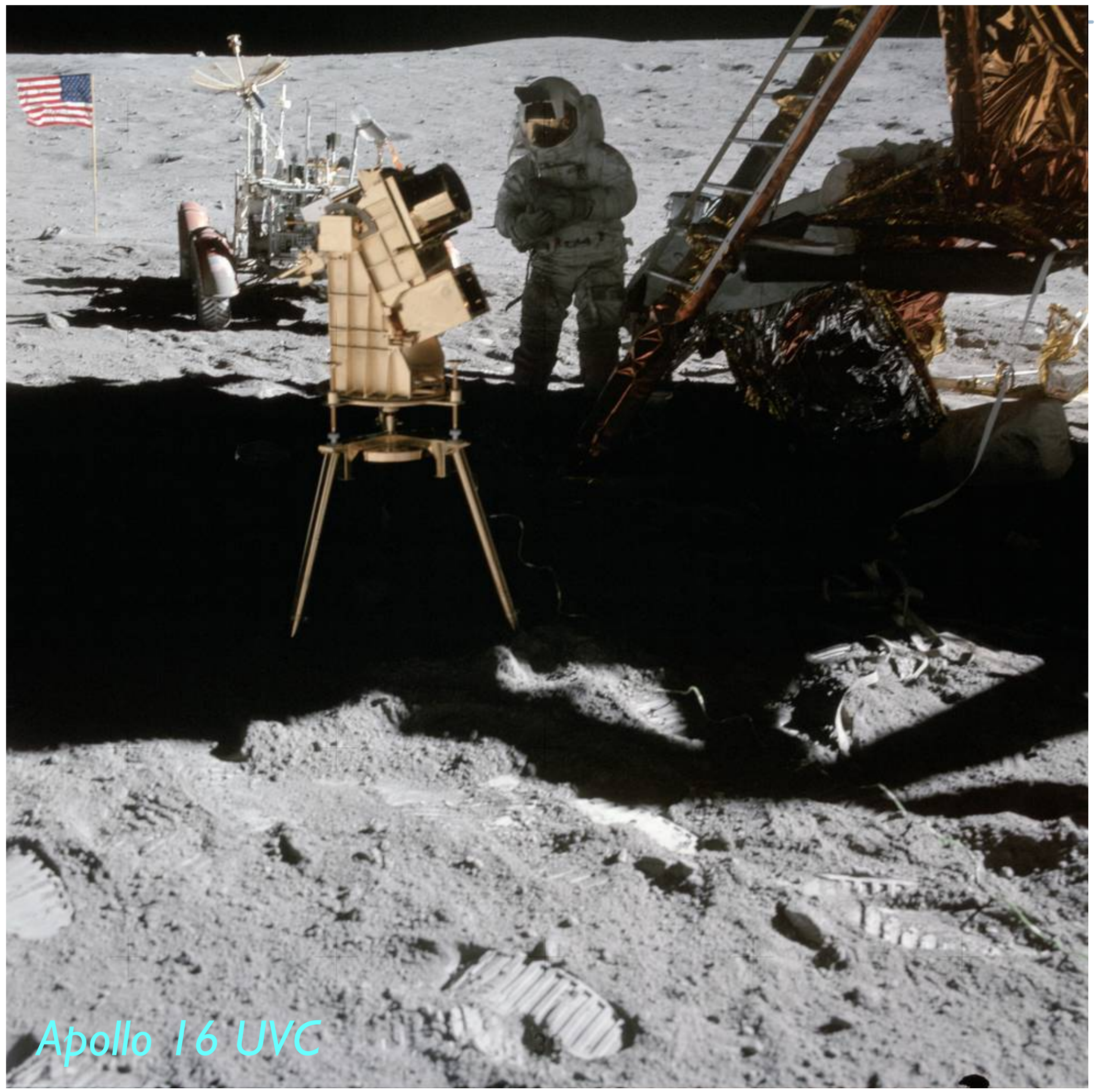


An Optical Interferometer on the Moon: Concept and Astrometric Science

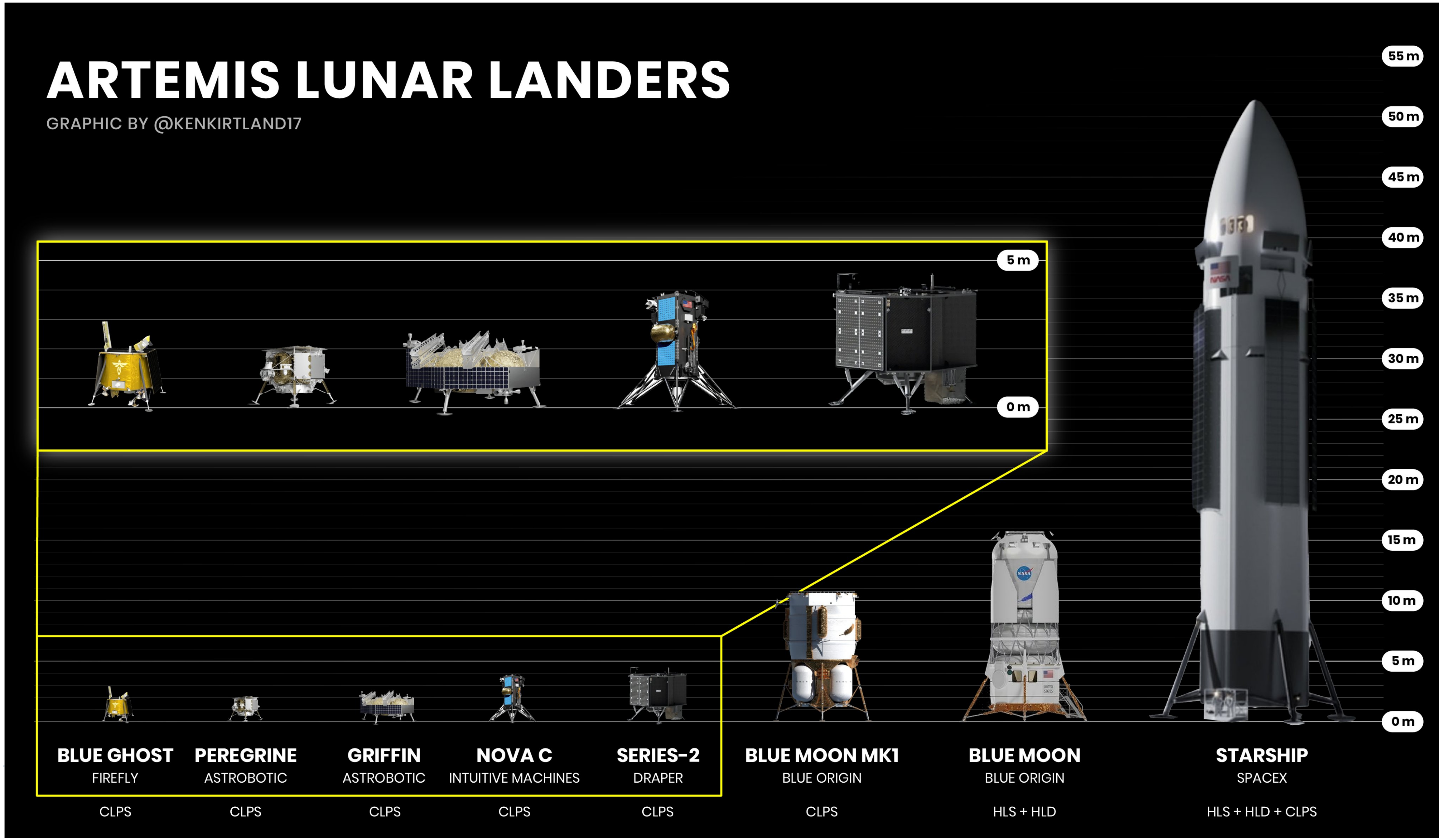
Gerard van Belle (Lowell Observatory)

If you are designing space observatories, and not considering the moon …

If you are designing space observatories, and not considering the moon …

Your mission design trade space is incomplete

Lunar Surface Access

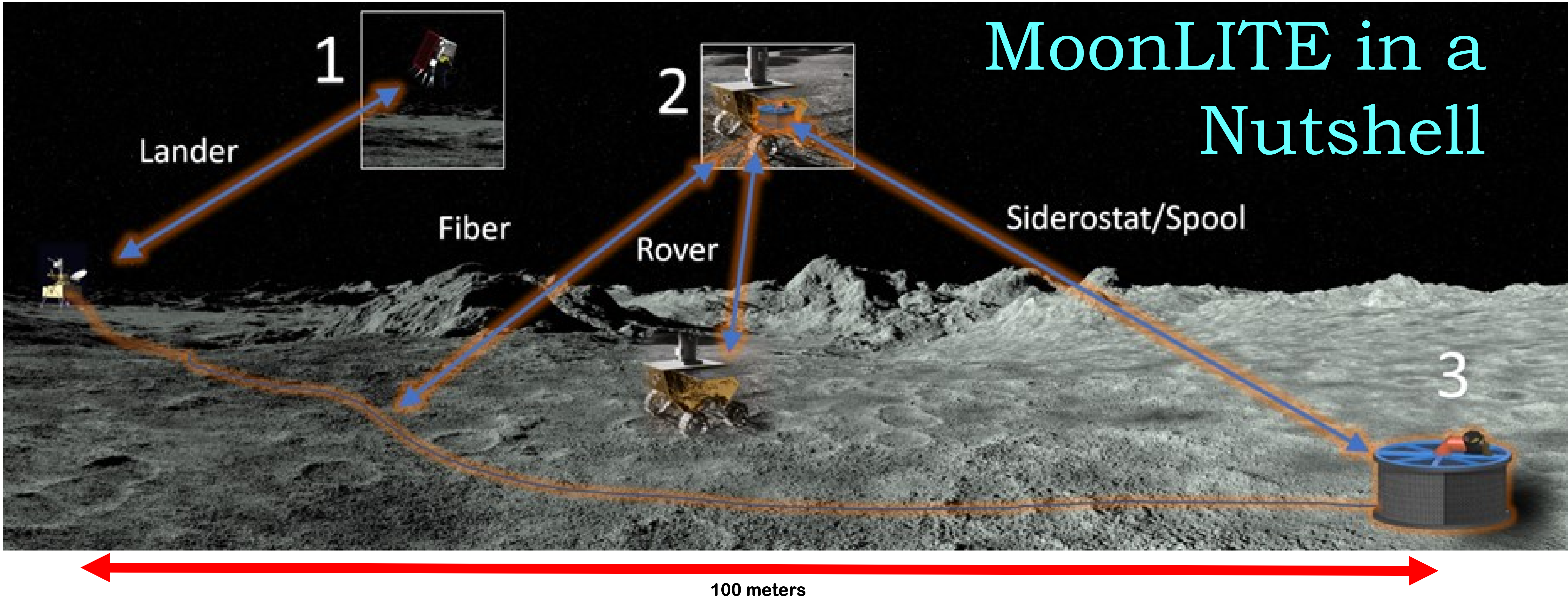


What is MoonLITE?

- LITE = Lunar InTerferometry Explorer

- A NASA Astrophysics Pioneers proposal, reviewed cycle 2022-2023
- A two-element, 100 meter Michelson interferometer
- CLPS-delivered to lunar surface
- Capable of V=17, for objects 0.1-1.6mas in size, measure 0.1-5.0% sizes

MoonLITE in a Nutshell



Emphasis on simplicity: one deployment step

Given lunar surface stability, hosting by lander, resources can be focused on the experiment itself

Lester (2006)

"The only thing the moon has to offer astronomy is

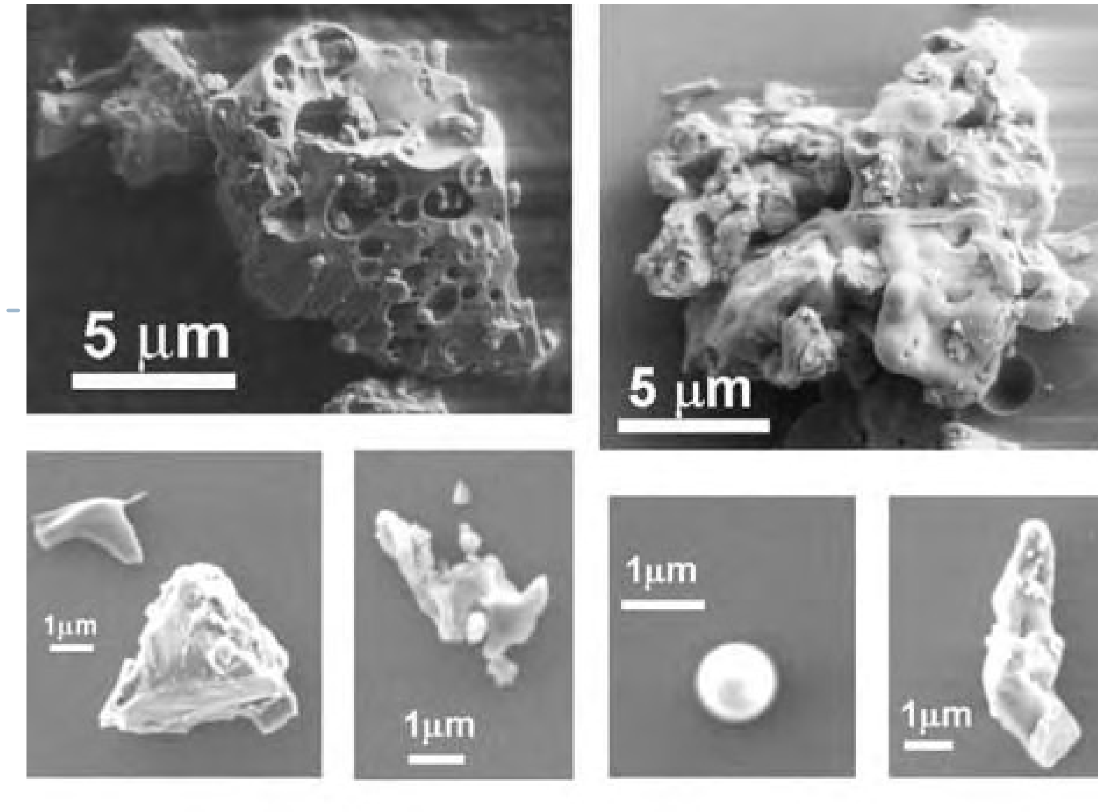
dust

and **gravity**"

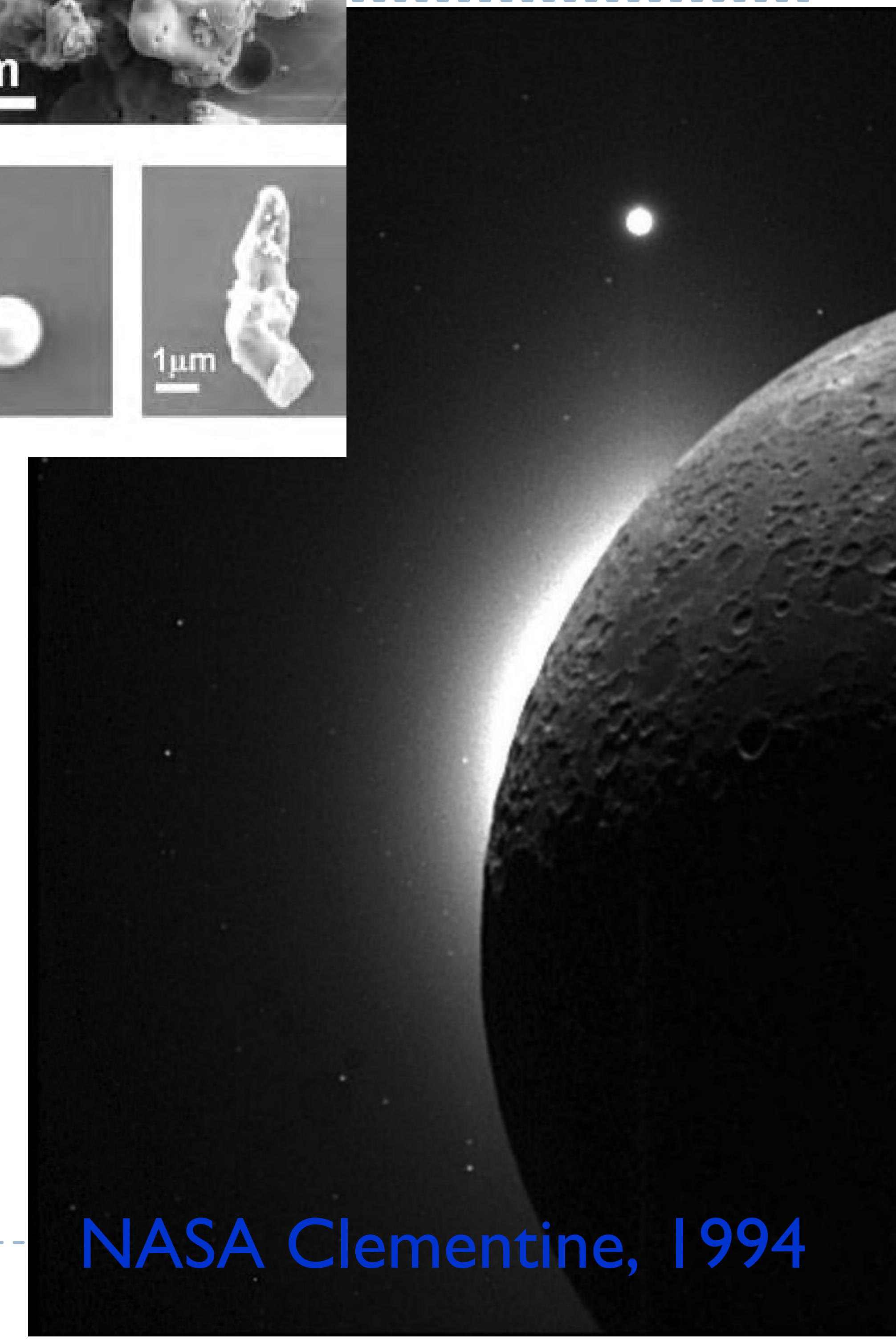
(slightly paraphrased)

Dust?

- Nasty, nasty stuff
  - Astronauts exhibited ‘black lung’ like symptoms
- Unweathered glass shards, sticky
- ‘Levitates’ above surface at sunrise, sunset



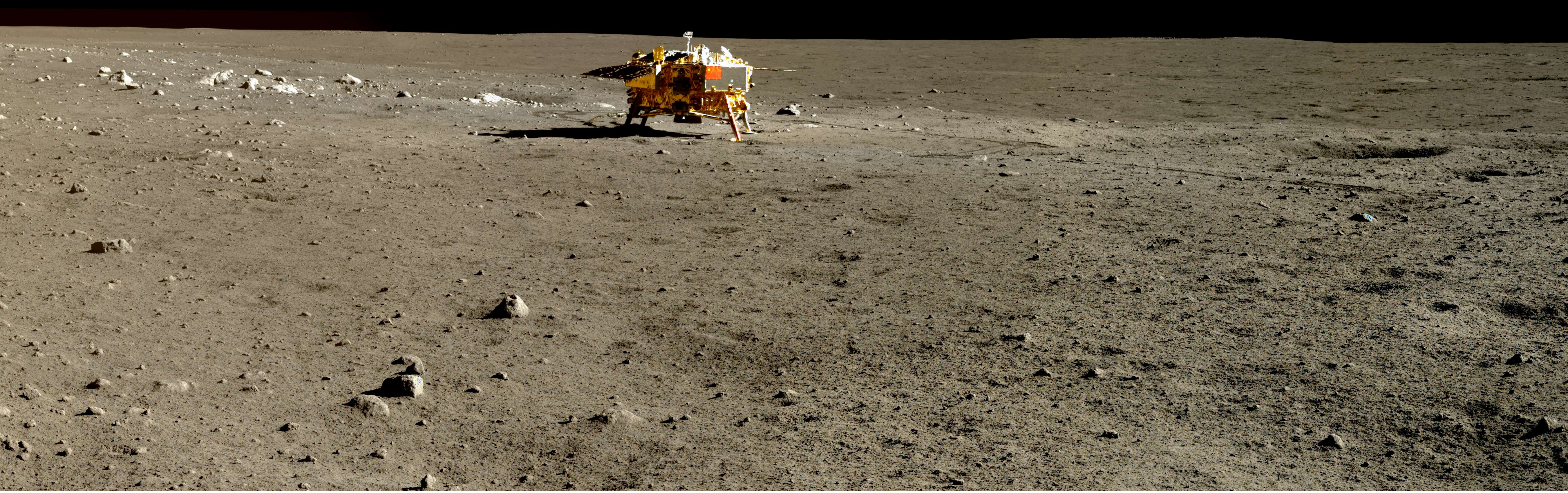
Park+ 2006



NASA Clementine, 1994

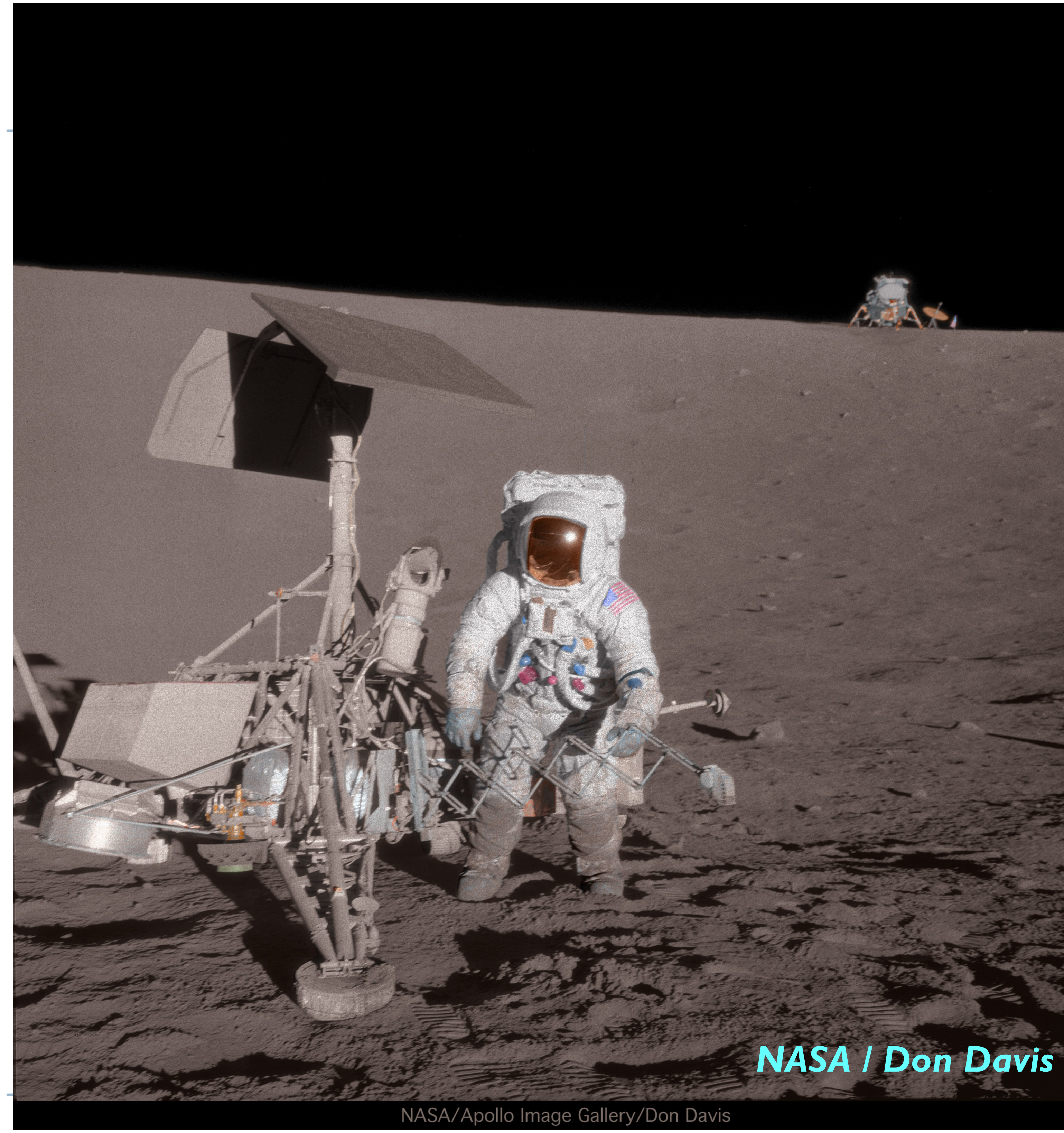
Dust: LUT on board Chang'e-3 Lander

- UV telescope with **years** of operations (2015 - 2018+)
  - For sunrise & sunset, a shutter aperture was closed
- **Dust not a problem**



Gravity

- It's not a bug, it's a **feature**
  - Eg. Surveyor 3, Apollo 12: 180m baseline, stable relative position for the past 50 years
  - Nearly perfect for large optical interferometers
  - Formation flying is unsolved, expensive
- Gravity makes stationkeeping **trivial**



Gravity

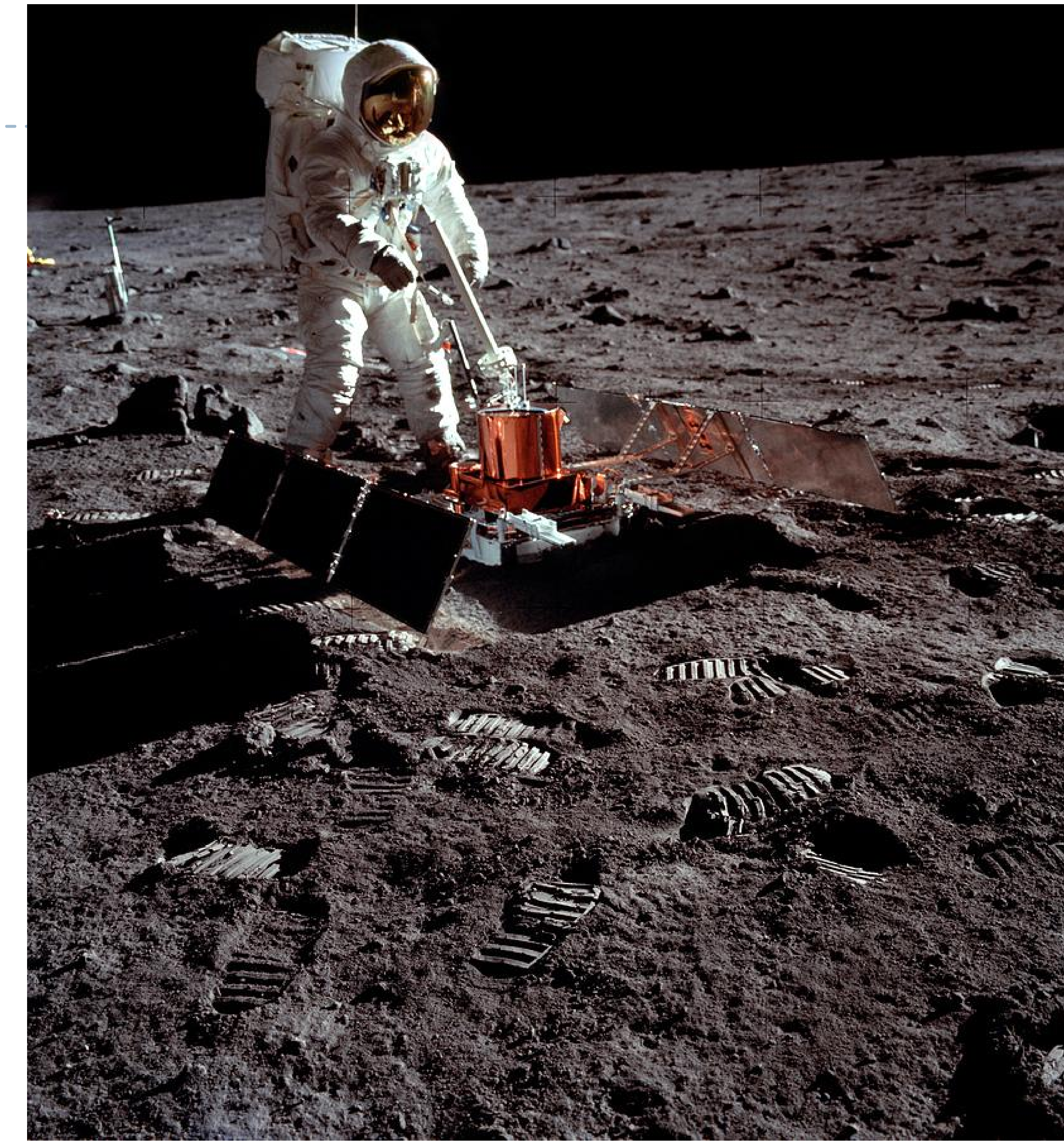
- Greatly simplifies pointing
  - Stable reaction mass
  - 'Solved' for orbital platforms, but expensive and buggy – Eg. HST reaction wheels, Kepler, IUE, etc.
- Also means one has an **absolute reference frame** for astrometry

Long Coherence Times

- No atmosphere
  - No atmospheric coherence time limit
  - Need to be mindful of instrumental coherence time
- A 2" aperture has greater sensitivity than an 8m VLTI aperture after first second of integration; 300+ sec possible
- Free vacuum → clean beam propagation, no vacuum machinery

Stable Surface

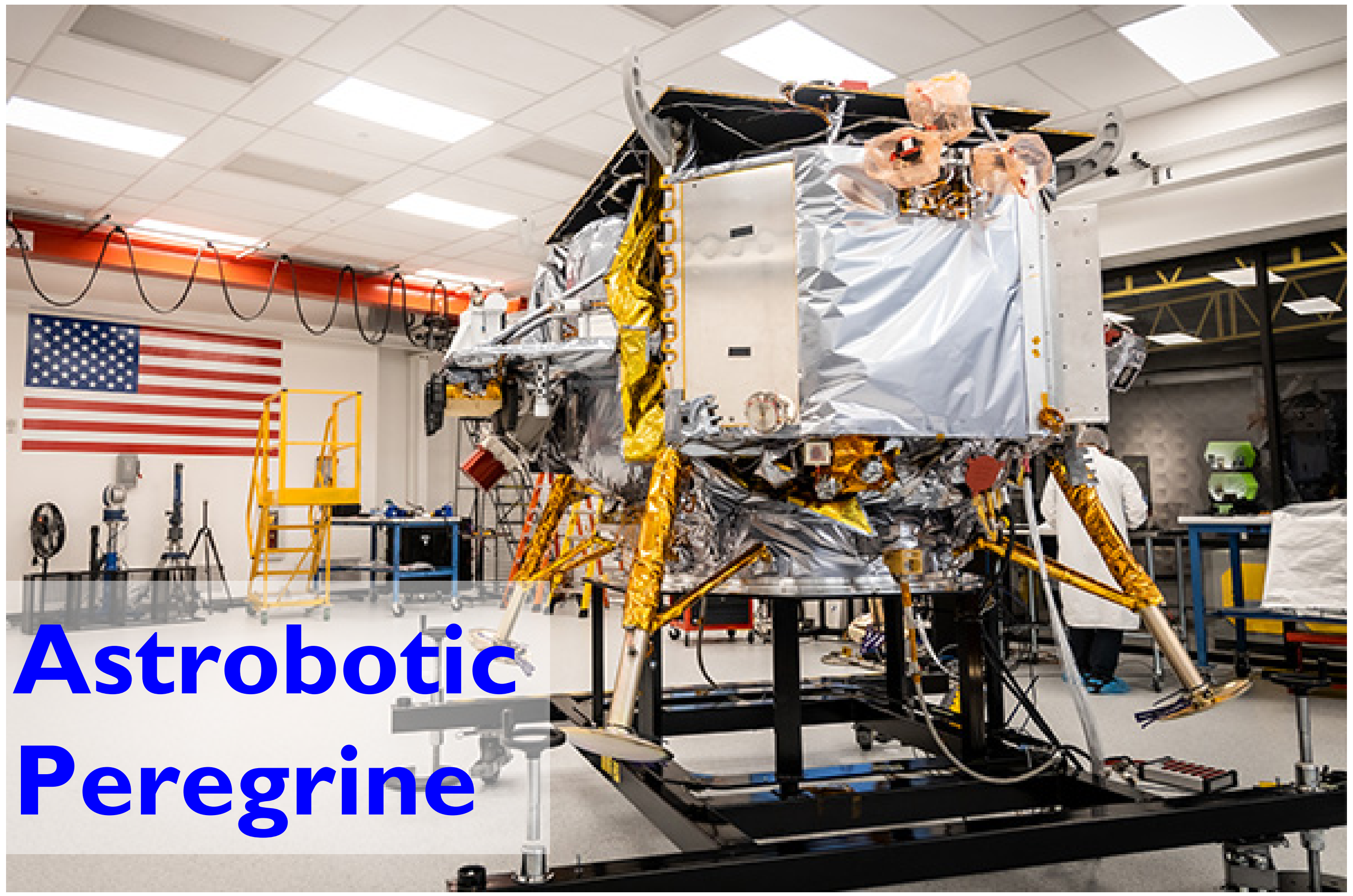
- *Incorrectly assessed* in ESA interferometry report (Bely 1996, "Kilometric Baseline Space Interferometry") as problematic
- Apollo seismometer data indicates <20nm vibrational background amplitude excursions on week+ timescales (Mendell 1998)



Lunar Surface Access

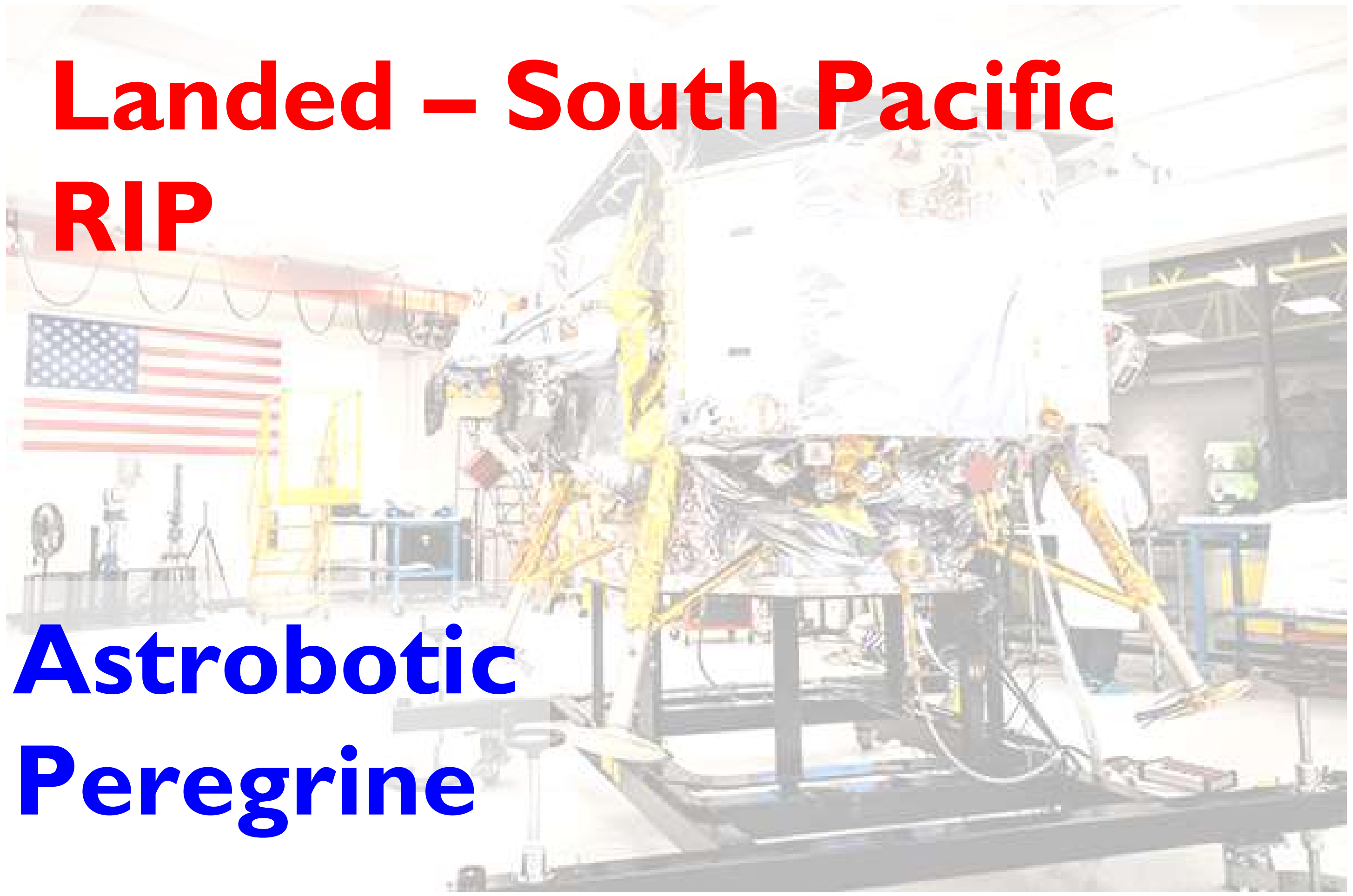
- Need a ride?

NASA Commercial Lunar Payload Services (CLPS) Landers



- Hosted payloads to the lunar surface, with rover
- **Allowable under NASA Astrophysics Pioneers**

NASA Commercial Lunar Payload Services (CLPS) Landers



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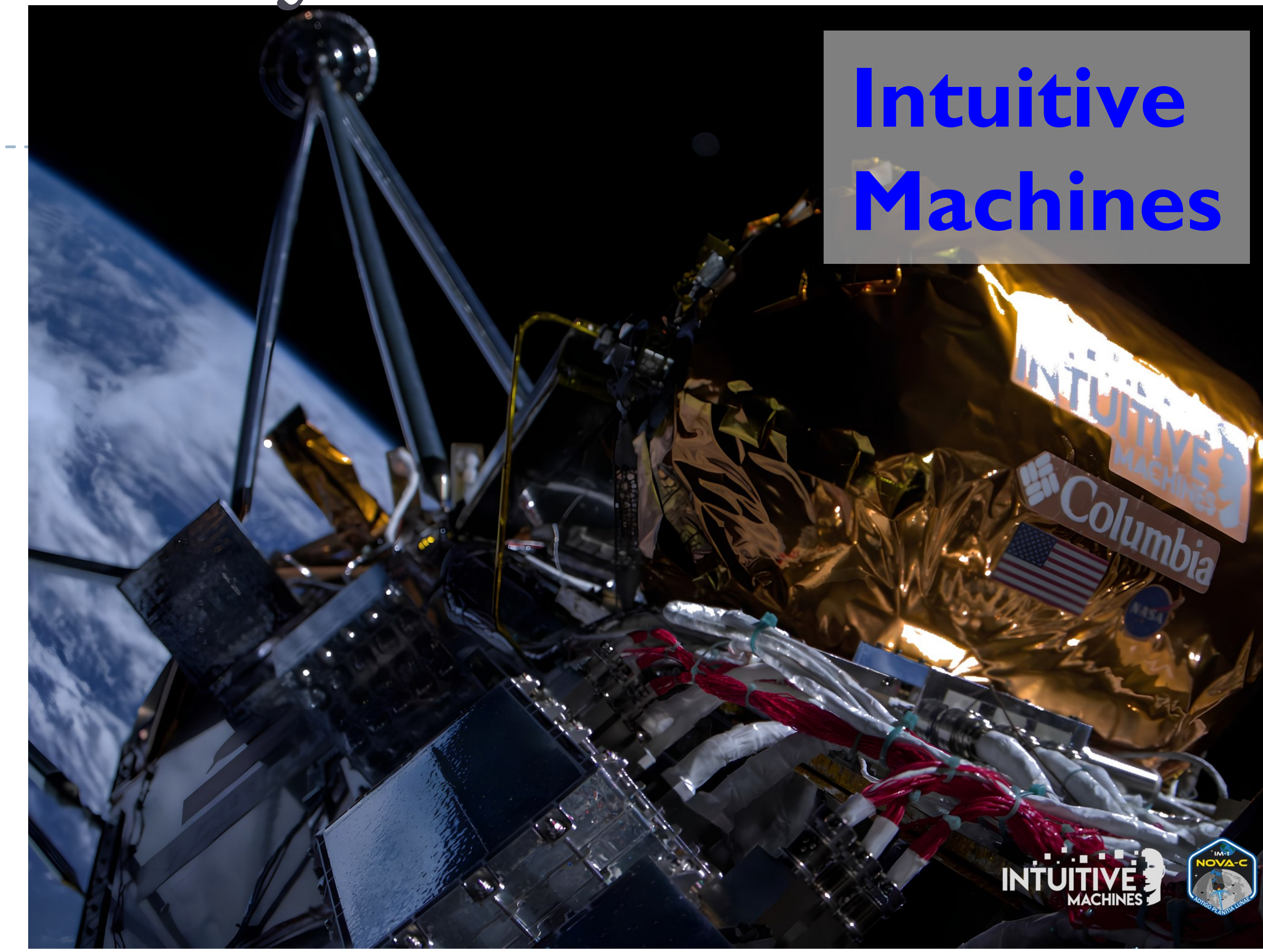
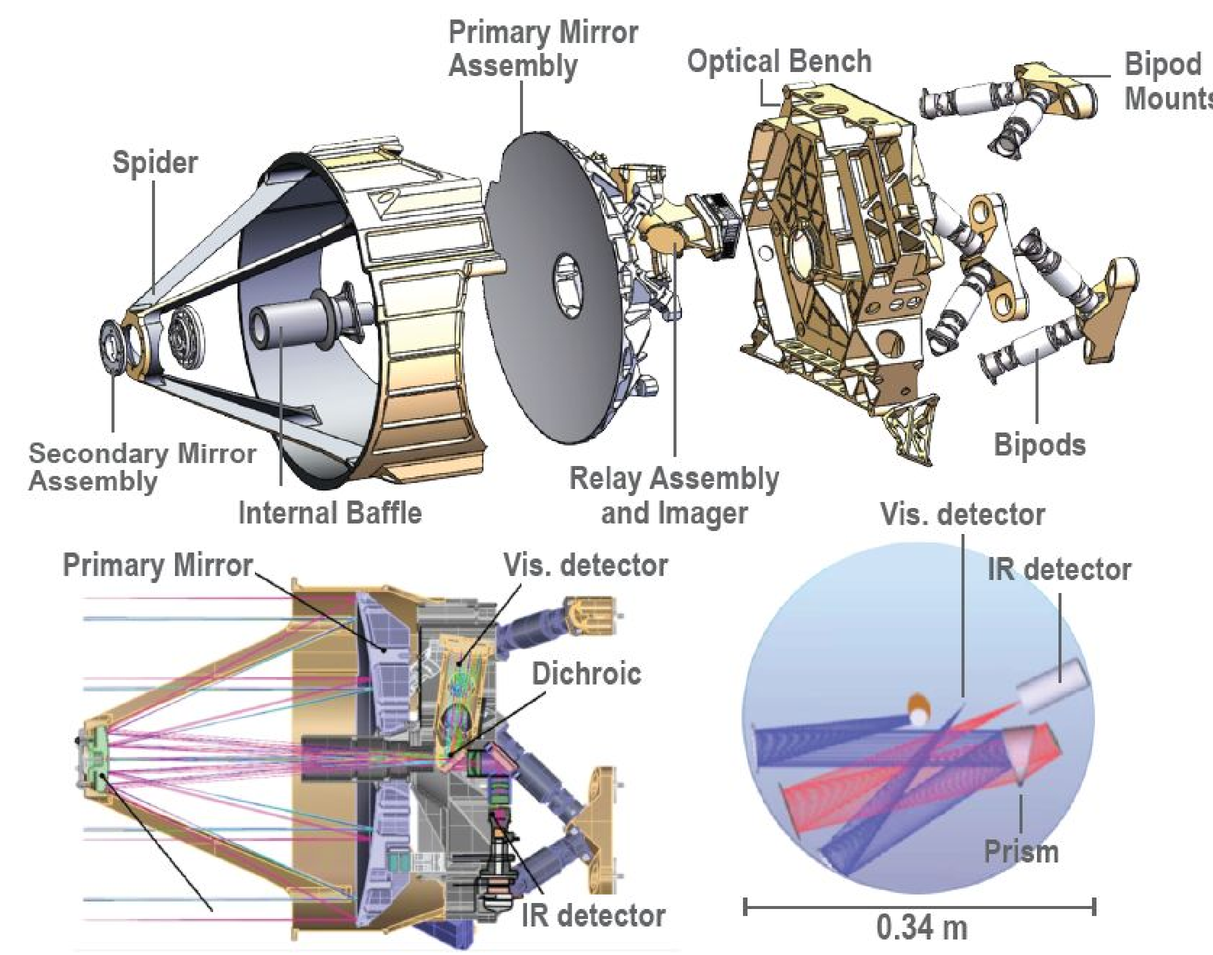


IM-1 Launched Feb 15, Landed Feb 22

2-3 more CLPS flights this year

NASA Pioneers: the Loophole

- NASA Pioneers have typically been cubesats / smallsats
  - Pandora
    - Transit spectroscopy
    - ESPA class smallsat,
      PI Elisa Quintana
  - Landolt
    - Absolute flux calibration
    - 12U cubesat,
      PI Peter Plavchan
- **Pioneers can request a CLPS ride**

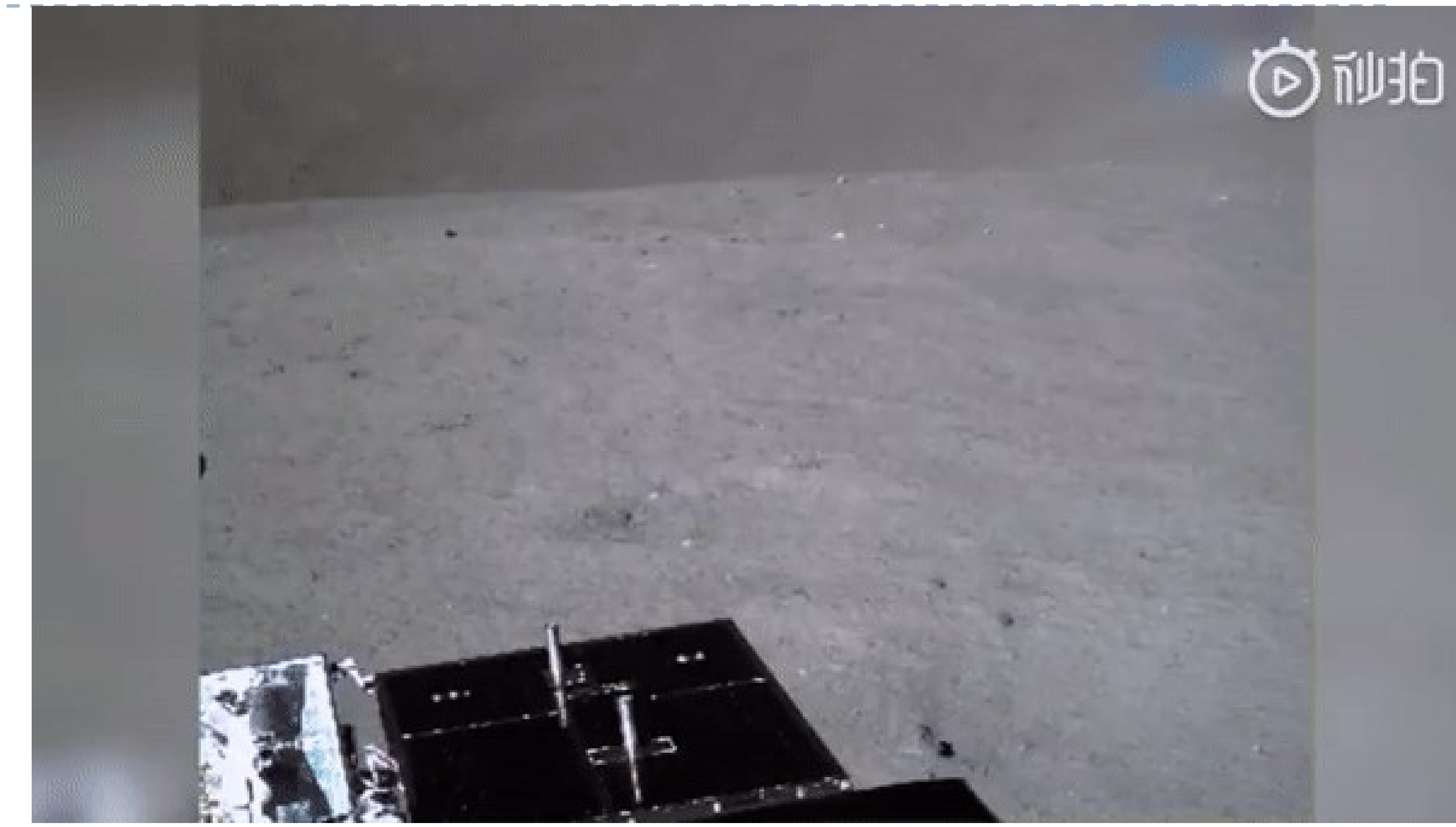


The Pioneers CLPS Box

- $20M cap
- 50 kg, 200 W, 300kbps
- Daytime operations *only*

MoonLITE **Simple** Deployment

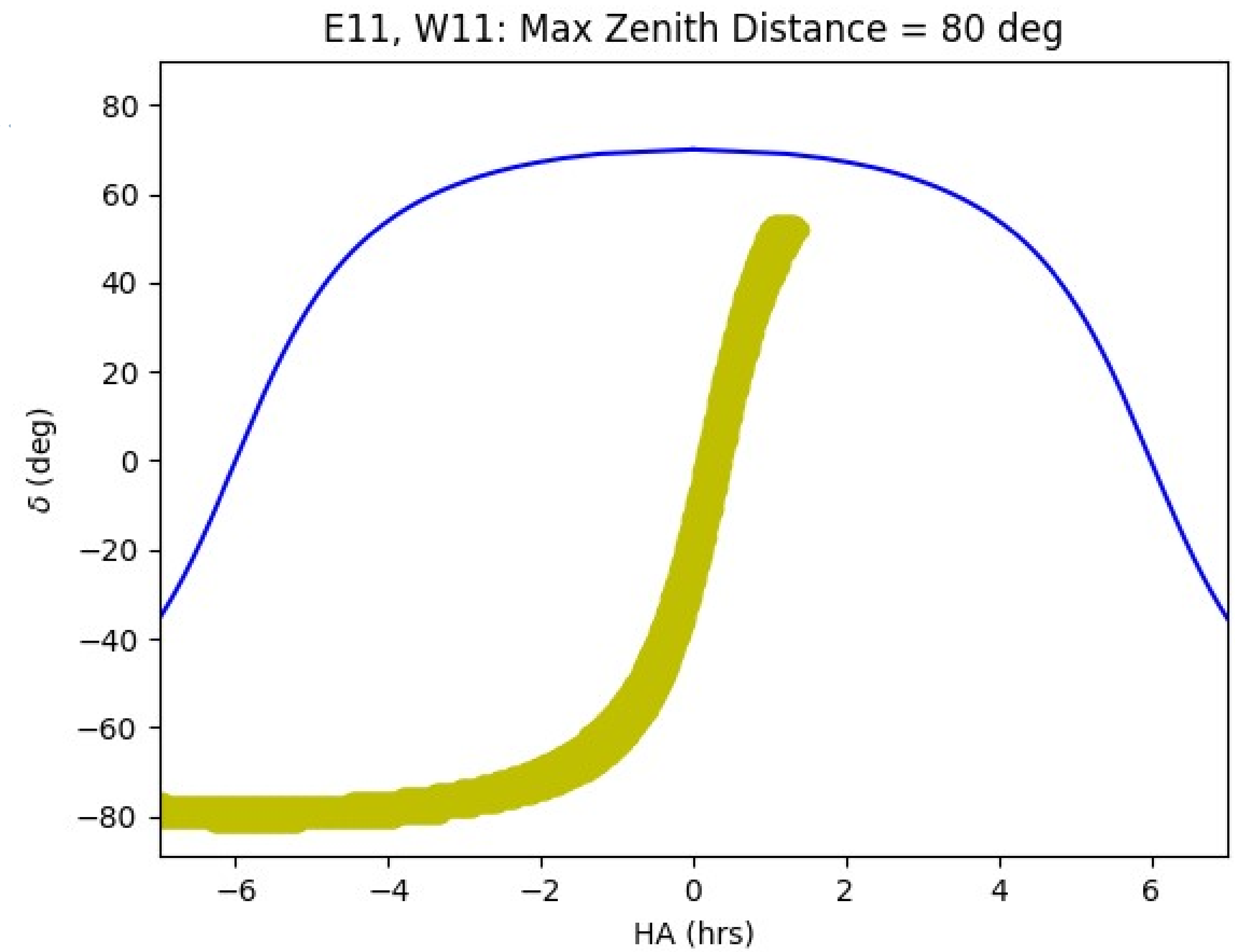
- Instrument compatible with all landing latitude, longitudes
- Outboard station is loaded on rover before launch
- Fiber connection from both outboard / inboard stations
  - No free space scattered light
  - Inboard station is equidistant (optically) from combiner
  - Fiber beam relay eliminates beam steering alignment, enables daytime operations without extensive baffling



Yutu-2 (Chang'e-4) on surface

Sky Coverage

- 100 m baseline, 3 m of delay line range
- East-West orientation to baseline
  - Slight 'kink' to orientation can tune region of extended HA coverage
- All objects pass thru zero OPD at meridian crossing
  - NB. Hours of observing time are 28× slower than hours of RA



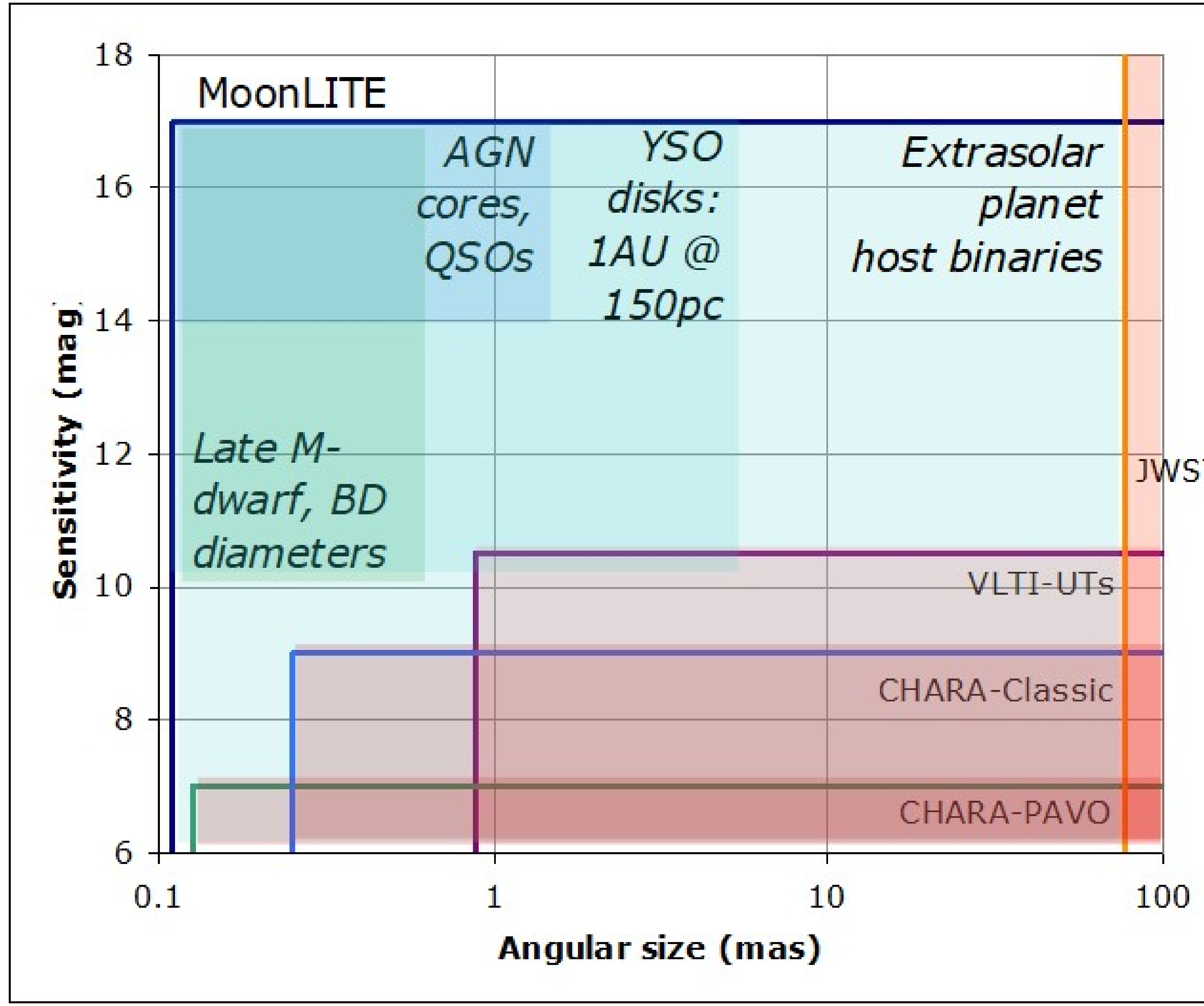
Plot for a notional landing latitude of -20°

(all other latitudes allowable)

Enabled Science

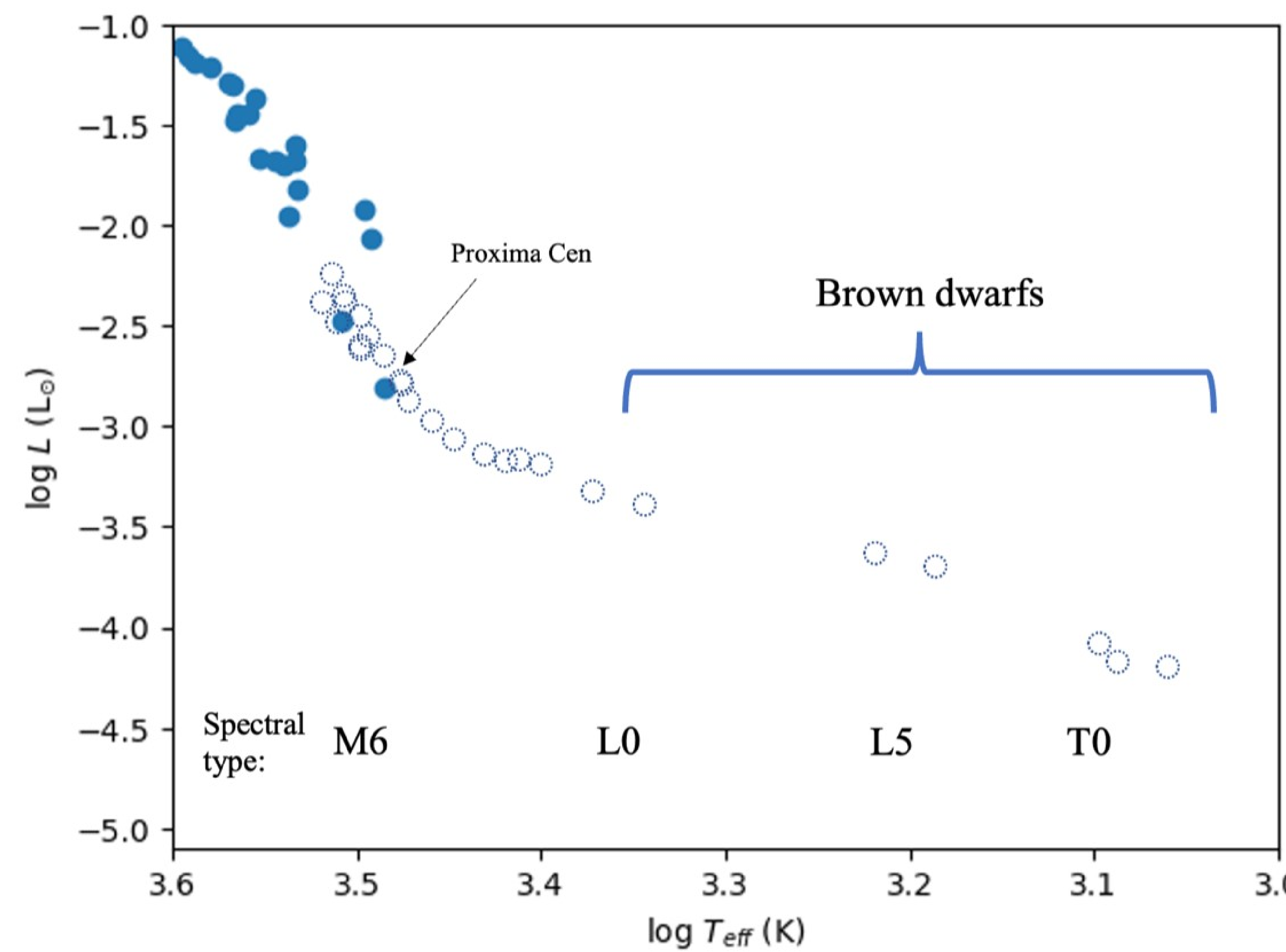
- m_V<17.1, θ > 110μas sizes

- Late M-dwarfs / BDs
- Exoplanet host multiplicity
- YSO diameters / disks
- AGN cores
- Spacetime foam limits



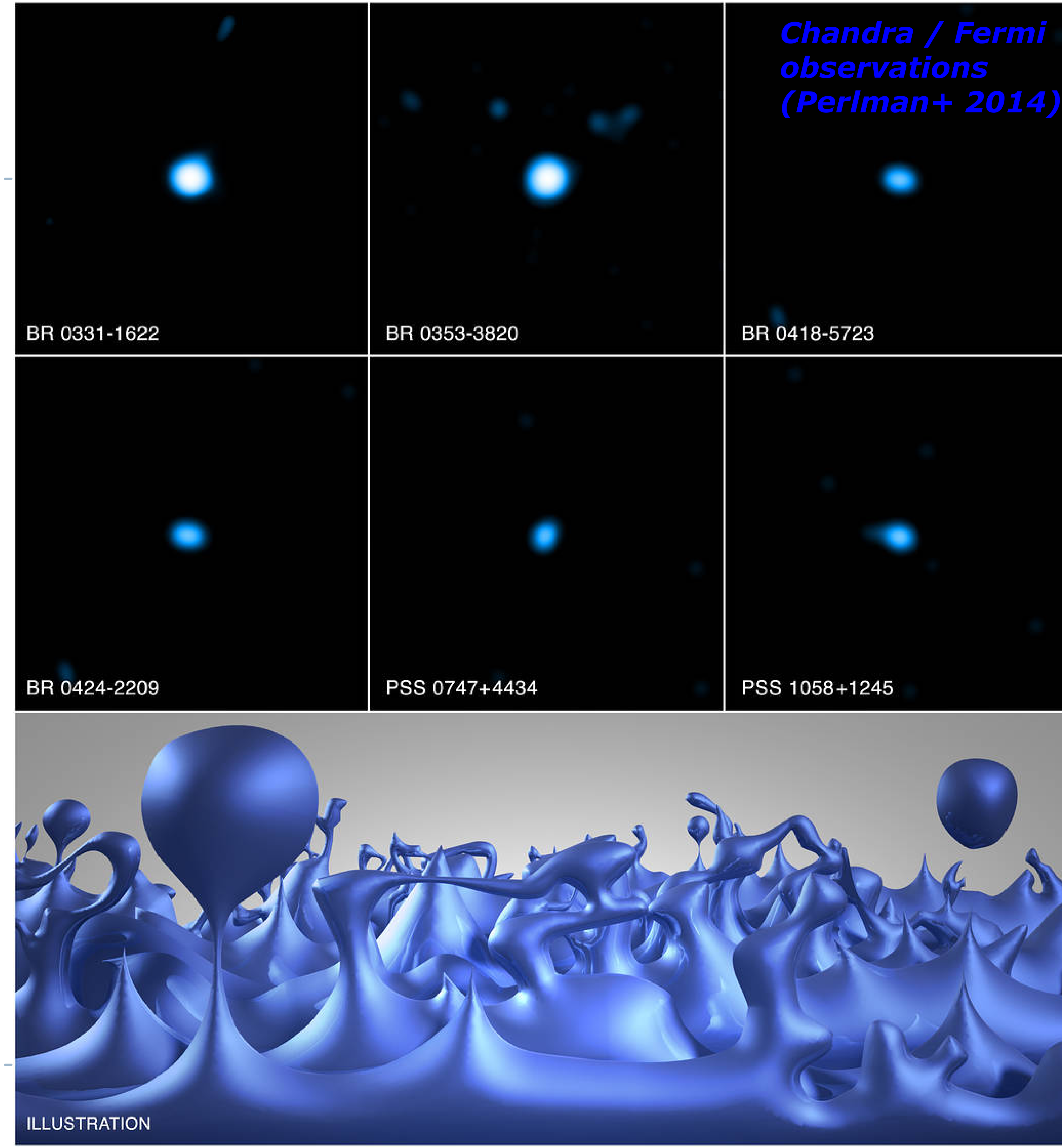
Late M-dwarfs / Brown dwarfs

- Direct diameters for **known** targets
  - Guides modeling of convection, equation of state
- In southern hemisphere
  - 11 M6.5V-M9.5V dwarfs
  - 2 L-dwarfs and 1 T-dwarf
  - additional 13 M5V-M6V dwarfs
  - similar number of N. hemisphere



Spacetime Foam Models

- ‘Granularity’ of spacetime at the Planck scale (10^{-35}m) can lead to decoherence in propagated light (according to *some* theories)
- MoonLITE can place new limits on Planck scale & spacetime foam models
- Observations come as part of AGN program



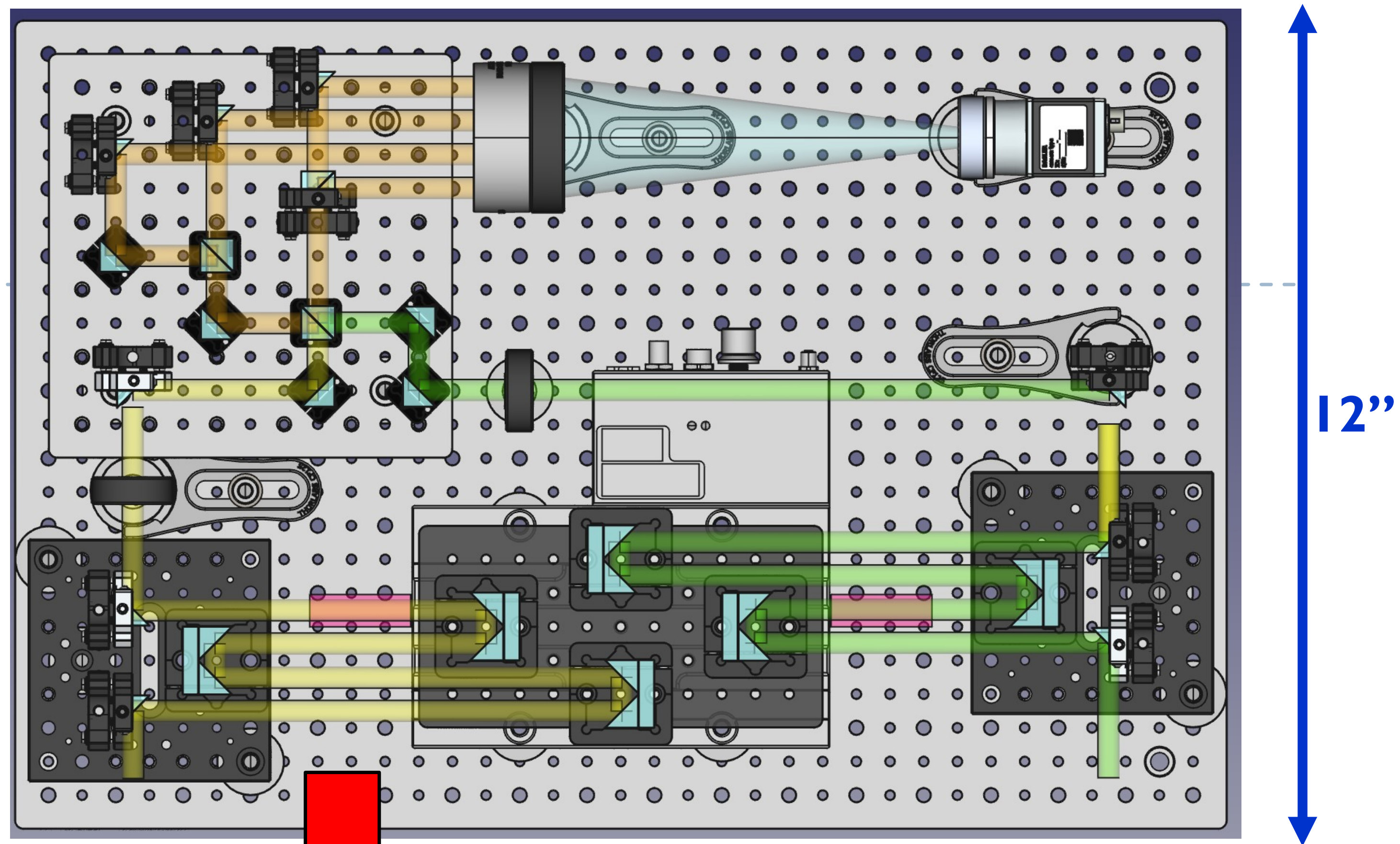
Guest Observer Program

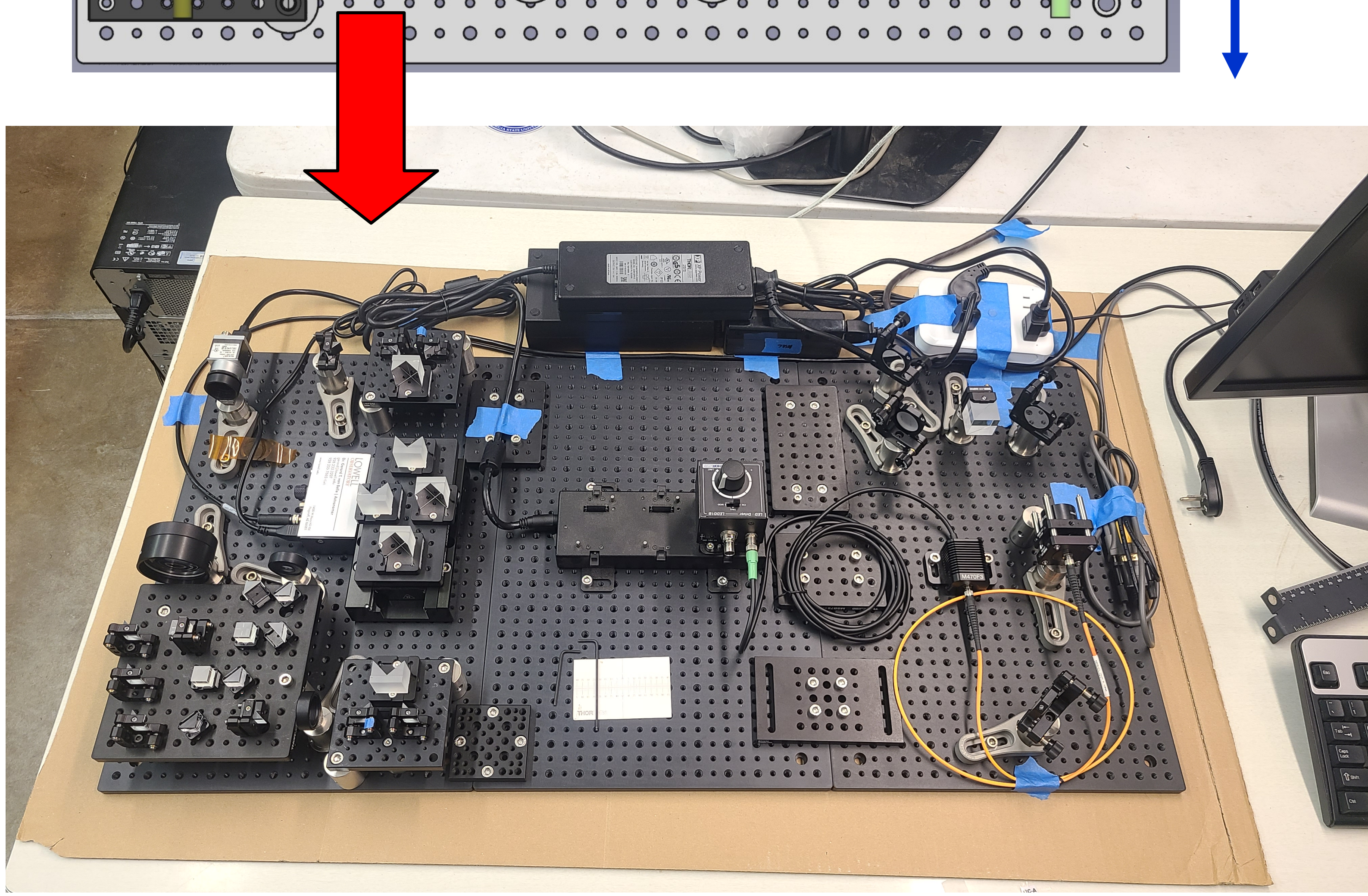
- 20% of available observing time
  - Avenue for further innovation with these unique capabilities
- GO program to be run thru NExScI

Topic	Lunar Day 1 Alloc. [hrs]	Lunar Day 1 Frac. [%]	Lunar Day 2 Alloc. [hrs]	Lunar Day 2 Frac. [%]
Low Mass Stars & BDs	50	19	60	19
Stellar Binarity	50	19	60	19
YSOs	50	19	60	19
AGNs	50	19	60	19
QSOs/Spacefoam	10	4	14	4
Guest Observer	53	20	70	20
Total Science Time	263	...	324	...
Engineering Time (§4.5.3)	37	...	20	...
Lander/Rover Startup (§4.5.3)	54	...	10	...
Total Time	354	...	354	...

Status

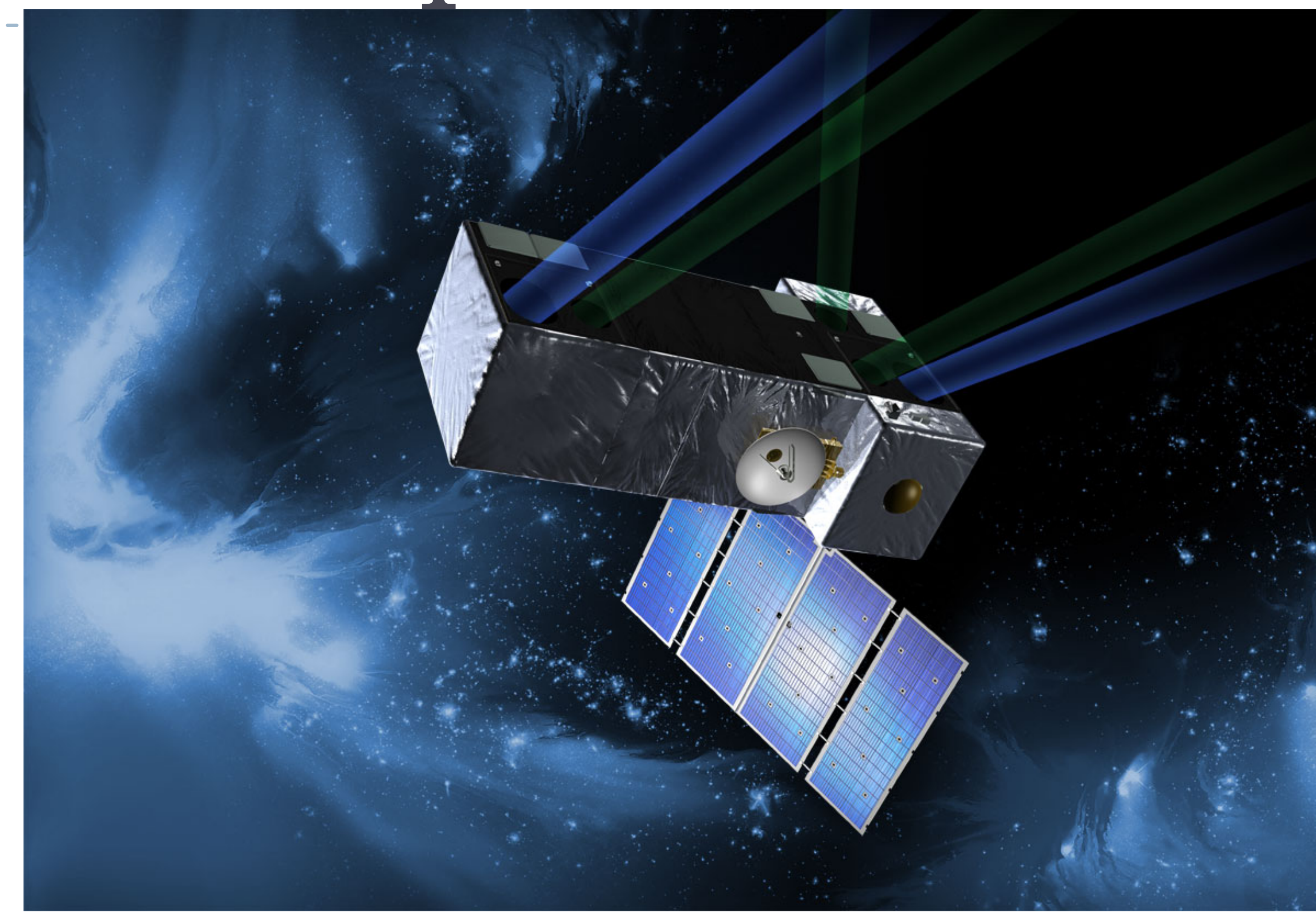
- Proposal was declined
  - **Re-submission encouraged**
- Progress with building opEDU with internal funds
- Aim to test opEDU in lab and then *on-sky* with telescopes available at Lowell
  - Fiber relay tests





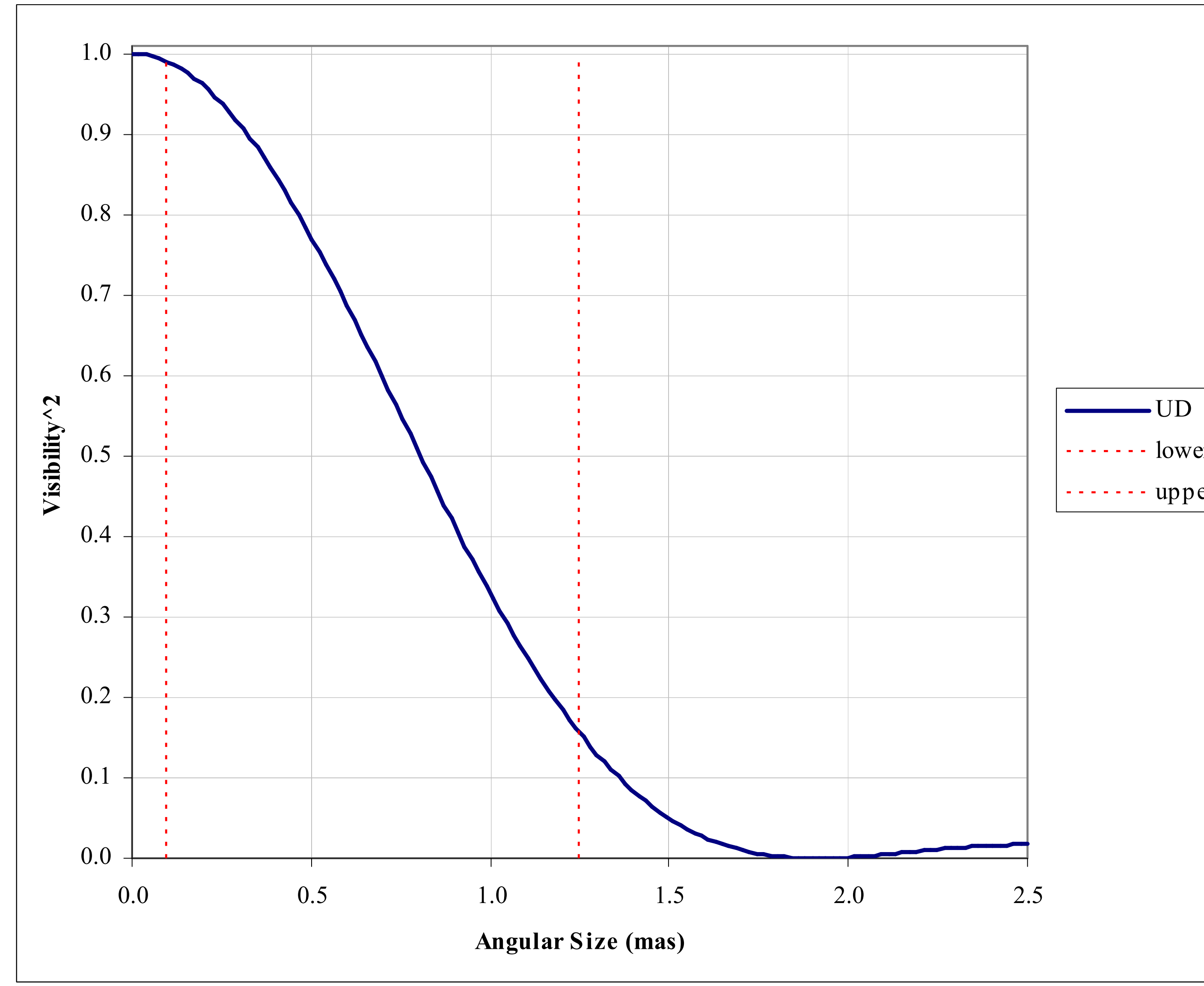
Astrometric Detection of Exoplanets

- 1 M_E @ 1 AU, 1M_S: 0.3 μas
- Space Interferometry Mission (SIM)
  - 6m baseline
- Differential astromeric **single-measurement** precision (not end-of-mission): 0.6 μas for V<7
  - SIM: 6 Earth-like planets
  - **This needs to be done in preparation for HWO, and for more than just six exo-Earths → aim for 0.1μas**

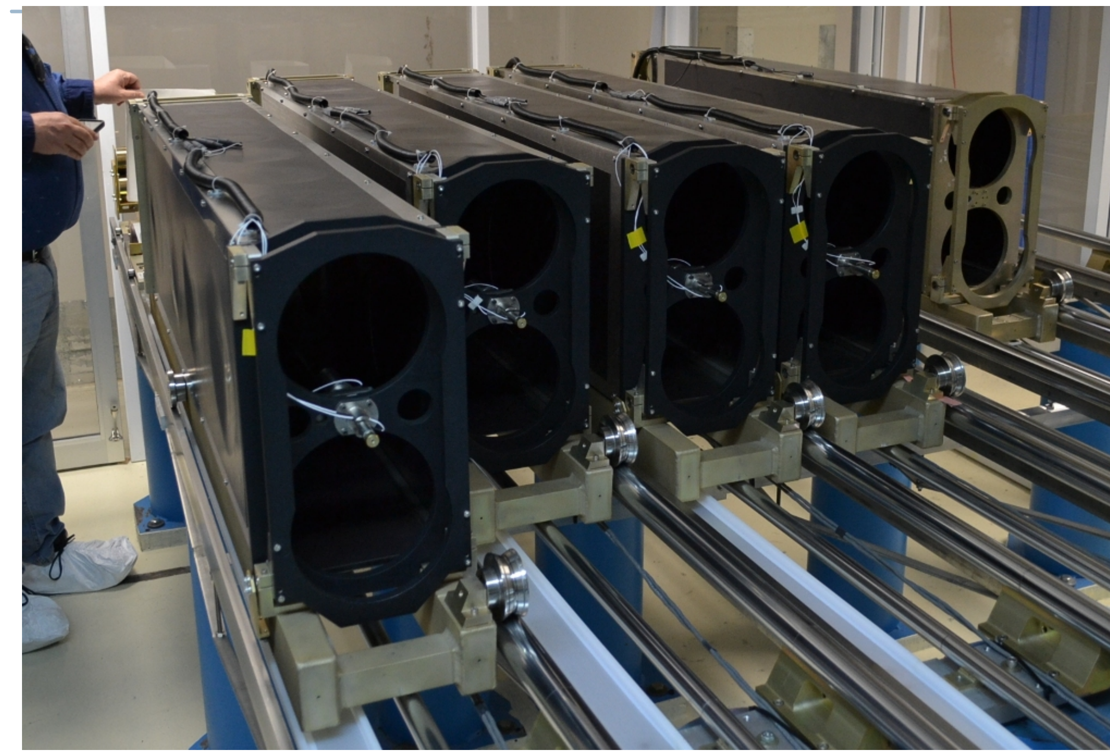


Son of MoonLITE: Lunar Astrometry

- Much longer baseline than SIM
  - Dual-beam like GRAVITY, Keck
- 85% of the ~150 HWO targets are <1.25mas
- Fringe tracking V^2>15%
  - NIR 290m baseline (VIS 80m baseline)
  - Still do science in VIS
- Baseline is 48× greater than SIM-Lite's 6m
  - Tolerances are 48× relaxed
  - Or 8× relaxed for 0.1μas precision



Delay Error Tolerances for Astrometry



- For SIM, delay error of 30pm on 6m baseline → MoonLITE 0.24nm for a 290m baseline
  - Includes tolerance adjustment for 0.6μas to 0.1μas
  - 1.0nm is routinely done with ground-based facilities
- Moon's surface is a 'fixed' local reference
- Main challenge: need lots of range relative to orbital platform

Aperture Size

- 0.20m apertures
- Frame time: 1s for NIR FTK, 10s for VIS SCI channels
  - V < 10, K < 9
- Account for multiply-folded delay line (~30 reflections)
- All other assumptions 'non-heroic'
  - QE, read noise, reflectivity, warm optics, beam train WFE

	A	B	C	D	E
1	**Parameter**	Units	K-band	V-band	Notes
2	wavelength	um	2.22	0.55	K-band (fringe tracking), V-band (science)
3	aperture 1 size	m	0.20	0.20	
4	aperture 1 strehl		0.90	0.85	aggregate WFE
5	num split		2	2	Two-way split for nearest-neighbor FTK
6	aperture 2 size	m	0.20	0.20	as above
7	aperture 2 strehl		0.90	0.85	as above
8	num split 2		2	2	as above
9	integration time	s	1.0	10.0	
10	read noise	e rms	1	1	As appropriate for detector system
11	optics temperature	K	290	290	Ambient temperature
12	object V^2		0.15	0.002	
14	reflections		40	40	30 for folded DL, 10 for BC
15	Reflectivity per mirror		0.985	0.985	
16	optics emissivity		0.45	0.45	After 40 reflections at 0.985
17	throughput to detector		0.49	0.46	40 reflections at 0.985, Strehl injection
18	detector qe		0.7	0.7	
19	etendue	l^2	1	1	
20	Nneighbors		2	2	
21					
22		magnitu	9.07	10.18	
23		SNR-->	10.00	10.00	

Astrometric Baseline Error

- Shao & Colavita 1992
- For bright(-ish) fiducial star references, V<10 gives 100% sky coverage at 0.12° star-to-star
  - ΔDL ~ 430mm at ZA~45°
- For 290m, baseline endpoint error requirement of < ~67nm
  - Well above the ambient background amplitude of 22nm

Potential of long-baseline infrared interferometry for narrow-angle astrometry

M. Shao and M.M. Colavita

Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasade

Received

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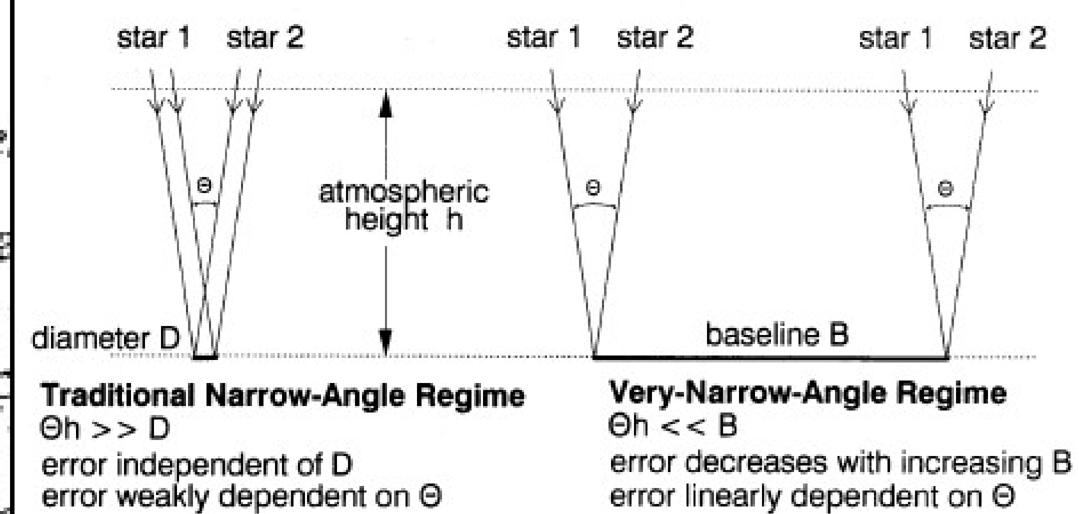


Fig. 1. Schematic of the atmospheric paths for narrow-angle astrometry with short and long baselines

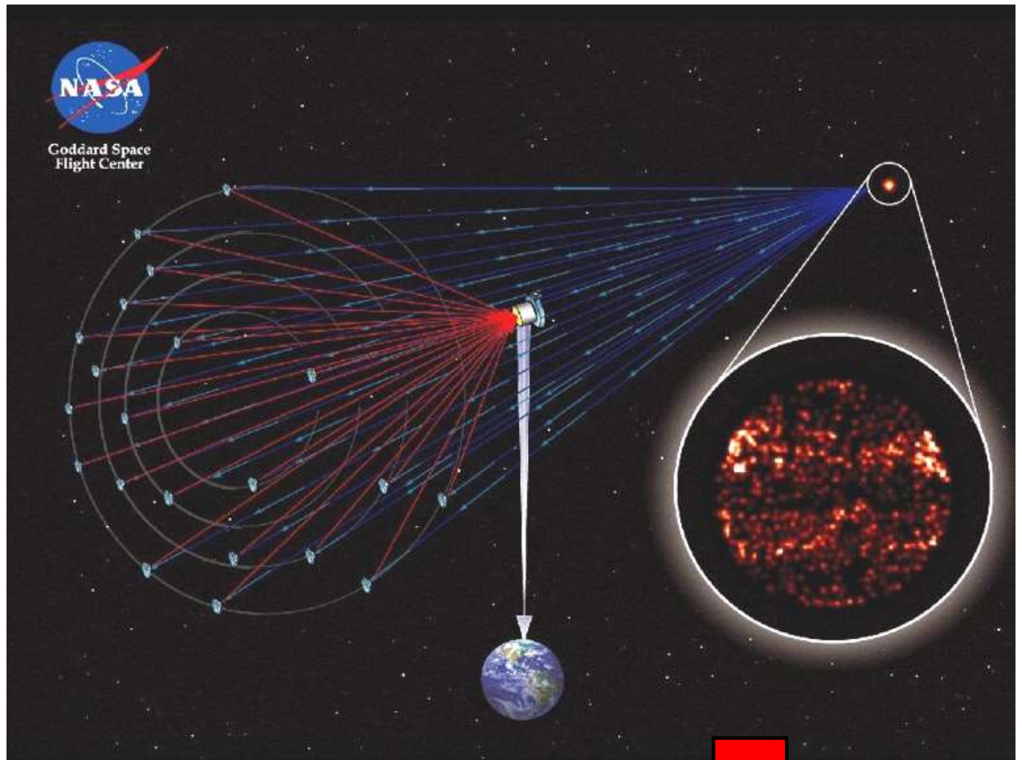
3.2. Syste

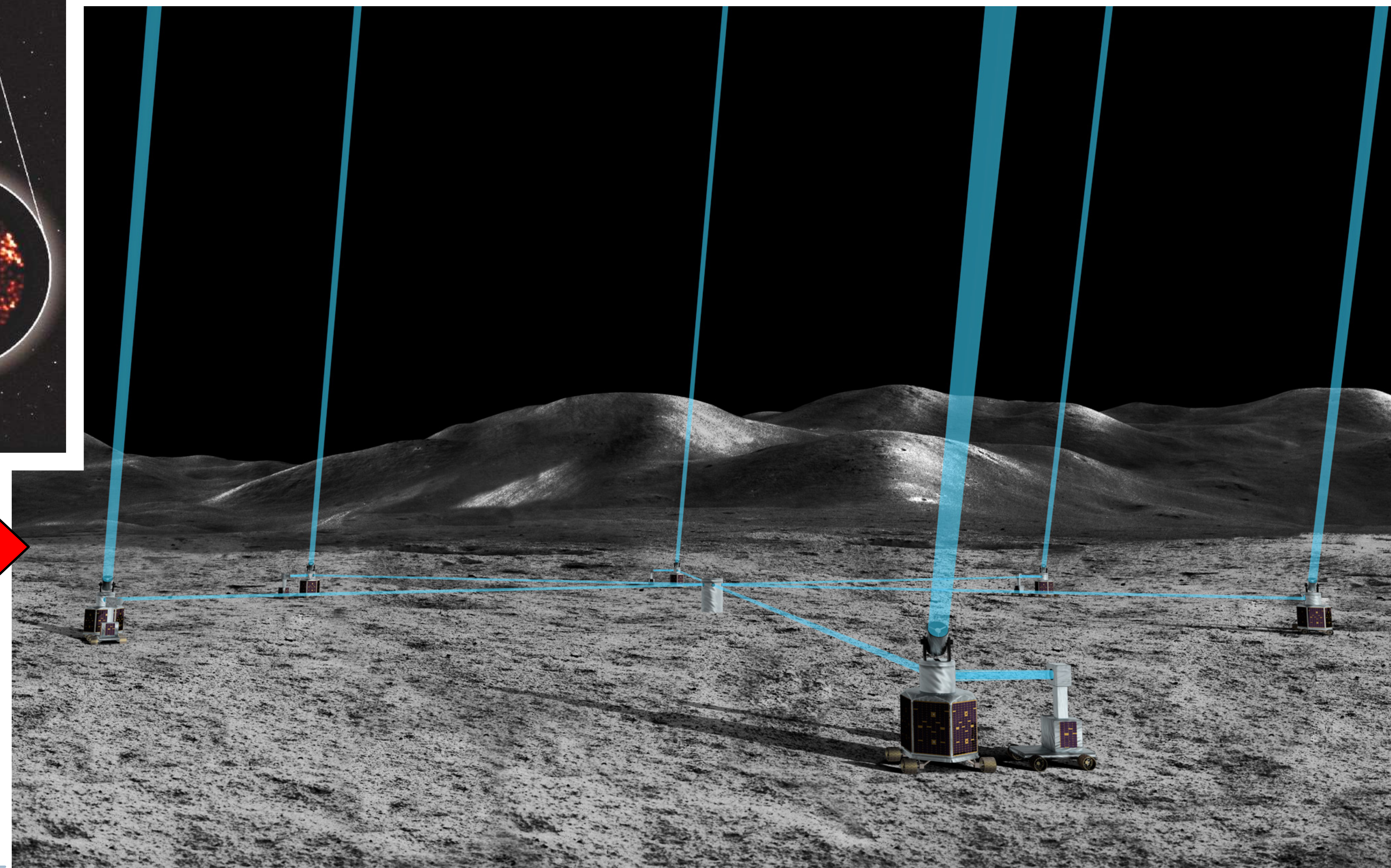
An accura … n inter-
ferometer … neasure-
ment of op … level of
accuracy, … xample,
precision c … ometers
(Shao et al … m error.
In fact, b … ometric
measurement, many error sources drop out. As an example, knowledge of the instrument baseline need not be very precise. The allowable baseline error ΔB is approximately $\Delta B/B = \Delta\theta/\theta$, where $\Delta\theta$ is the desired astrometric accuracy and θ is the star separation. For $B = 200$ m, $\Delta\theta = 10$ μas, and $\theta = 15''$, the baseline must be known to ~100 μm – this is approximately 100 times looser than the achieved baseline stability for wide-angle astrometry with the Mark III optical interferometer (Shao et al. 1990).

Compelling Motivation

- Still simple with a small number of small apertures
  - Slightly more apertures than MoonLITE (3 or 4), slightly larger (200mm)
  - Challenge: much more delay range needed
- Can do SIM exoplanet science, *better than SIM*
  - Increased baseline greatly relaxes engineering tolerances
  - Possible within the scope of a MIDEX?
- HWO (& LIFE) precursor science
  - Planet masses are essential for atmospheric retrieval

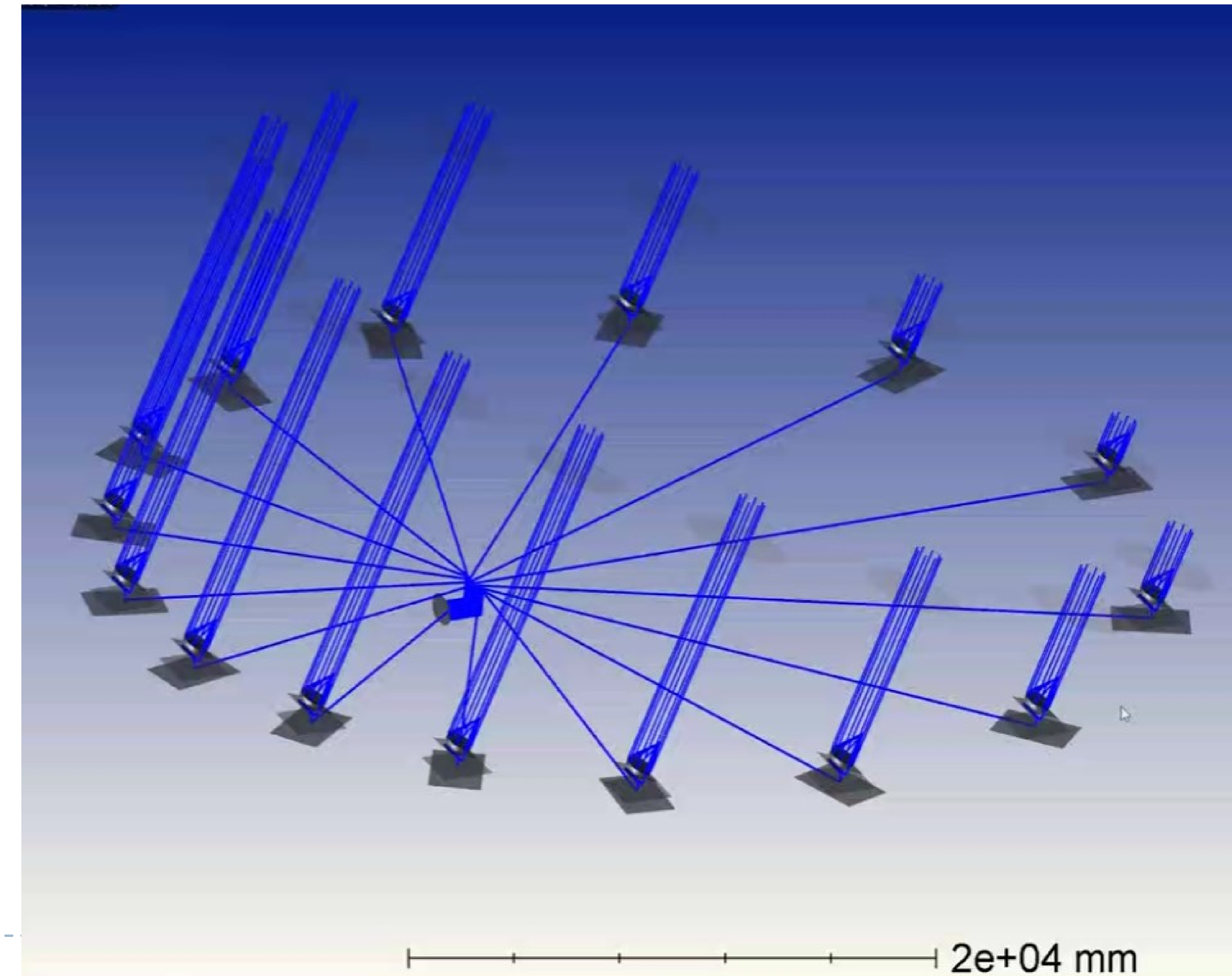
Artemis-enabled Stellar Imager NIAC Study





AeSI: Dense Imaging array in the UV

- Operating as short as Lyman-α (1216Å)
  - Coatings are a challenge
- 15 to 30 apertures, each ~1 meter
- Visible FTK



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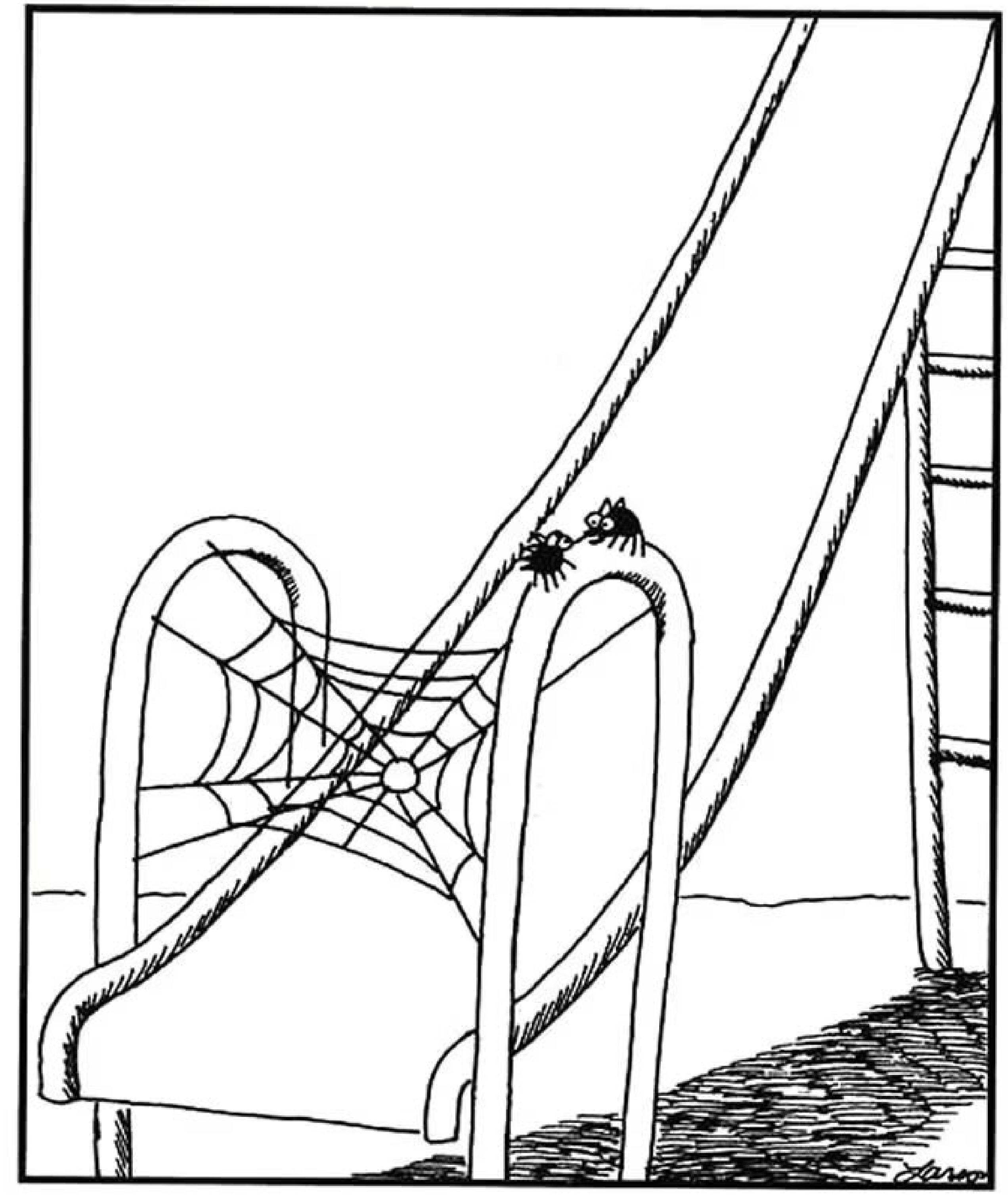
- Capable of V=17, for objects 0.1-1.6mas in size, measure 0.1-5.0% sizes
- **First of a family of lunar observatories**

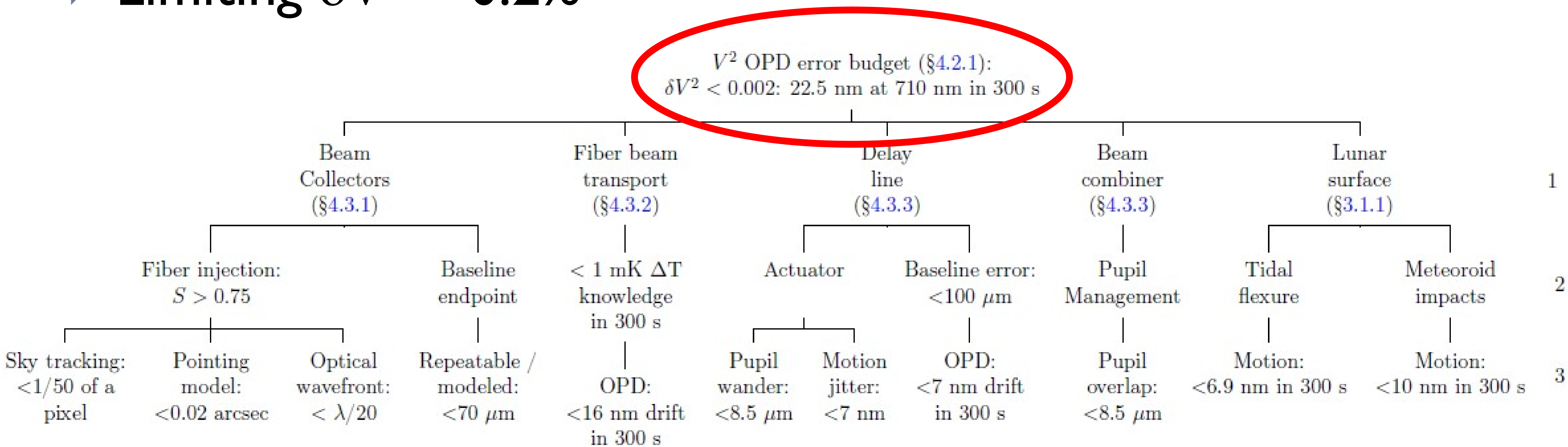


“If we pull this off, we’ll eat like kings.”

backup slides

OPD Error Budget

- Limiting $\delta V^2 = 0.2\%$



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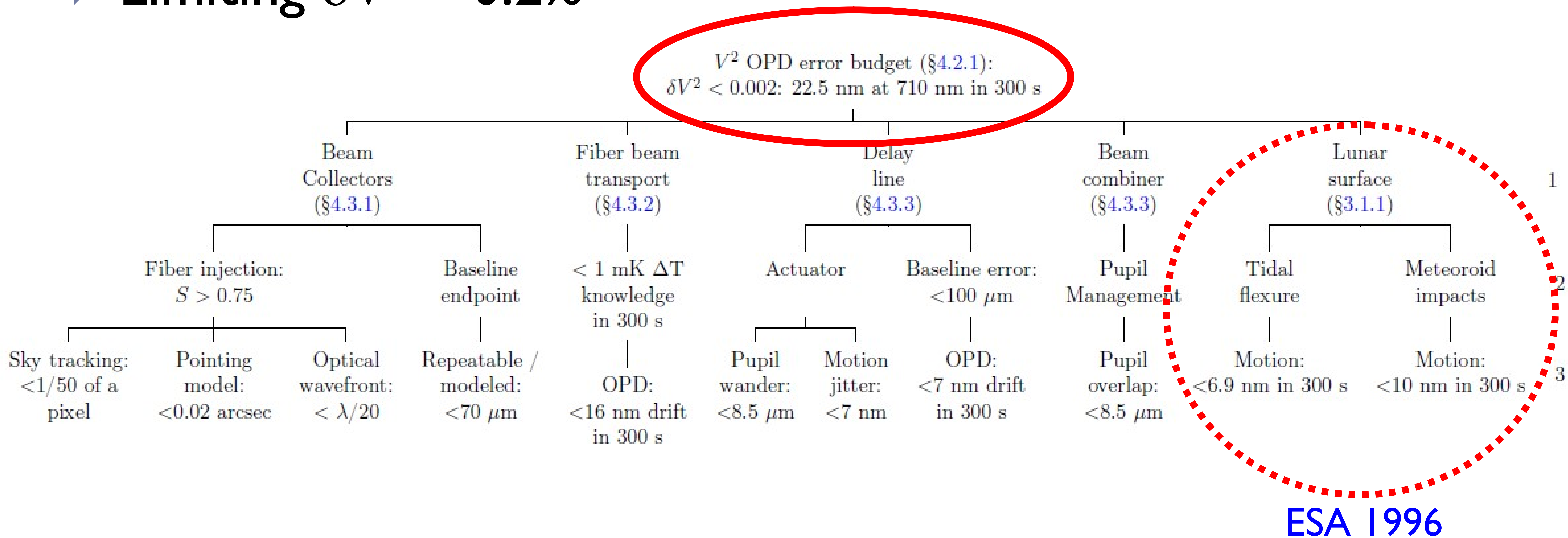

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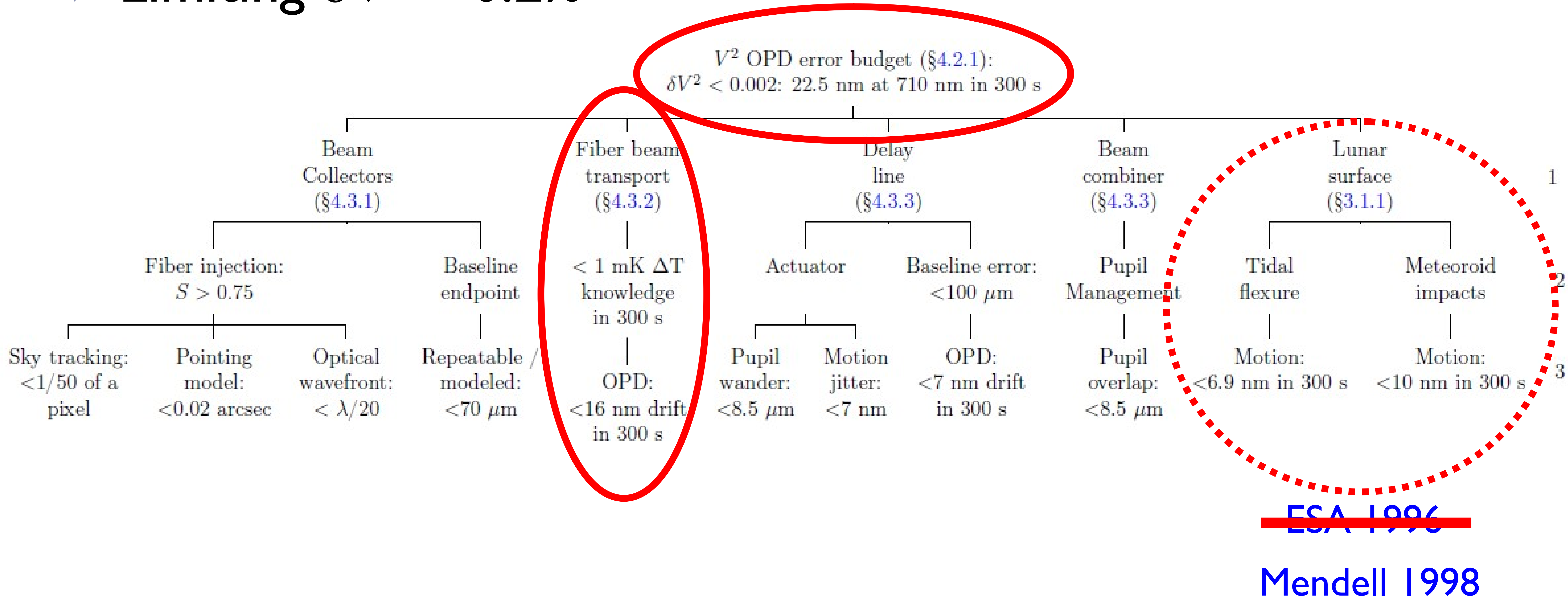
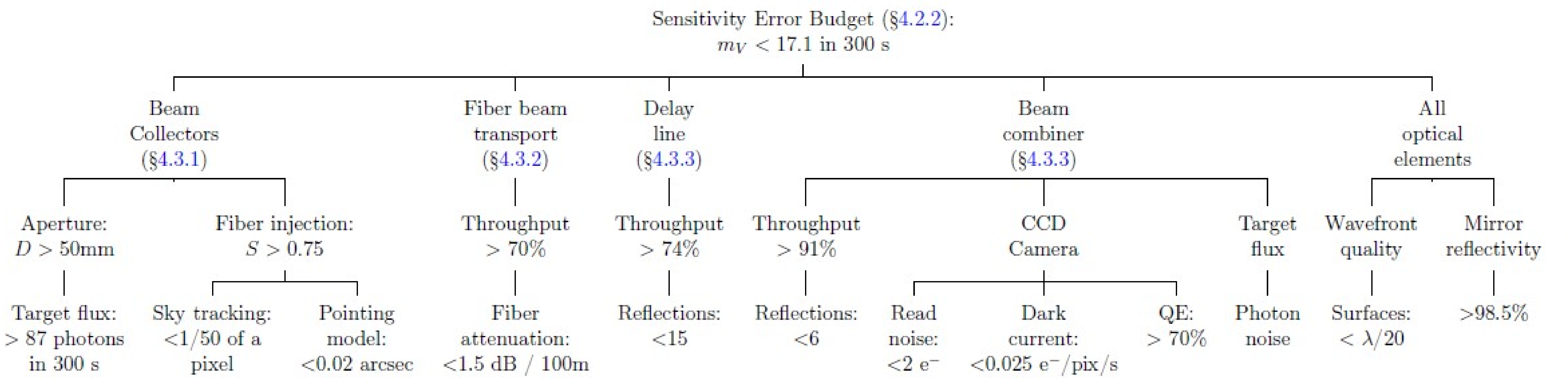
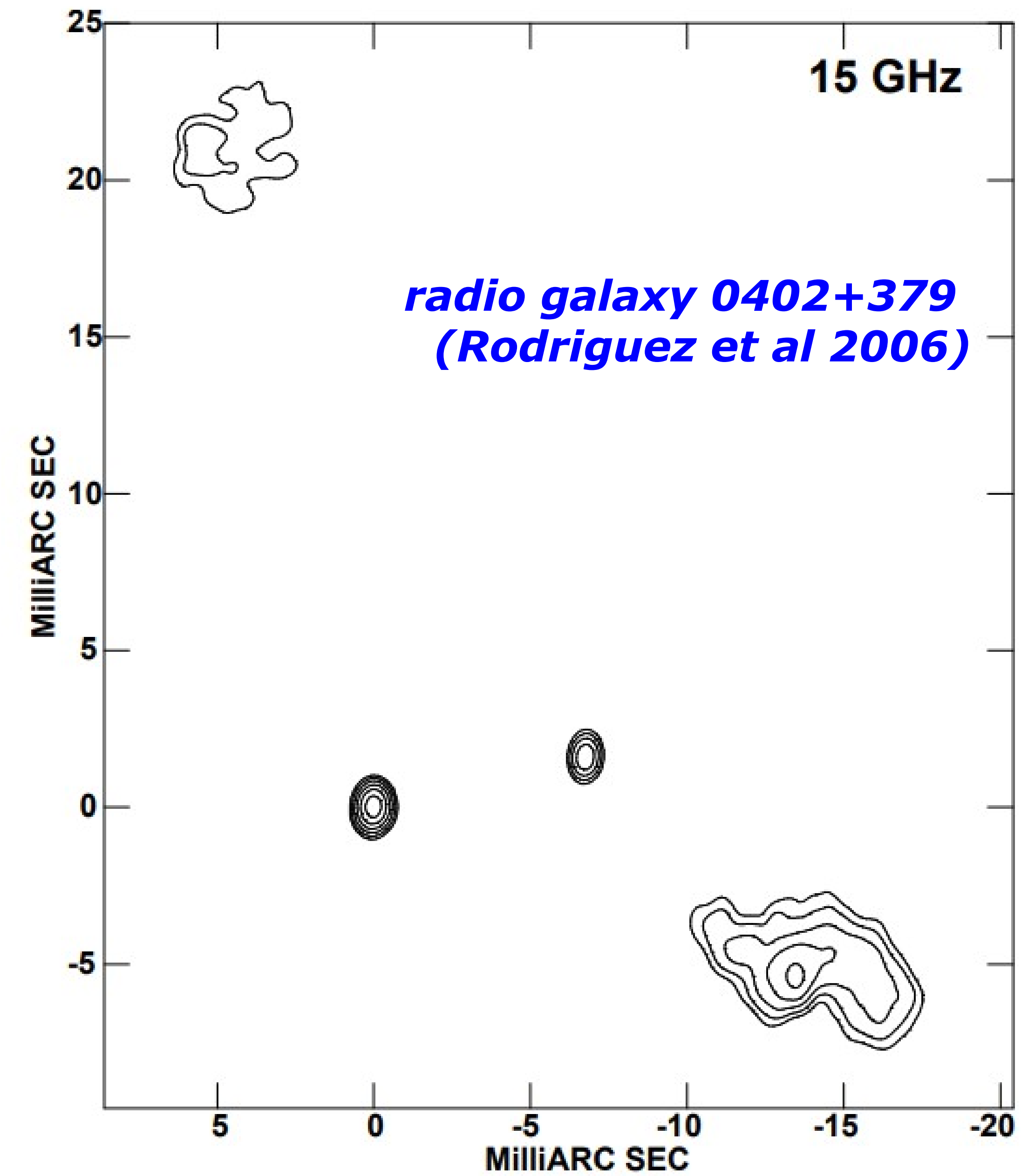


Sensitivity Error Budget



Active Galactic Nuclei

- Investigate AGN at scales in the visible, comparable to ALMA and radio
- Investigate jet structures and/or binarity (right)
- Can approach the "Final parsec problem" in the visible
- 12+ objects for detailed morphology, 12+ for core object size & binarity



Lunar Libration

- ‘Nodding’ of the face of the Moon as it orbits Earth
- Comes out of the engineering data at the ~1 mas level
- Can constrain the size, density, and state of the lunar core and lower mantle

Remarkable Opportunity

- MoonLITE delivers elements of a SMEX- and MIDEX-level science case in an Astrophysics Pioneers package
- Leverages existing technology of ground-based interferometry, and investments in space-based prototypes
  - Demonstrates system-level flight ops of optical interferometry
- Builds on CLPS opportunity
  - **A pathfinder for a family of facilities on the moon**