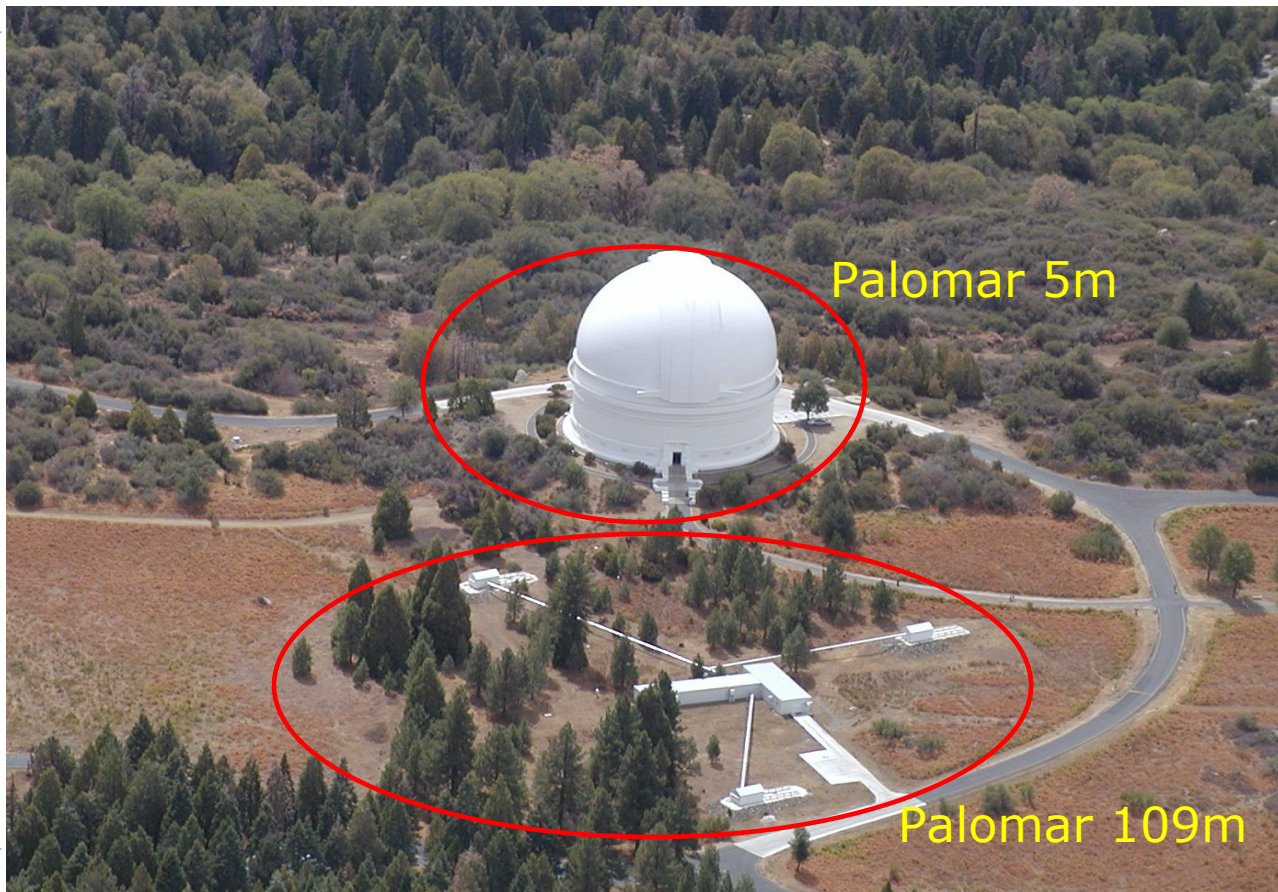




Science Cases for Optical Interferometry from the Moon

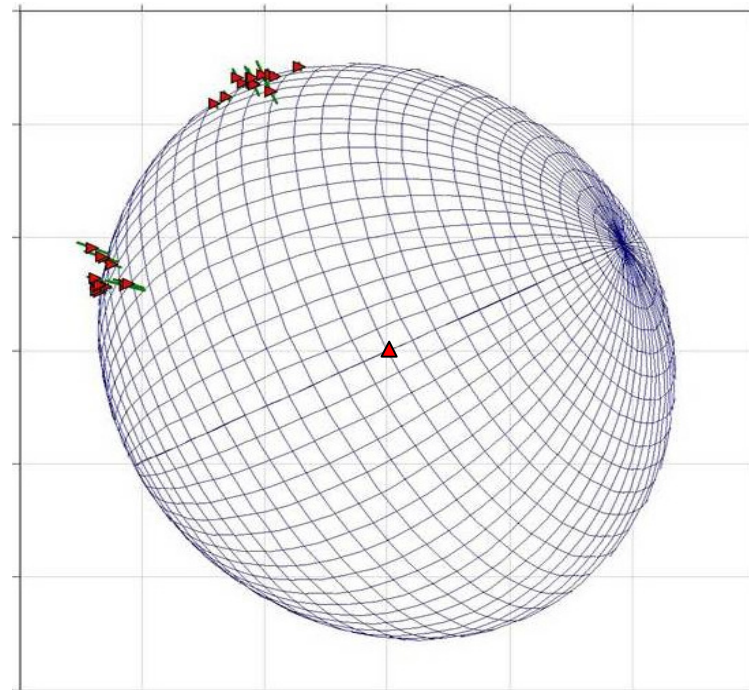
Gerard van Belle (Lowell Observatory)

Optical Interferometry 'Early Days'



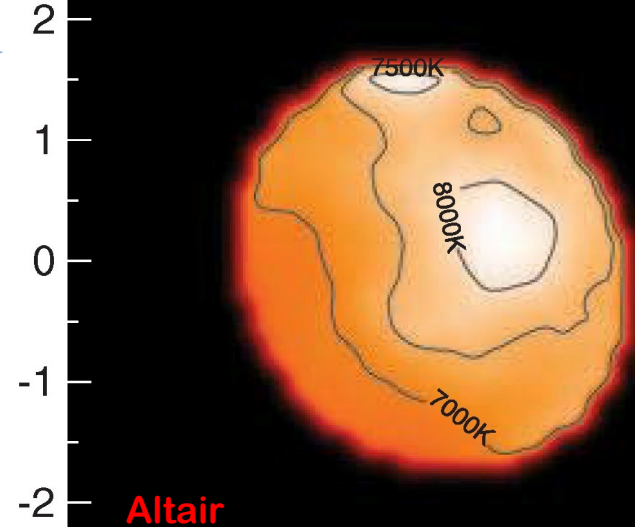
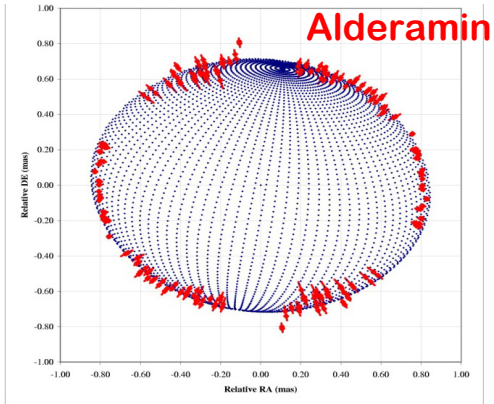
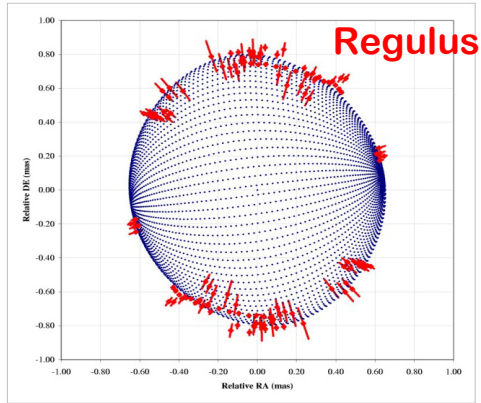
Direct Determination of Altair's Oblateness

- ▶ A surprising observation: Altair was not spherical
- ▶ Unique solution for $v \sin i = 210 \pm 12$ km/s
 - ▶ Independent of, and agrees with, $v \sin i$ from spectra
- ▶ Rapid rotator cottage industry spurred on by discovery



*Rotational Oblateness of Altair (HD 187642)
Measured with Palomar Testbed Interferometer
(van Belle et al 2001)*

Stellar Shapes → Stellar Surface Imaging



30-03-2021

29-05-2021

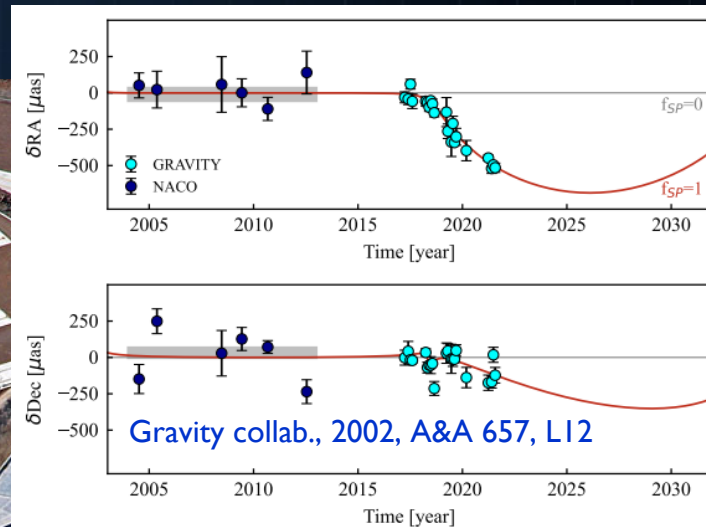
24-06-2021

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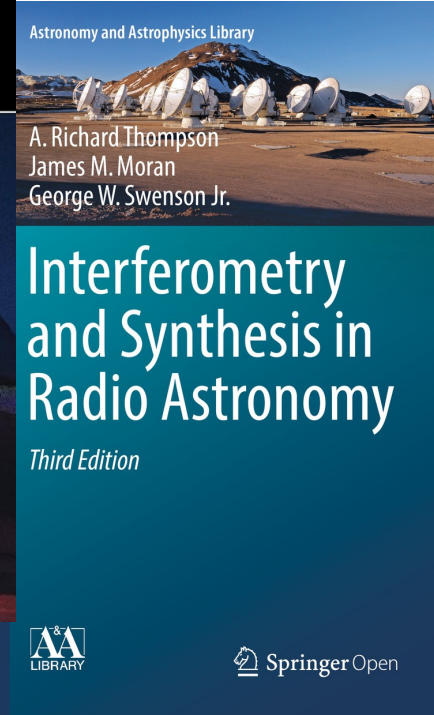
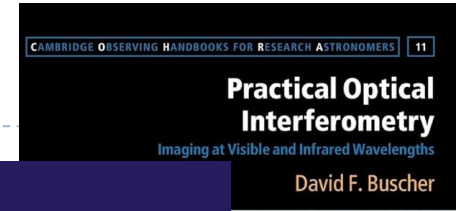
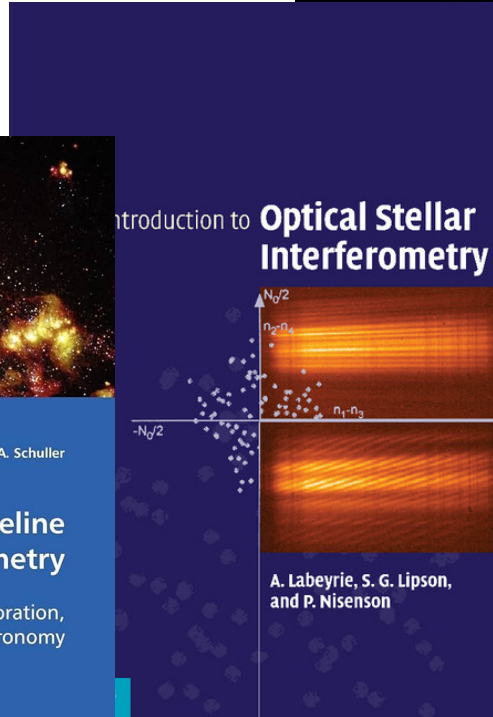
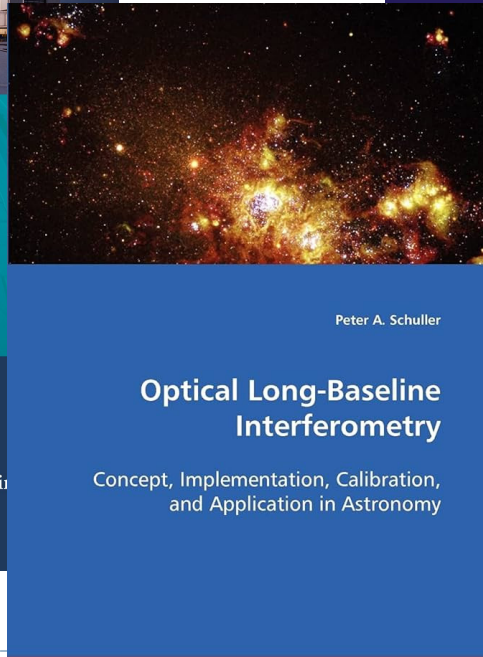
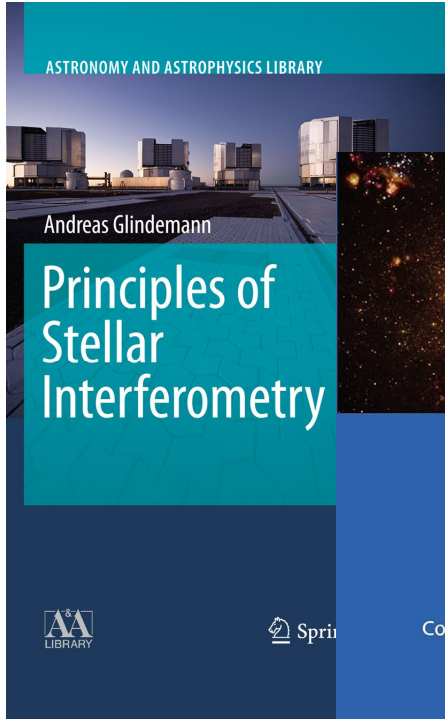
Optical Interferometry at the Limit



Neptune's orbit



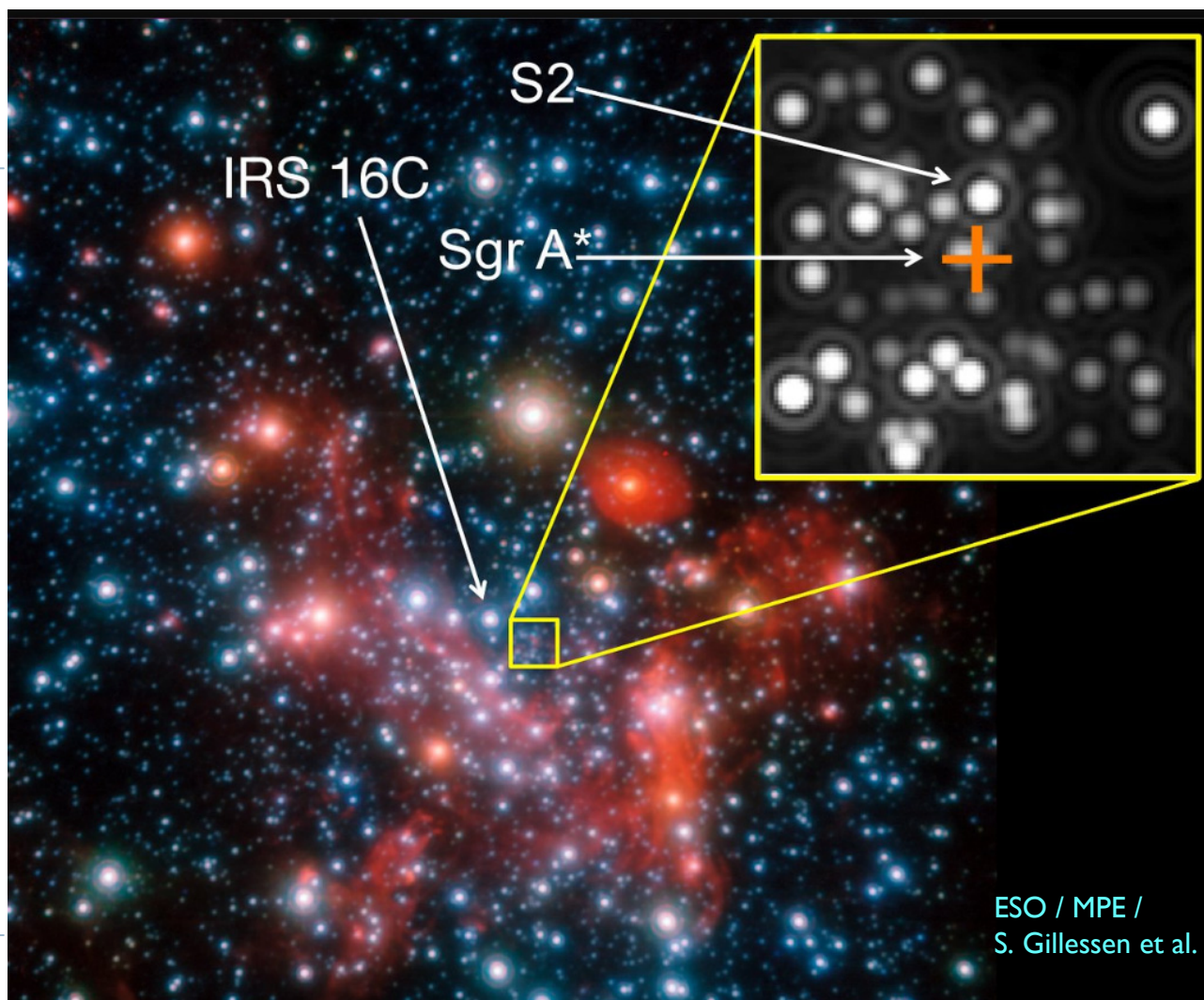
Interferometry



Dreaming of Long Coherence Times

- ▶ Leaving the Earth
 - ▶ No **~ 1 ms atmospheric coherence time** limit
 - ▶ Need to be mindful of instrumental coherence time
- ▶ A 2" aperture has greater sensitivity than an 8m VLT aperture after first second of integration; 300+ sec possible
- ▶ Free vacuum $\rightarrow$ clean beam propagation, no vacuum machinery





ESO / MPE /
S. Gillessen et al.

2025 Jul 29

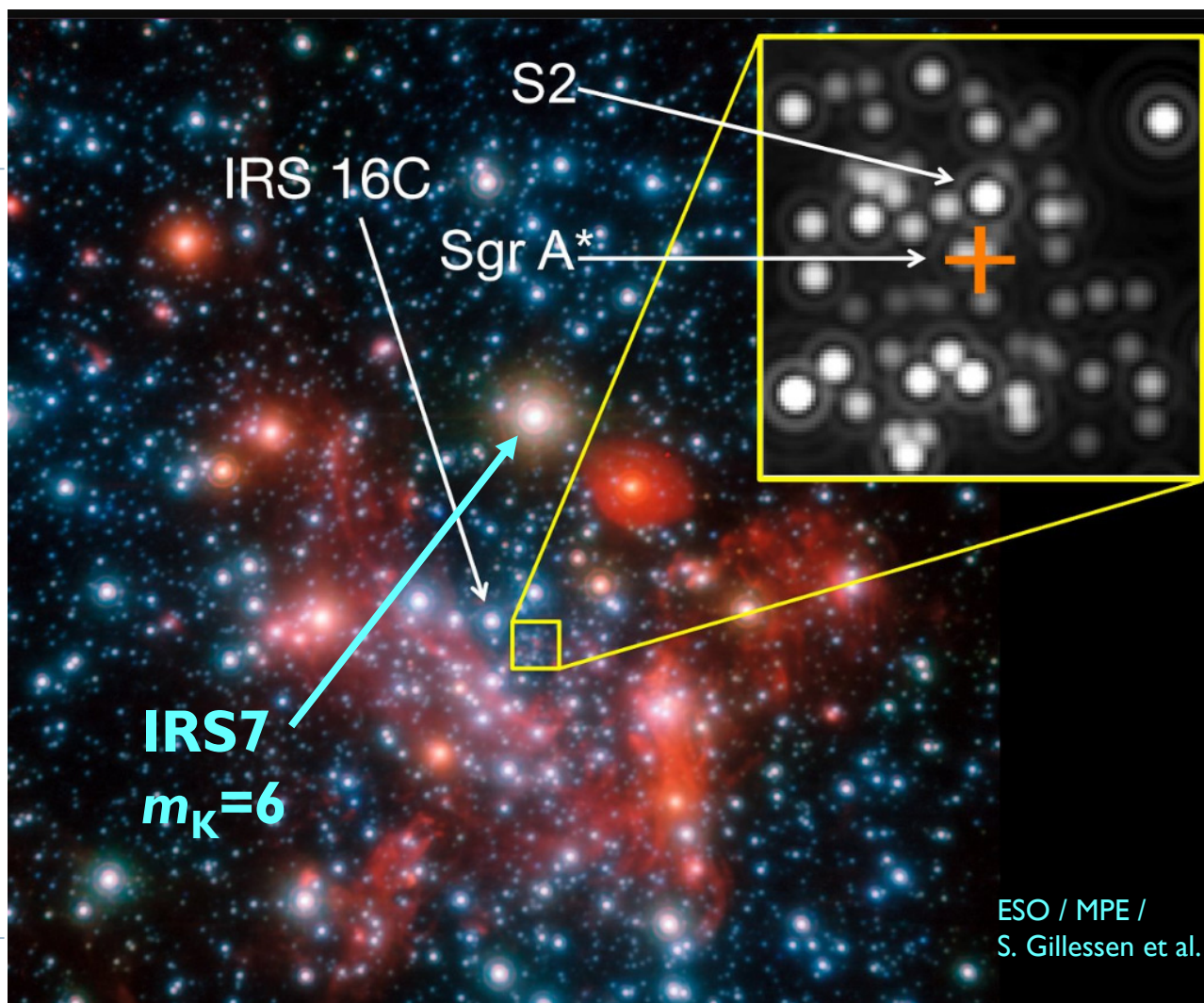


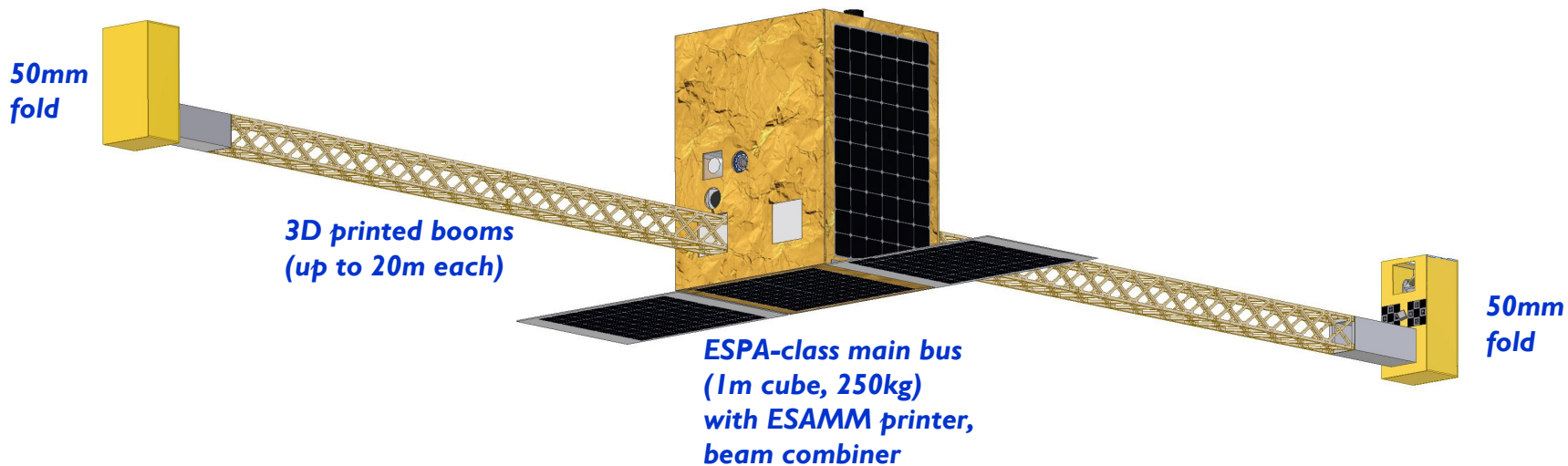
Table 1: Proposed space interferometer concepts (NASA/ESA)

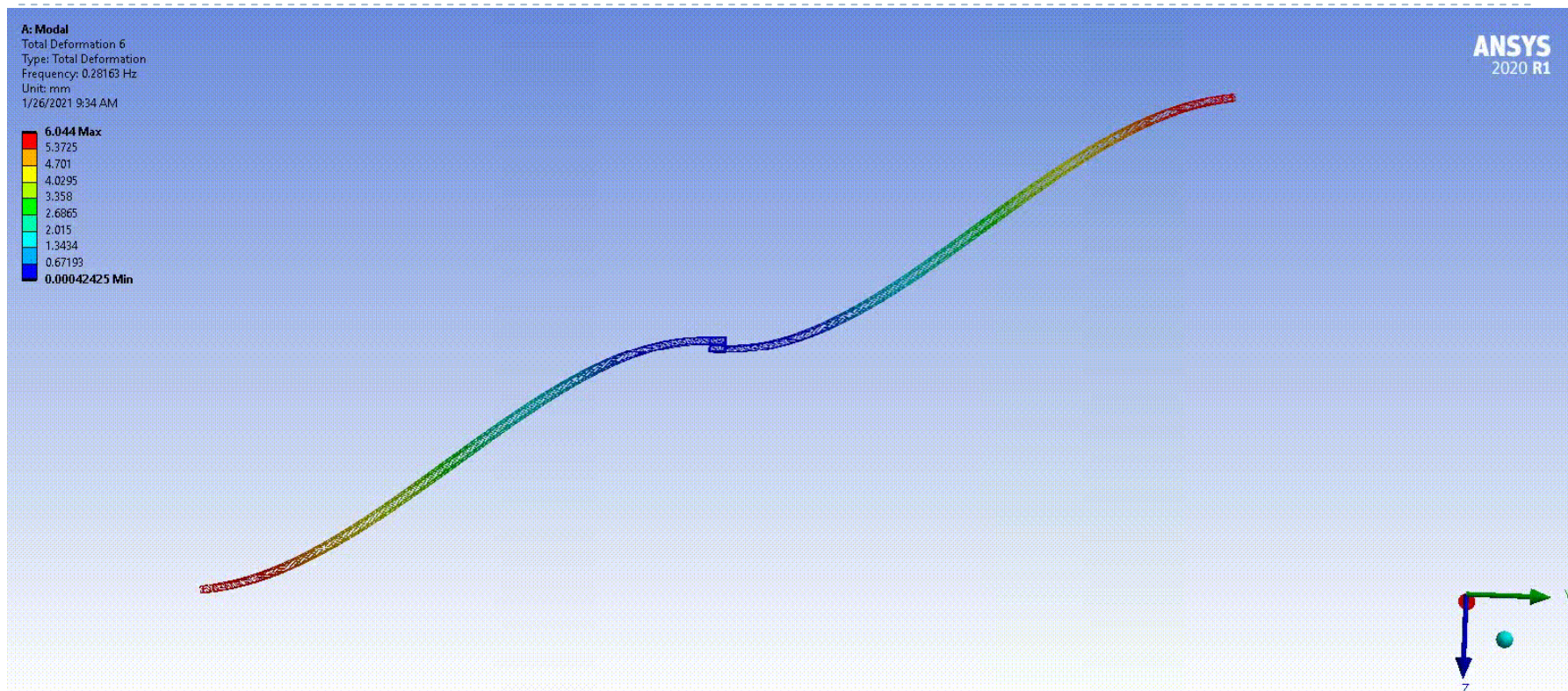
Name	Wavelength	Reference
SIM	visible	Shao (1998)
OSIRIS	visible	Bagrov et al. (1999)
MAXIM	X-ray	Cash et al. (2004)
MAXIM Pathfinder	X-ray	Gendreau et al. (2004)
PEGASE	vis/NIR	Le Duigou et al. (2006)
SPECS	far-IR	Harwit et al. (2006)
ESPRIT	far-IR	Wild and Helmich (2008)
SPIRIT	far-IR	Leisawitz et al. (2007)
FIRI	far-IR	Helmich and Ivison (2009)
DARWIN	mid-IR	Cockell et al. (2009)
SIM-LITE	visible	Shao et al. (2010)
FKSI	mid-IR	Danchi and Barry (2010)
Stellar Imager	UV/visible	Carpenter et al. (2010)
TPF-I	mid-IR	Martin et al. (2011)
SHARP-IR	far-IR	Rinehart et al. (2016)
DARE	radio	Plice et al. (2017)
LISA	n/a	Amaro-Seoane et al. (2017)
SunRISE	radio	Lazio et al. (2018)
LIFE	mid-IR	Quanz et al. (2018)
IRASSI	far-IR	Linz et al. (2019)

**Monnier et al.,
2019**

Flying an Optical Interferometer in Space

Lowell – Redwire “Optimast” NASA SBIR study





Formation Flying

- ▶ Darwin, TPF, ST-3 / Starlight
- ▶ Current state of the art: Proba-3

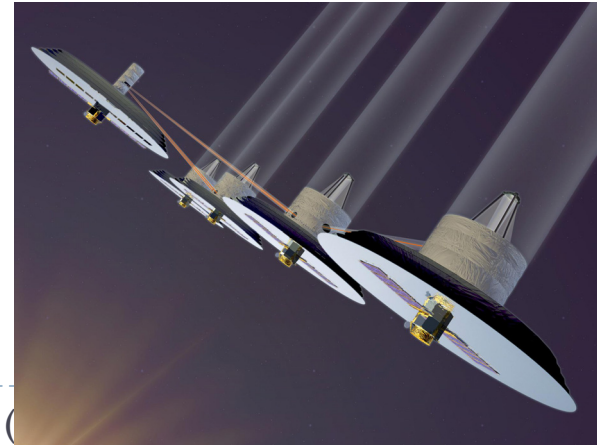
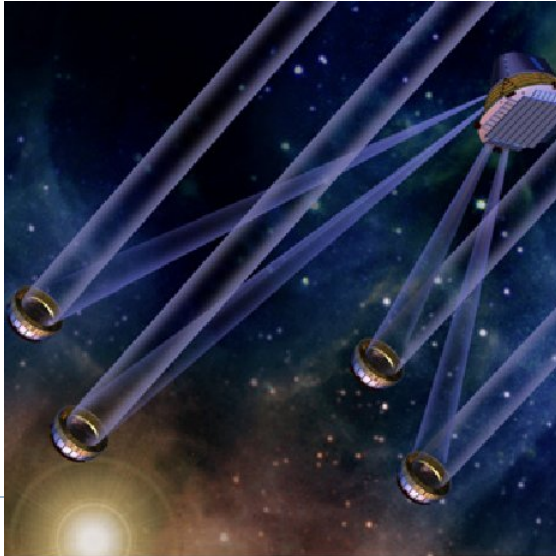
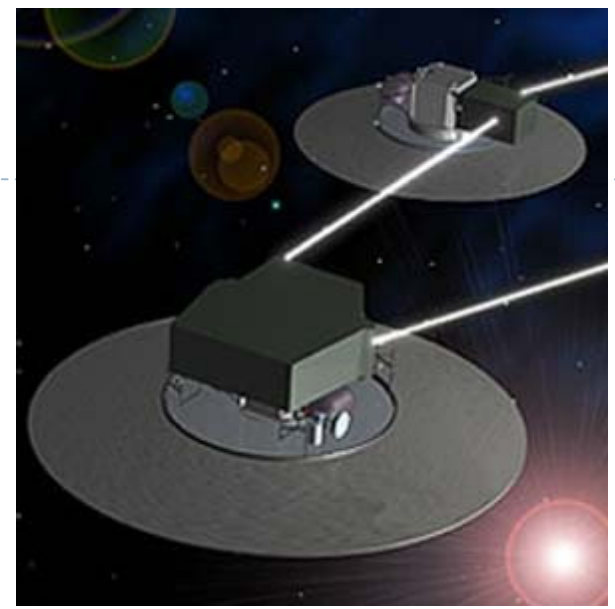


Table 2: Missions developing enabling technology for formation flying space interferometry

Name	Status	Primary Goal/s
Starlight (NASA-JPL)	cancelled 2002	Formation flying space interferometer (Blackwood et al., 2003)
TechSat-21 (AFRL)	cancelled 2003	Test formation flight technology
PRISMA (Sweden)	launched 2010	Autonomous formation flying, 800m-5km, $\pm 0.1m$ (Persson et al., 2010)
TanDEM-X (Germany)	launch 2010	Formation flying (Jäggi et al., 2012)
F6 (DARPA)	cancelled 2013	Fractionated free-flying spacecraft (\$ > 200M spent)
CanX-4/5 (Canada)	launched 2014	GPS formation flying 50m-2300m separations Achieved positioning $\pm 0.5m$ w/cold gas (Kahr et al., 2018)
MMS (NASA)	launched 2015	GPS-assisted formation flying; 4.5km apart
MinXSS (Colorado)	launched 2016	Precision pointing (Mason et al., 2017)
OCS-D-A (AeroSpace)	launched 2015	Laser communication &
& OCS-D-B/C	launched 2017	Proximity sensing/maneuvering (Welle et al., 2018)
FLOCK 2p (Planet Lab)	launched 2017	Constellation phasing with drag (Foster et al., 2018)
RANGE (Georgia Tech)	launched 2018	Laser ranging, controlling formation actively
PICSAT (Obs. Paris)	launched 2018	Starlight injection into single mode-fiber; APD detector (Nowak et al., 2018)
ASTERIA (MIT-JPL)	launched 2018	Sub-arcsec pointing stability; $\Delta T \pm 0.01K$ (Pong et al., 2010)
GRACE-FO (NASA)	launched 2018	Laser ranging interferometry over 230km with $< 10nm$ precision (Abich et al., 2019)
DeMi (MIT)	to launch 2019	MEMS mirror testing (Allan et al., 2018)
TARGIT (Georgia Tech)	to launch 2020	LIDAR, ranging measurement of two spacecraft
PROBA-3 (ESA)	to launch 2020	Precision formation flying 150m apart Goal $\pm 5cm$ transverse positioning (Focardi et al., 2015)
FIRST-S (Obs. Paris)	TBD >2022	Interferometer on single spacecraft (Lapeyriere et al., 2018)
VTXO (NASA-GSFC)	TBD >2023	Formation flying (Rankin et al., 2018)
mDOT (Stanford)	TBD >2025	Formation flying (Koenig et al., 2015)
SunRise (NASA-JPL)	TBD >2025	GPS formation flying with 6 spacecraft; radio interferometry near GEO (Lazio et al., 2018)
LISA (ESA/NASA)	TBD >2034	Formation flying 2.5 million km apart (Danzmann and LISA Science Team, 2003)

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Actual launch: 2024
\$200M

So, what about the moon?

“The only thing the moon
has to offer astronomy is

dust

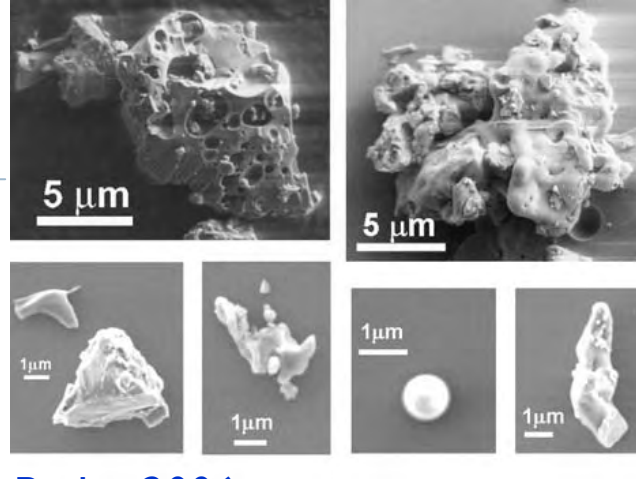
and **gravity**”



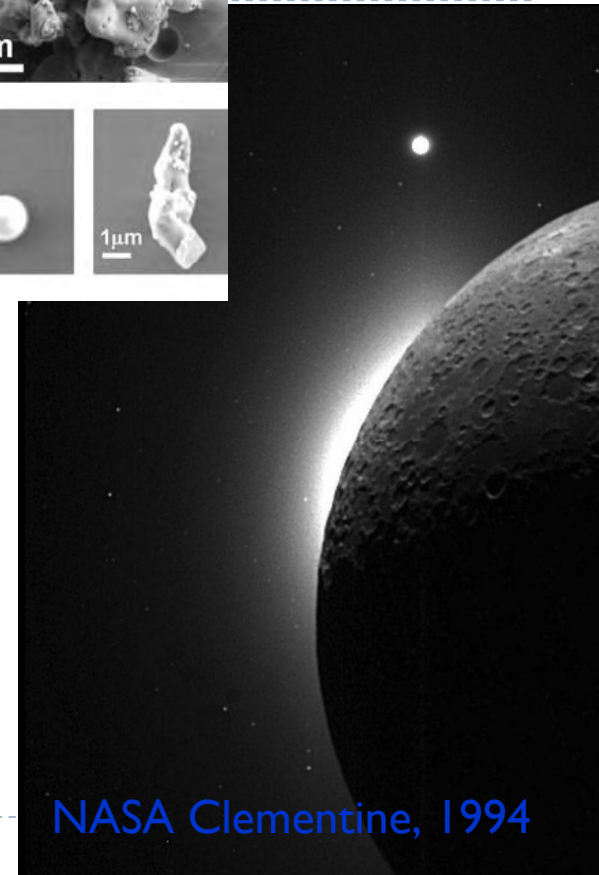
(Lester, 2006, slightly paraphrased)

Dust?

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



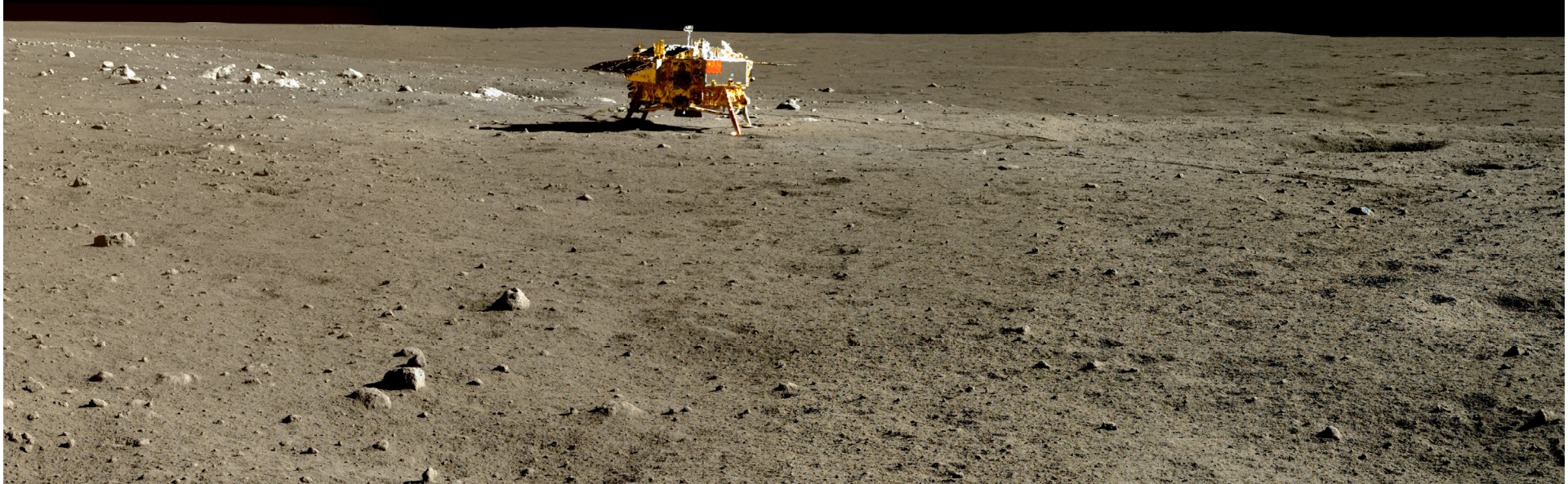
Park+ 2006



NASA Clementine, 1994

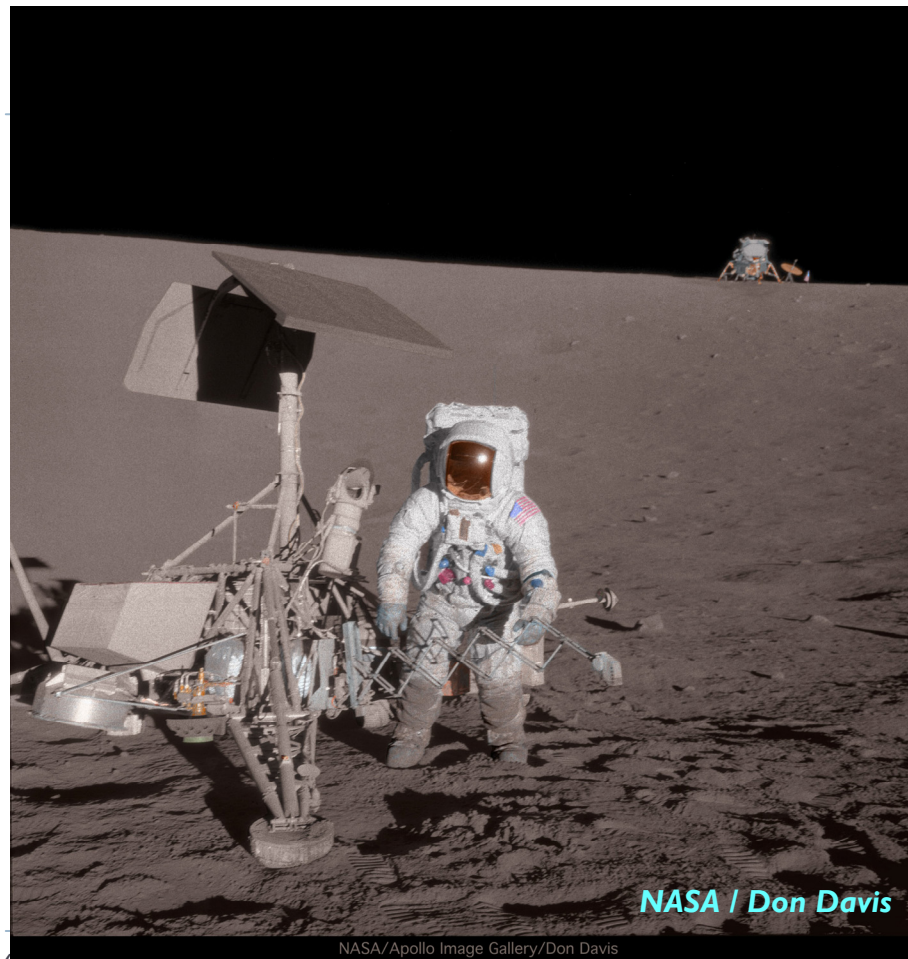
Dust: LUT on board Chang'e-3 Lander

- ▶ UV telescope with **years** of operations (2015 - 2018+)
 - ▶ For sunrise & sunset, a shutter aperture was closed
- ▶ **Dust can be dealt with via operational mitigations**



Why the moon?

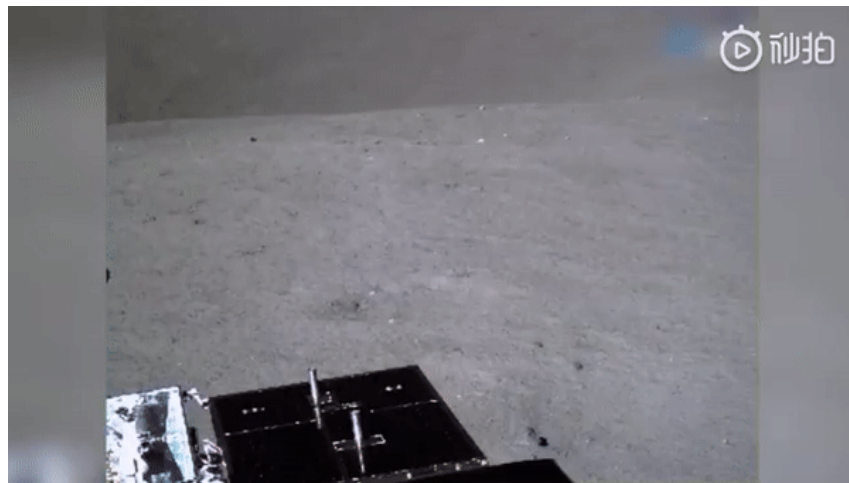
- ▶ Stable surface
 - ▶ Seismology not a problem
 - ▶ Things stay put
 - ▶ Natural home for arrays of telescopes
 - ▶ No atmosphere
 - ▶ Dust not a showstopper
- Small systems can outperform terrestrial, orbital systems



Access to the Lunar Surface



Firefly Blue Ghost CLPS lander

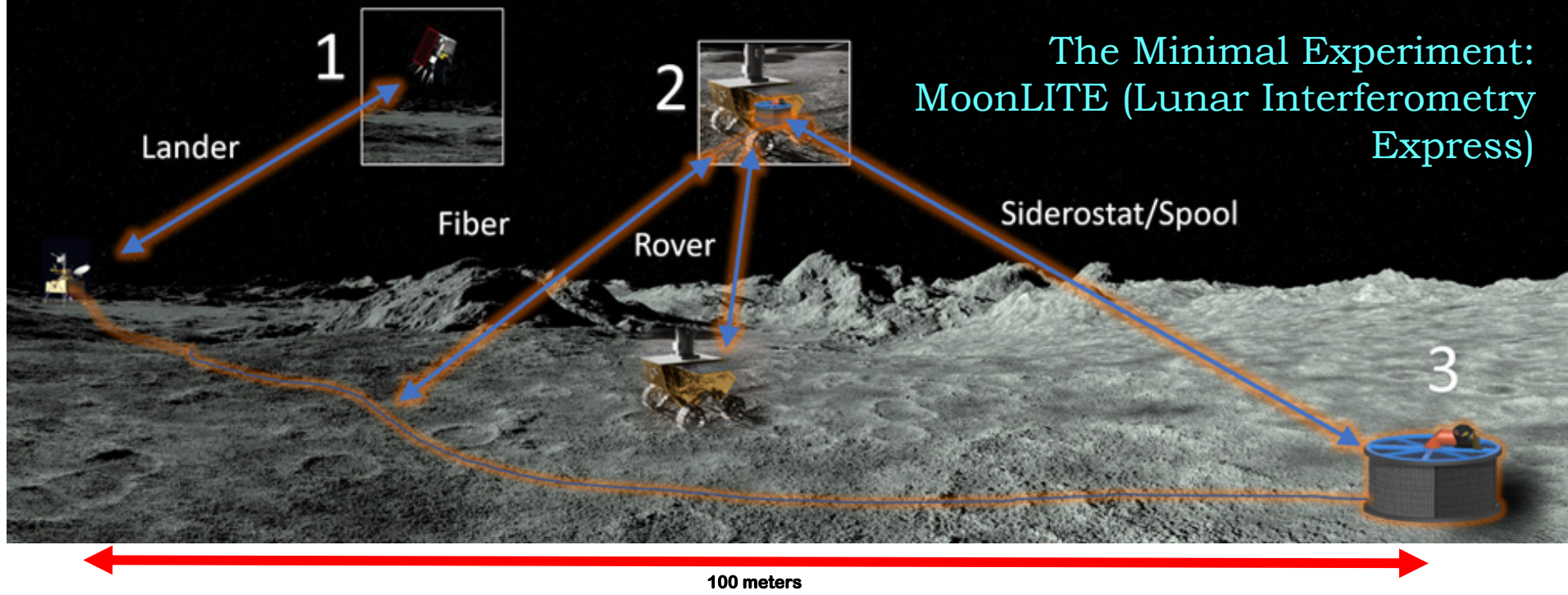


Chang'e-3 Yutu rover

KISS Workshop: Astronomical Interferometry from the Lunar Surface (Nov 2024)



- ▶ Roughly half interferometry, half lunar experts
- ▶ US, Canada, Japan, Europe, Australia
- ▶ Academia, industry, government

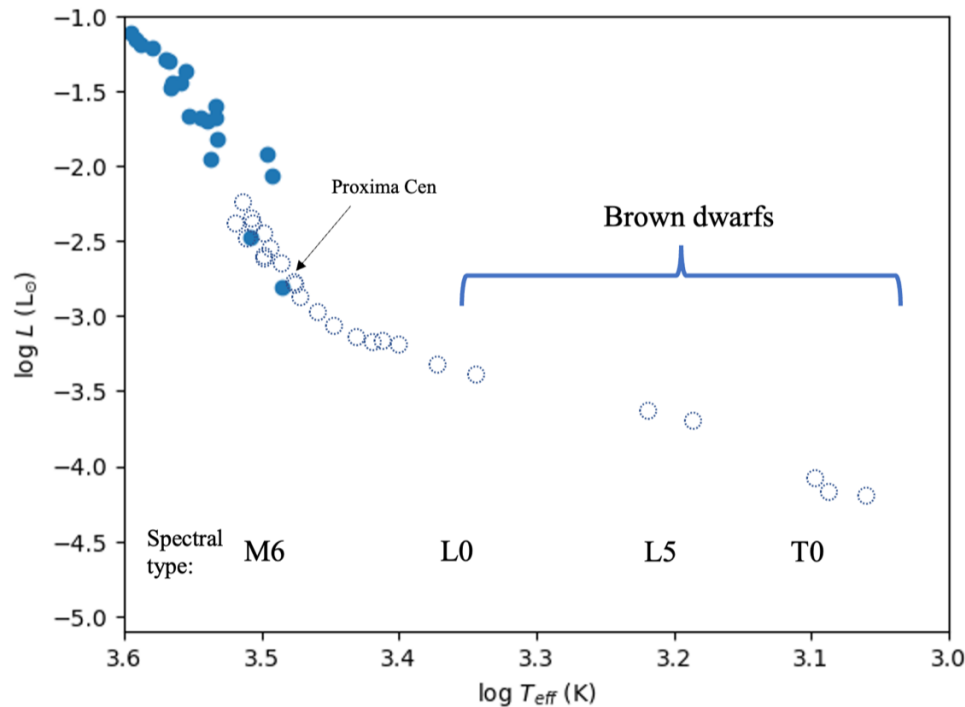


Emphasis on simplicity: one deployment step

Simple system for size measures of faint objects: beats terrestrial interferometers by ~5 magnitudes

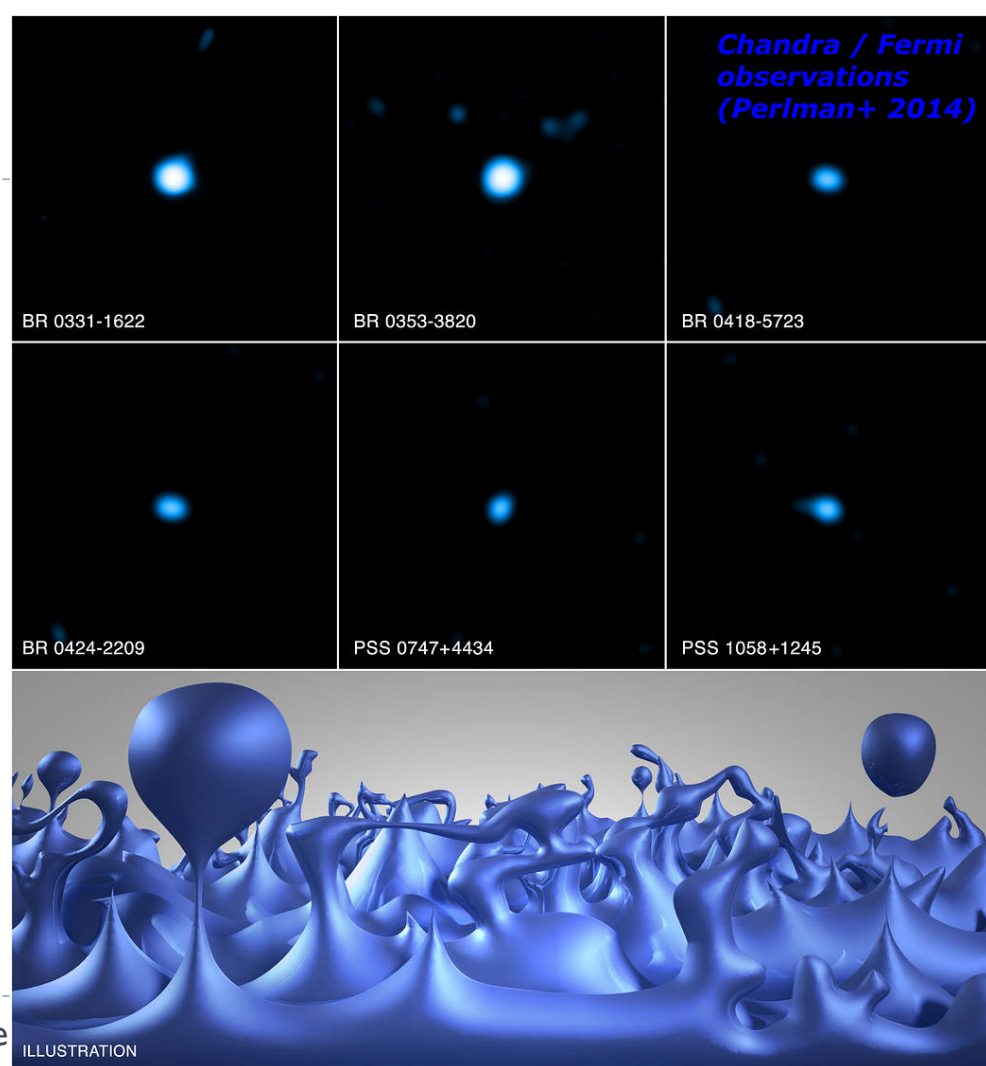
Late M-dwarfs / Brown dwarfs

- ▶ 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



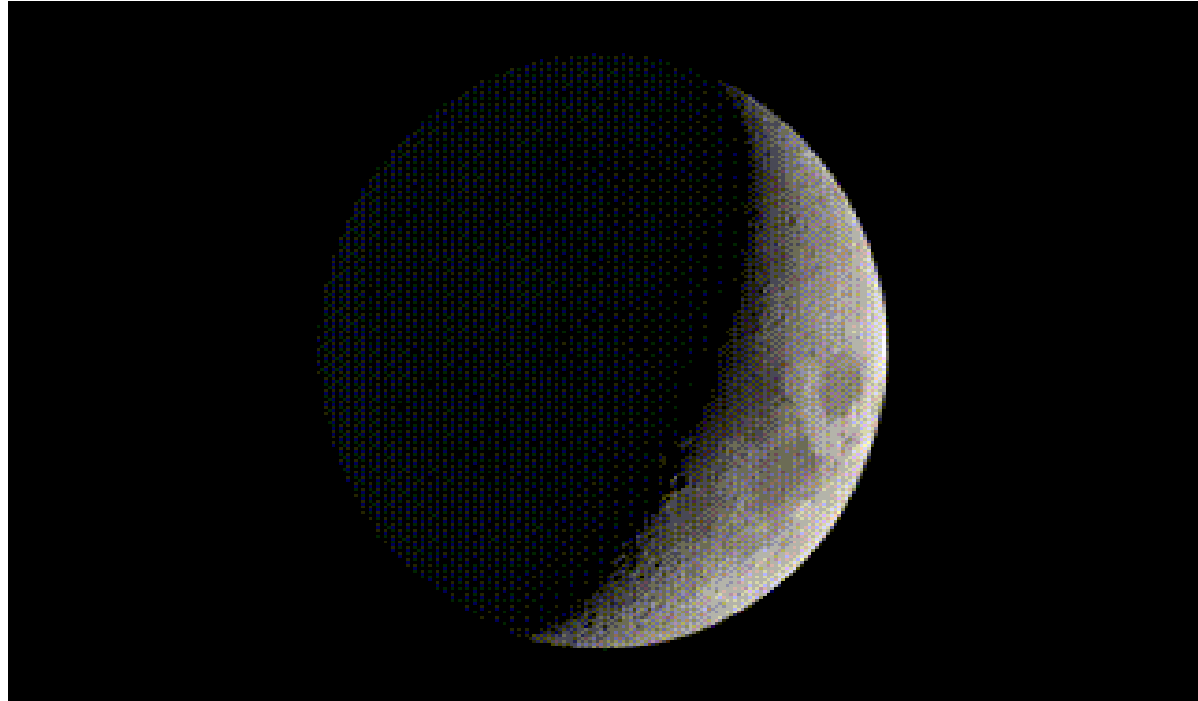
Spacetime Foam Models

- ▶ ‘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 a AGN program



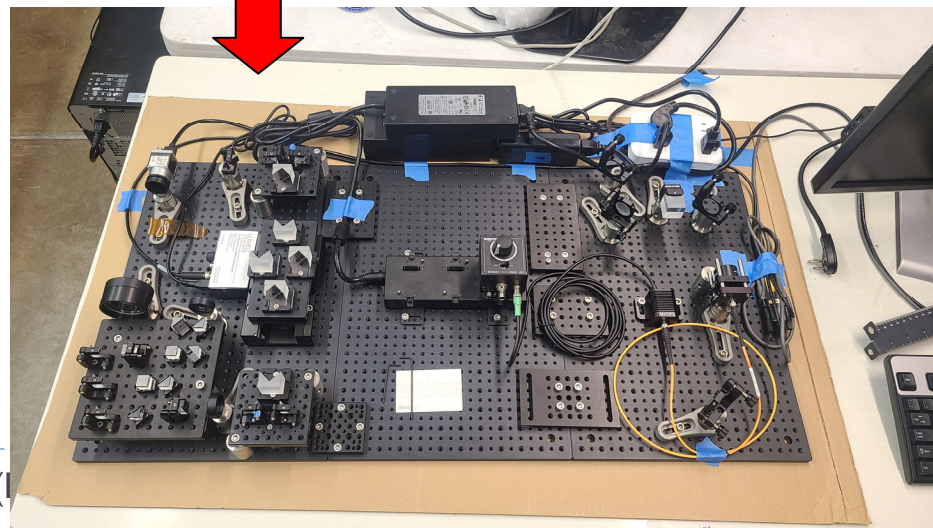
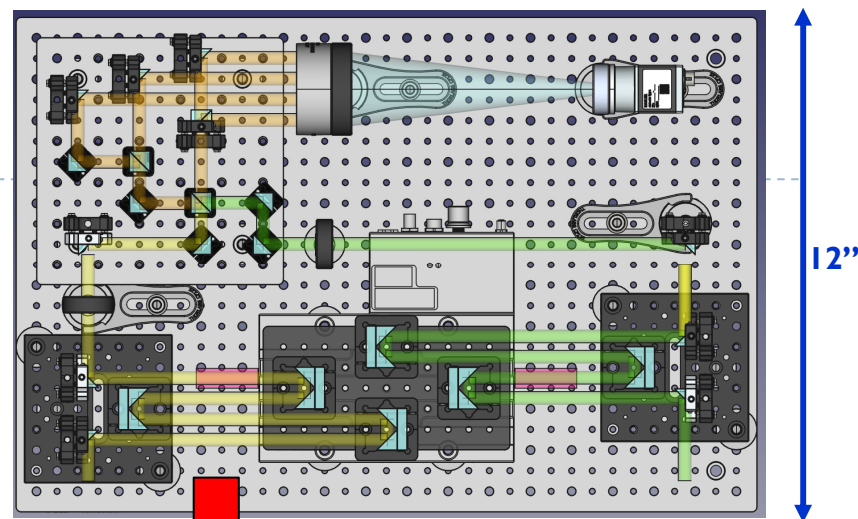
Lunar Libration

- ▶ ‘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



MoonLITE Status

- ▶ Proposed in 2023, 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



MIDEX: Astrometric Detection of Exoplanets

- ▶ $1 M_E$ @ 1 AU, $1 M_S$: $0.3 \mu\text{as}$ signal

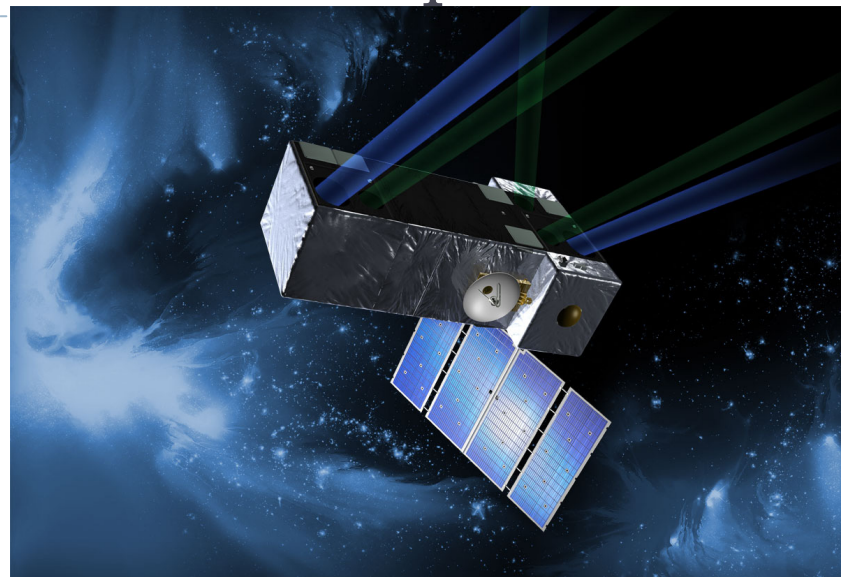
- ▶ Space Interferometry Mission (SIM)

 - ▶ **6m baseline**

- ▶ Differential astrometric **single-measurement** precision (not end-of-mission):

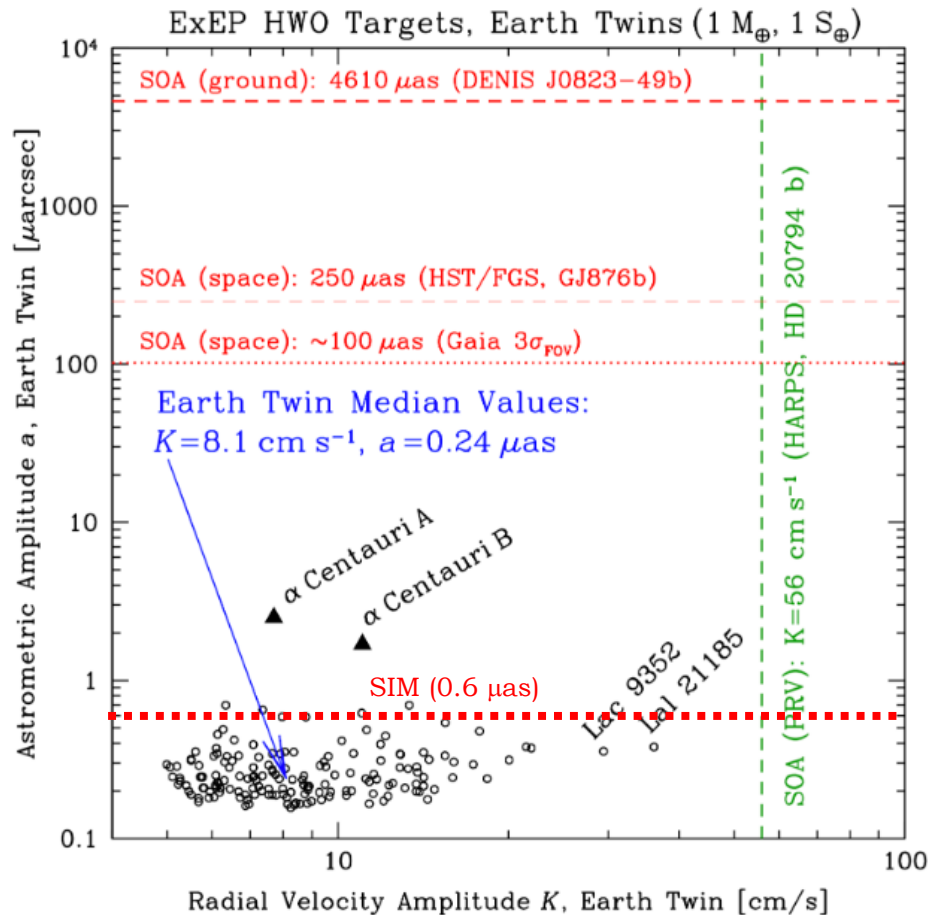
$0.6 \mu\text{as}$ for $V < 7$

 - ▶ SIM: projected yield would have been 6 Earth-like planets
 - ▶ **This needs to be done in preparation for HWO, and for more than just six exo-Earths → aim for $0.1 \mu\text{as}$**



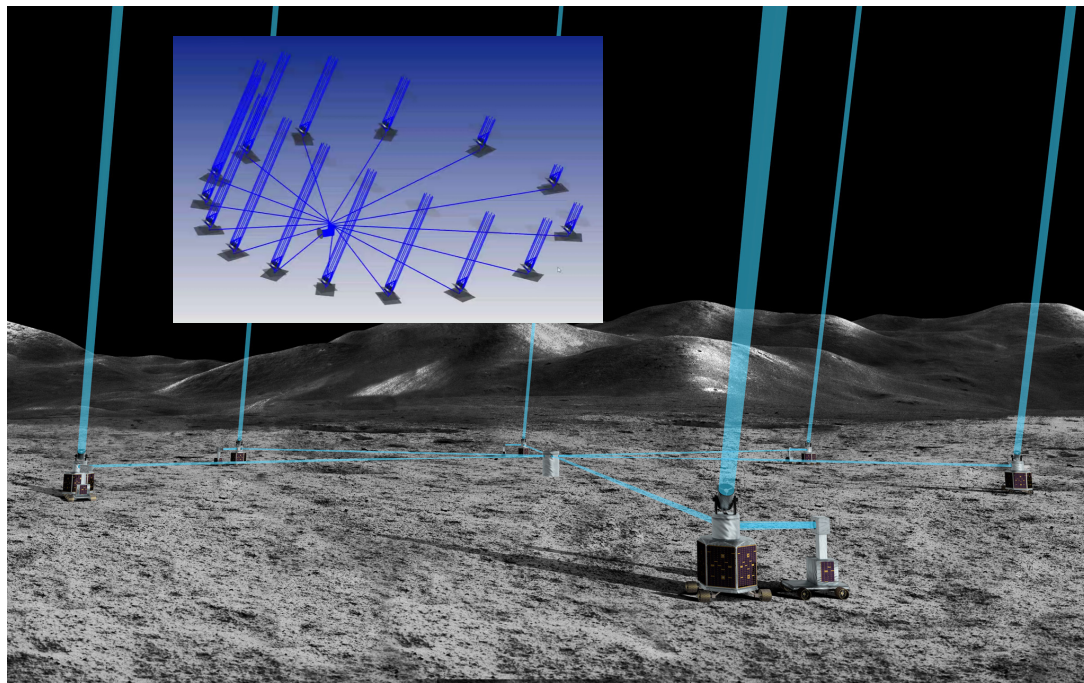
Searching for Earth 2.0

- ▶ HWO target detection & characterization
 - ▶ HWO doesn't know where to point
 - ▶ Masses needed for atmospheric retrievals
- ▶ **Lunar baselines can be much longer than orbital**
- ▶ Going from 0.6 to 0.1 μas single-measurement precision has significant yield benefits



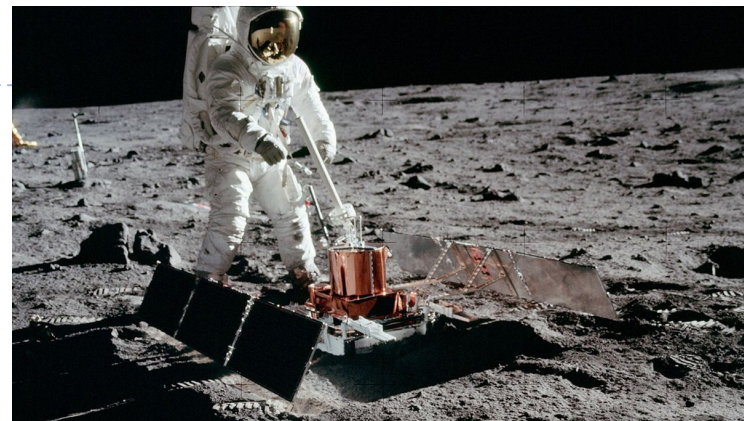
Flagship: Dense Imaging array in the UV

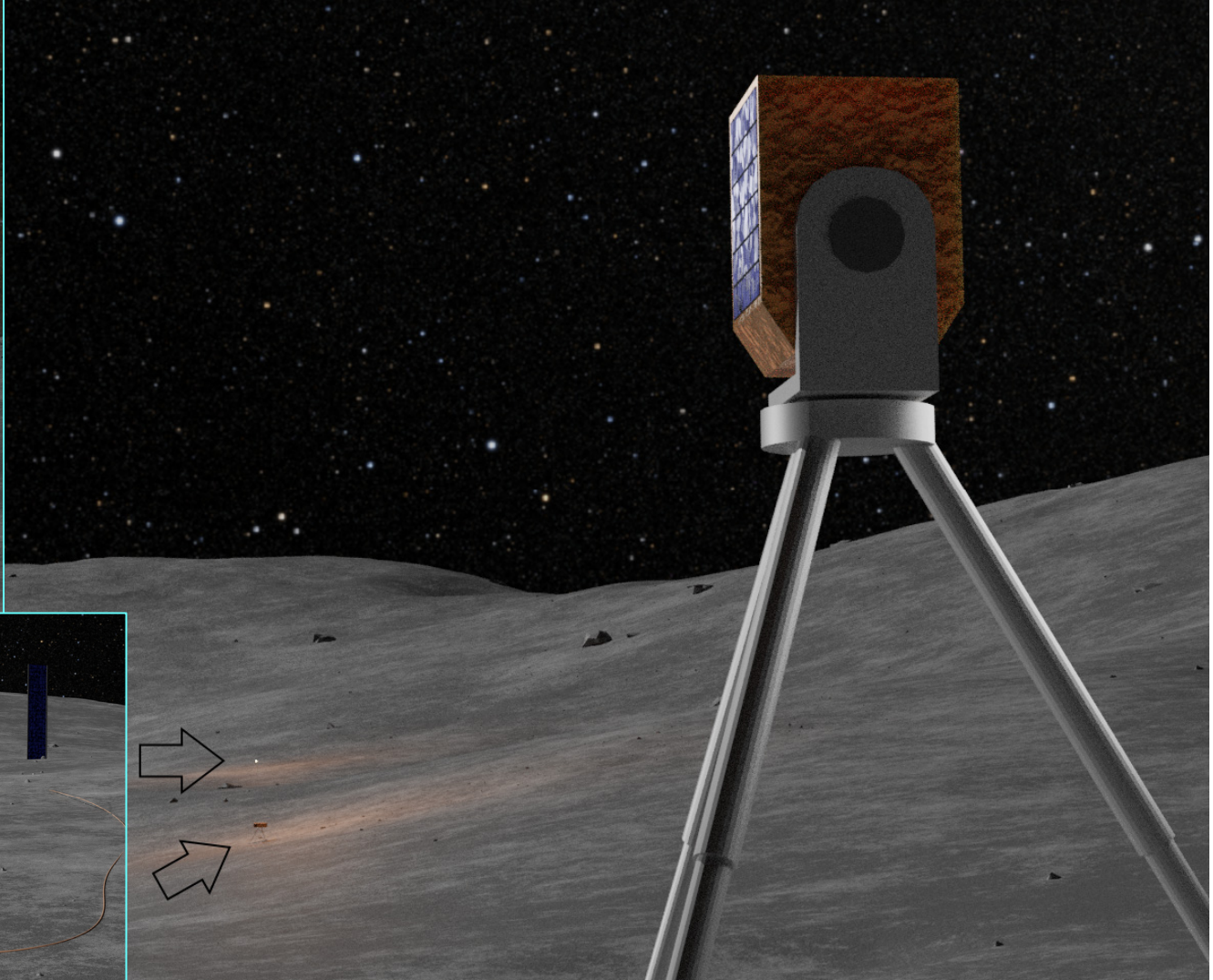
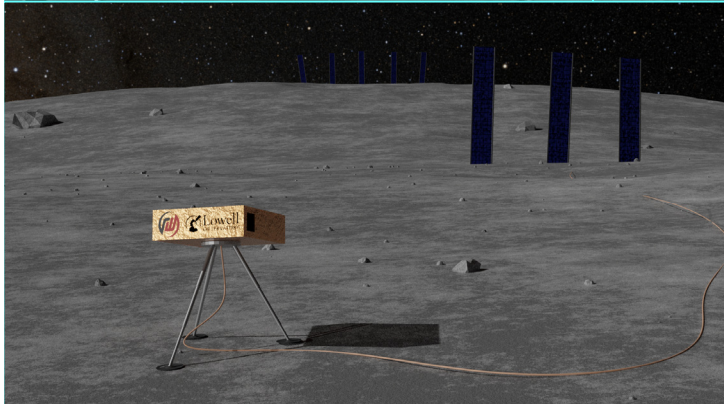
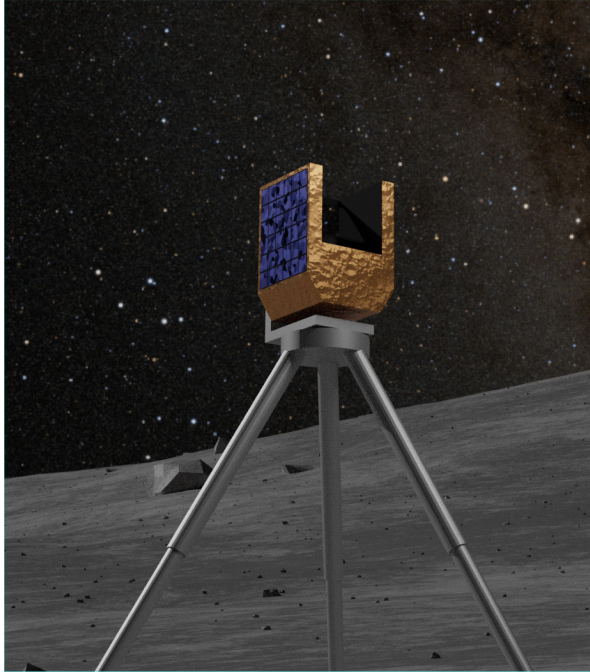
- ▶ NIAC AeSI study report (2503.02105) / “Black Hole Imager”
- ▶ Operating down to Lyman- α (1216Å)
- ▶ 15 to 30 apertures, each ~1 meter
- ▶ Stellar surface imaging, black hole imager



MoonLITE + Astronauts

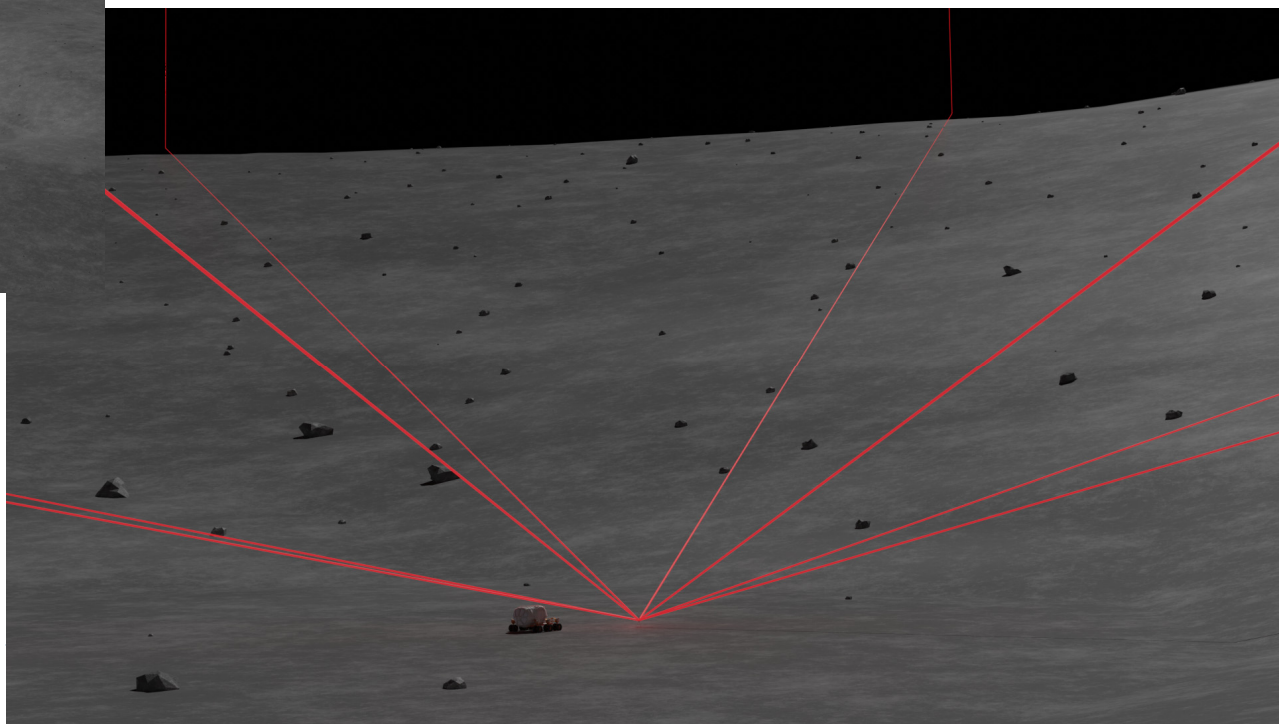
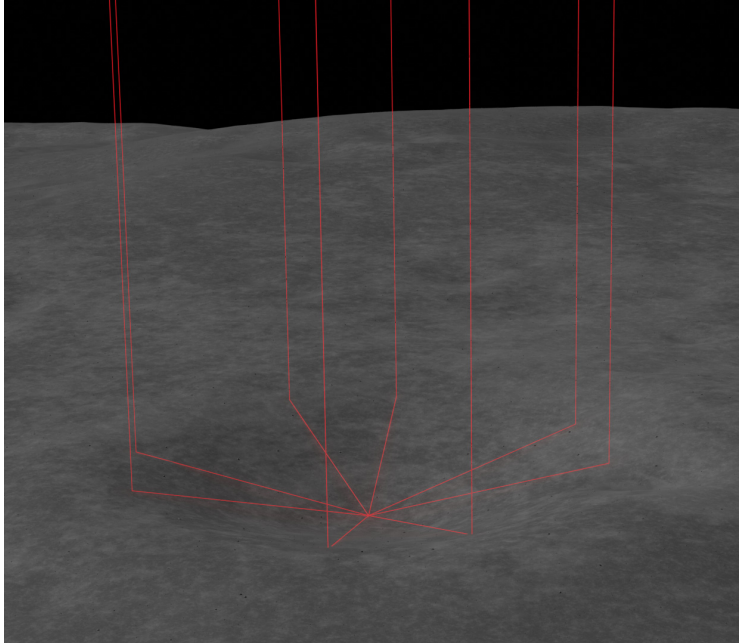
- ▶ Further simplification: ‘bespoke’ deployment
 - ▶ Multiple stations – a suitcase and two carry-ons
- ▶ Assembly
 - ▶ Tripod erection, trenching for optical fiber, increased delay line length via assembly
- ▶ Does a Blue Moon or Lunar Starship ride mean more available mass?
 - ▶ Batteries for nighttime operations
- ▶ But still plug-and-play





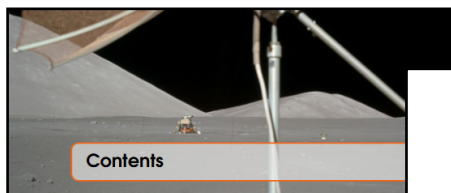
Design could be Extensible

- ▶ Initial delivery of combiner, two stations → added to with later visits



KISS Study Report

► In pipeline for NASA (JPL), USGS document review approval



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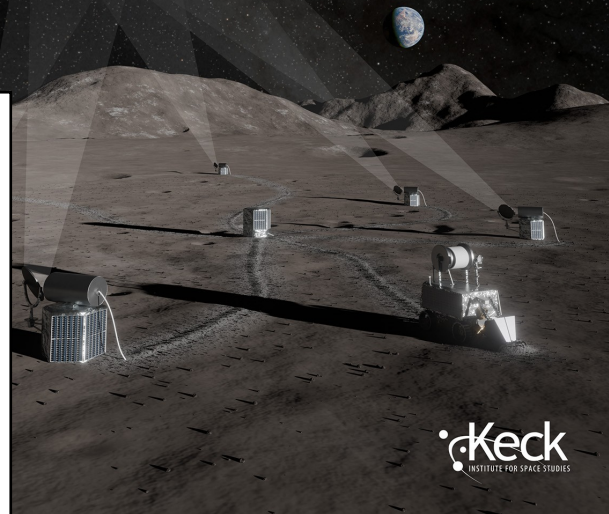
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Astronomical Optical Interferometry from the Lunar Surface

High Sensitivity at Sub-Milliarcsecond Scales



Keck
INSTITUTE FOR SPACE STUDIES

Summary

- ▶ Terrestrial optical interferometry is mature and offers **high spatial resolution**
- ▶ Lunar surface offers stable platform for **high sensitivity**
- ▶ Advancements in imaging lead to **discovery** and **new physics**
- ▶ Developments in lunar infrastructure make this **timely**

