NIAC annual meeting 2006

Tuesday October 17, 2006

NIAC Phase II Study

A Deep Field Infrared Observatory Near the Lunar Pole

Study team

• Roger Angel	University of Arizona
• Ermanno Borra	Laval University
• Jim Burge	University of Arizona
• Daniel Eisenstein	University of Arizona
• Paul Hickson	University of British Columbia
• Ki Ma	University of Houston
• Ken Seddon	Queen's University Belfast
• Suresh Sivanandam	University of Arizona
• Paul van Susante	Colorado School of Mines
• Pete Worden	NASA Ames
• Stan Dubyn	Millennium Space systems
• Vince Deno	Millennium
• Tomas Svitek	Millennium

Organization of Phase B Study

- Pete Worden was original PI
- Roger Angel PI since Pete became Ames Director
- Paul van Susante continuing as deputy PI
- Major collaboration with separately funded Canadian team, Ermanno Borra (Laval) and Paul Hickson (UBC)

advantages of the moon for astronomy

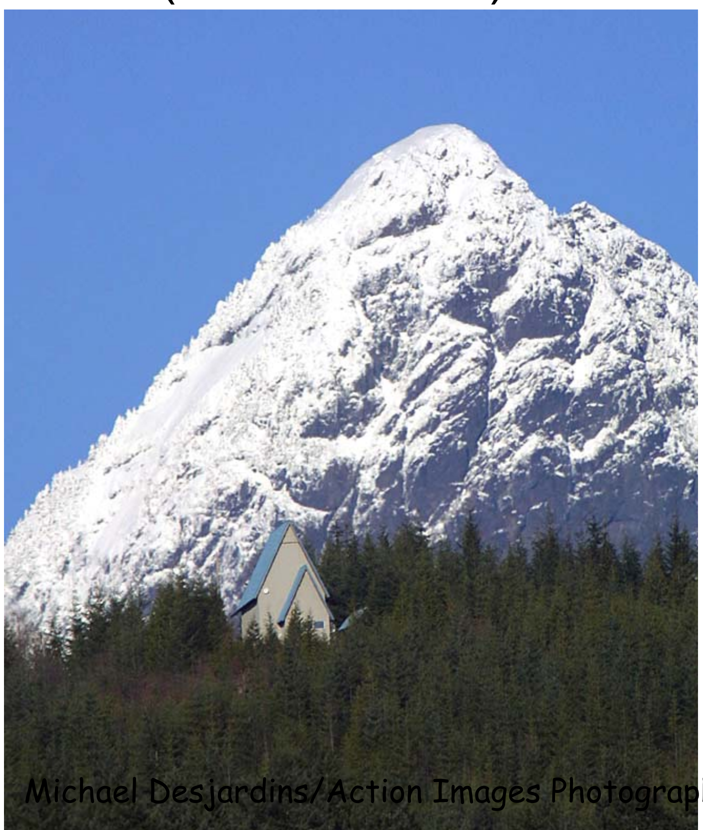
- Potential for very long lived observatories
  - Lifetimes of ~ 50 years rather than ~ 5
- Big stable platform for many telescopes across the electromagnetic spectrum
  - Good for viewing along spin axis (near ecliptic poles)
- Possibility of huge cryogenic liquid mirrors at poles
- aperture of 20-100 meters diameter and capable of integrations of days to years with Hubble quality imaging
- NASA exploration program could enable large construction

Comparison with free space location

- Common advantages with free space:
  - No atmospheric aberration or distortion
  - Strong radiative cooling possible for infrared spectrum (at poles)
- Unique lunar advantages
  - Large permanent platform for many telescopes
  - Exploration initiative may result in infrastructure for large telescope assembly and maintenance
  - Gravity
- Lunar disadvantage vs L2
  - Powered descent needed for surface landing
  - dust might be a problem for optics or bearings
  - bearings and drives required for pointing and tracking (versus gyros for free space)

Liquid mirror telescopes - already operating on Earth

6-m liquid mercury telescope in British Columbia
(Paul Hickson)

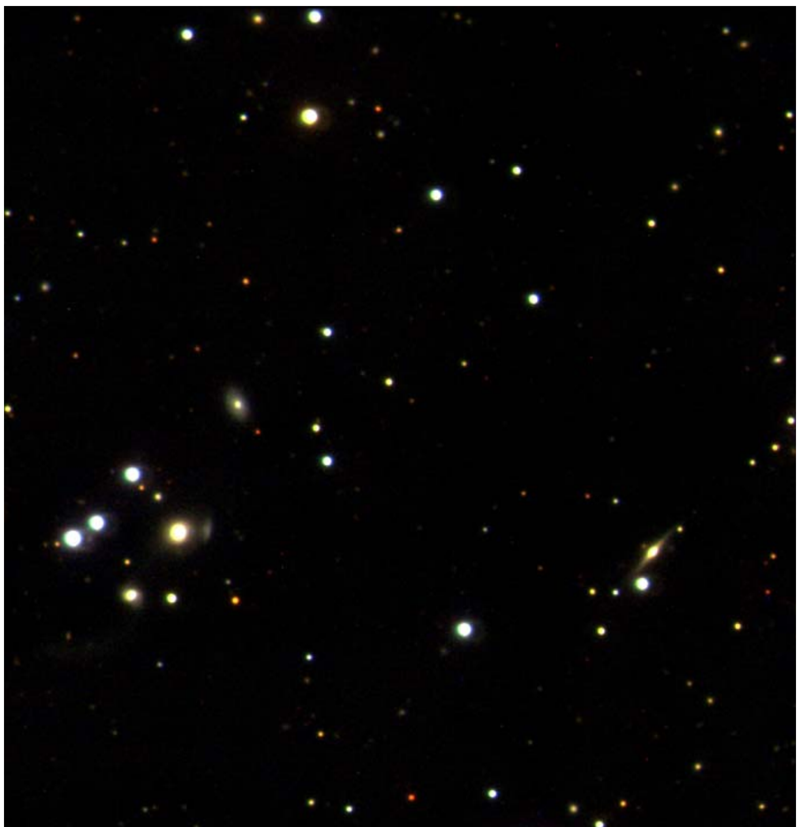


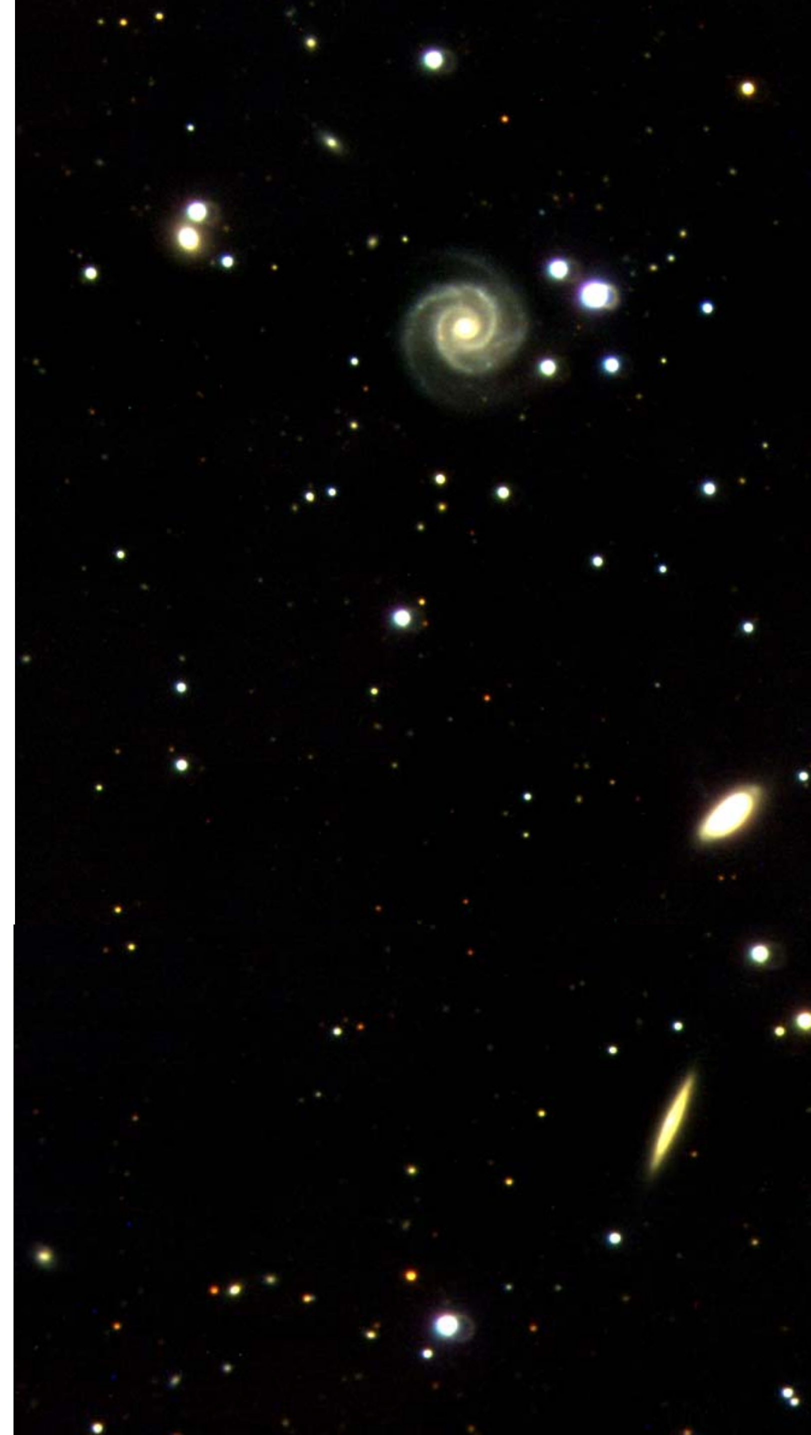
Michael Desjardins/Action Images Photography

Peter Kan

6-m Performance

- R ~ 22 in 100 sec
- FWHM ~ 1.4 - 2.5” (seeing limited)
- ~ 40 nm RMS surface error (S ~ 0.6)





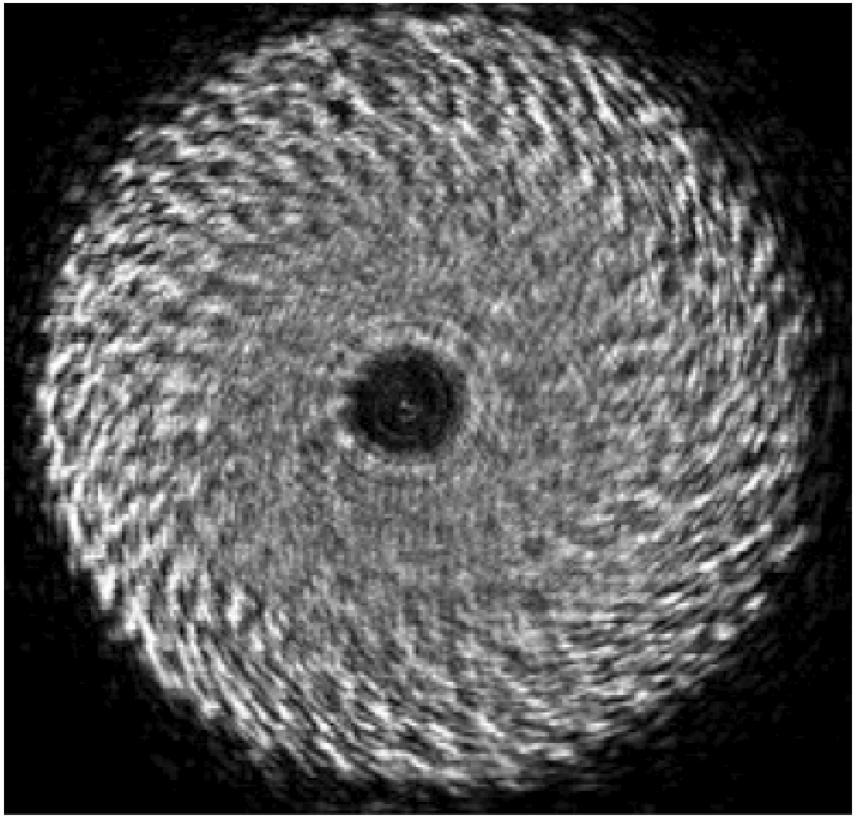
8-m ALPACA for Chile (Advanced Liquid-mirror Probe for Asteroids, Cosmology and Astrophysics)

- Wide-field survey telescope
- Cerro Tololo, Chile
- Columbia, Stony Brook, Oklahoma, UBC
- 8 m f/1.5
- 3-degree field of view
- 0.3” image quality
- 240 2kx2k CCDs
- 1000 sq degrees in 6 bands
- AB ~24 /night, 26.5 /year
- Supernovae, lensing, LSS, NEOs, TNOs, …

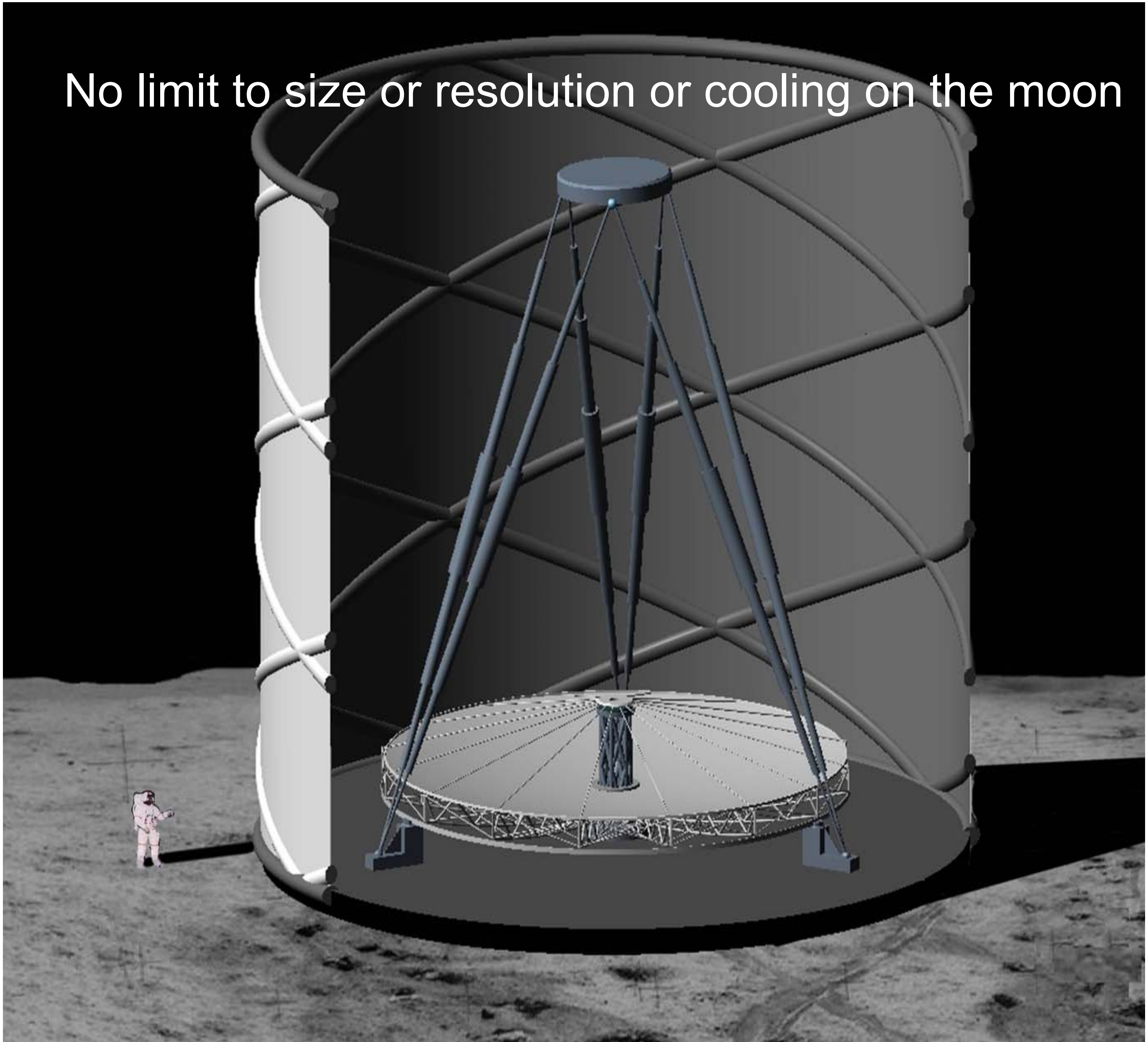
Limits on Earth – atmospheric blurring, spiral waves from air limit size, heat from warm mirror

- These are waves raised on the mercury surface by vortices in the boundary layer above the rotating surface
- Onset of turbulence occurs at ~ 0.6 m radius
- These waves have large amplitude and diffract most of the light out of the PSF for large liquid mirrors

Laval 2.5m defocussed image



No limit to size or resolution or cooling on the moon



Scientific potential

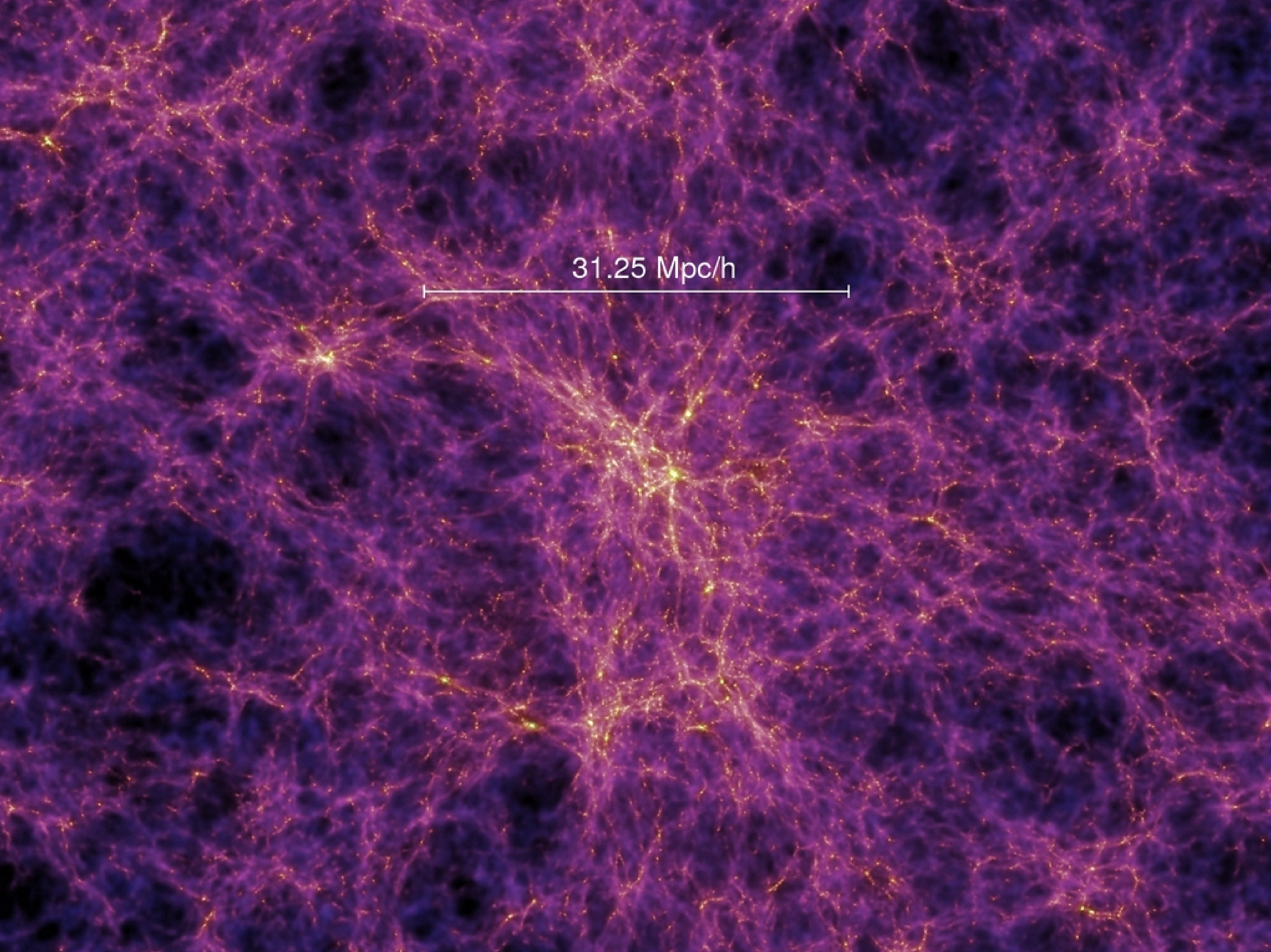
- Ultra-deep survey of early universe
- formation of the first stars and their assembly into galaxies.
- radiation of the first stars emitted primarily at rest wavelengths from 0.1 – 1 μm is red shifted by around a factor 20 to this region.
- zodiacal sky background is lowest in the 2-5 μm spectral region, allowing for extremely deep images, to be first explored by JWST

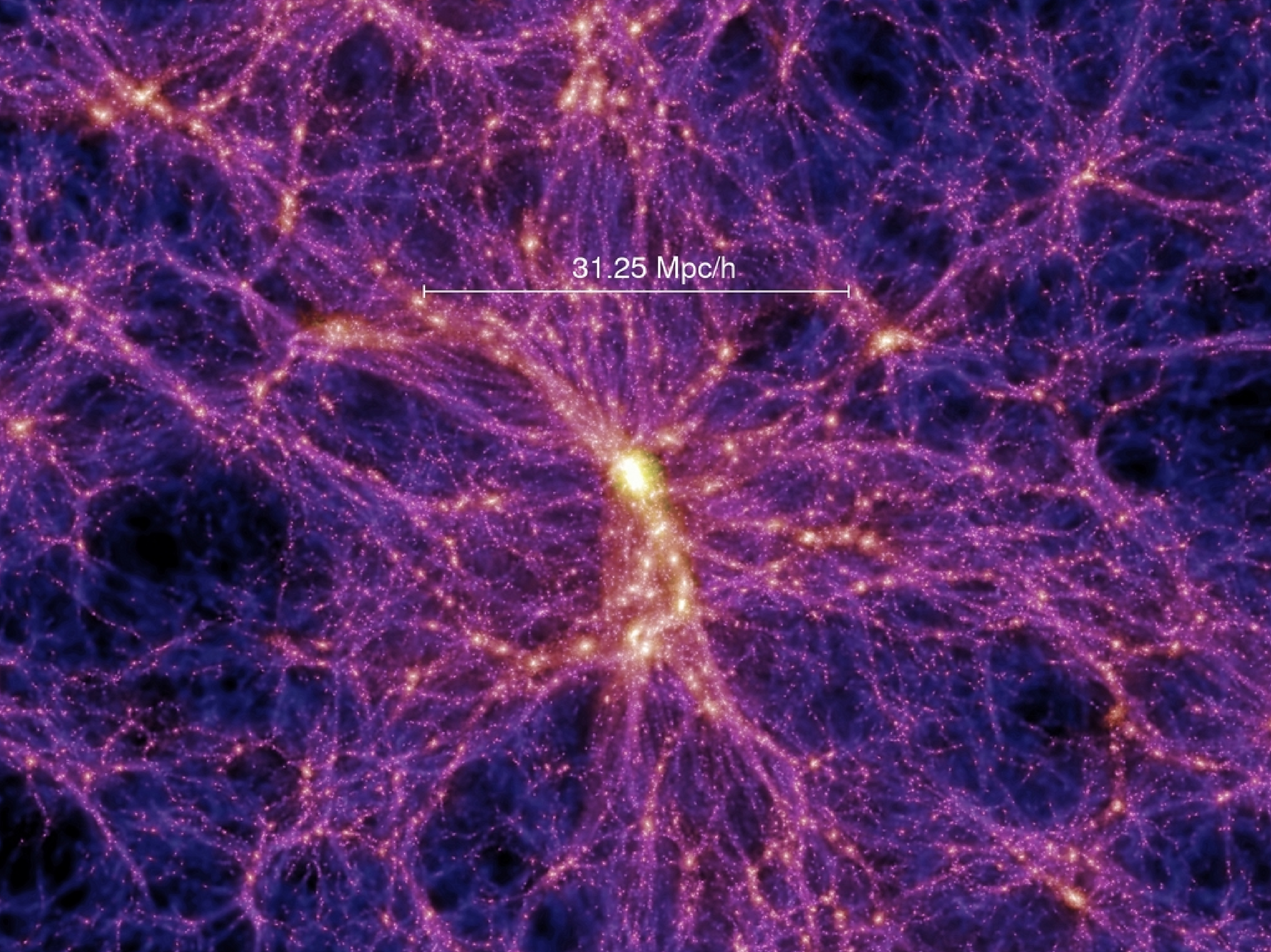
Galaxy Formation major goal

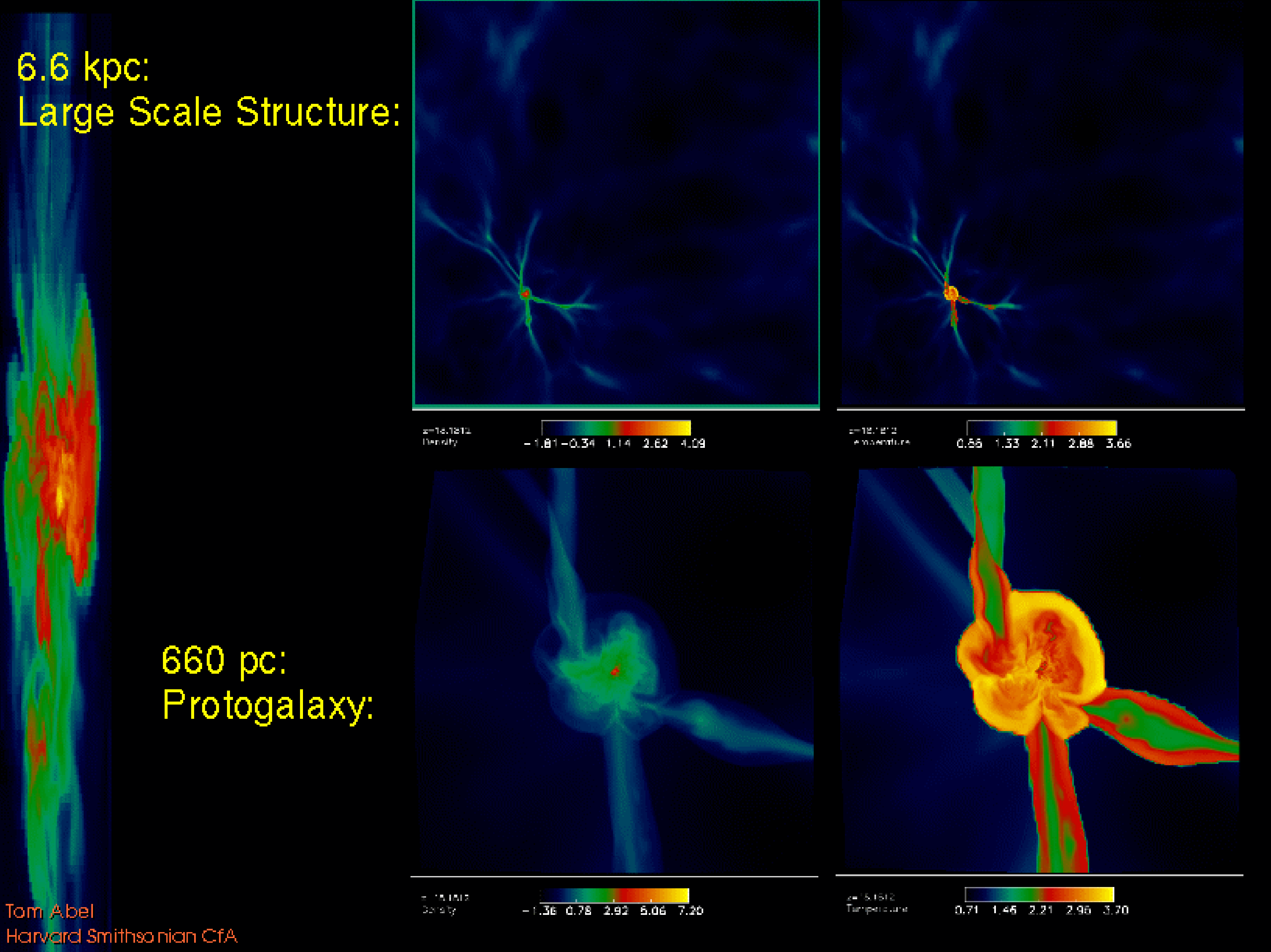
- Since a liquid mirror telescope must point ~vertically, the interesting targets must be ones that have no closer examples elsewhere on the sky.
  - Galaxies at $z>0.5$: galaxies evolve and so there is no substitute for looking far away.
  - Special objects where the best example happens to fall in the field of view, e.g. the Large Magellenic Cloud.

A Rough History of Galaxies

- First stars (z~20)
- First galaxies (z~15)
- Larger galaxies & reionization (z~10)
- Current frontier (z~6)
- Peak epoch of formation (z~2-3)
- Growth of hot halos (z~1)
- Shut-off and cluster formation (z<0.7)


31.25 Mpc/h


31.25 Mpc/h



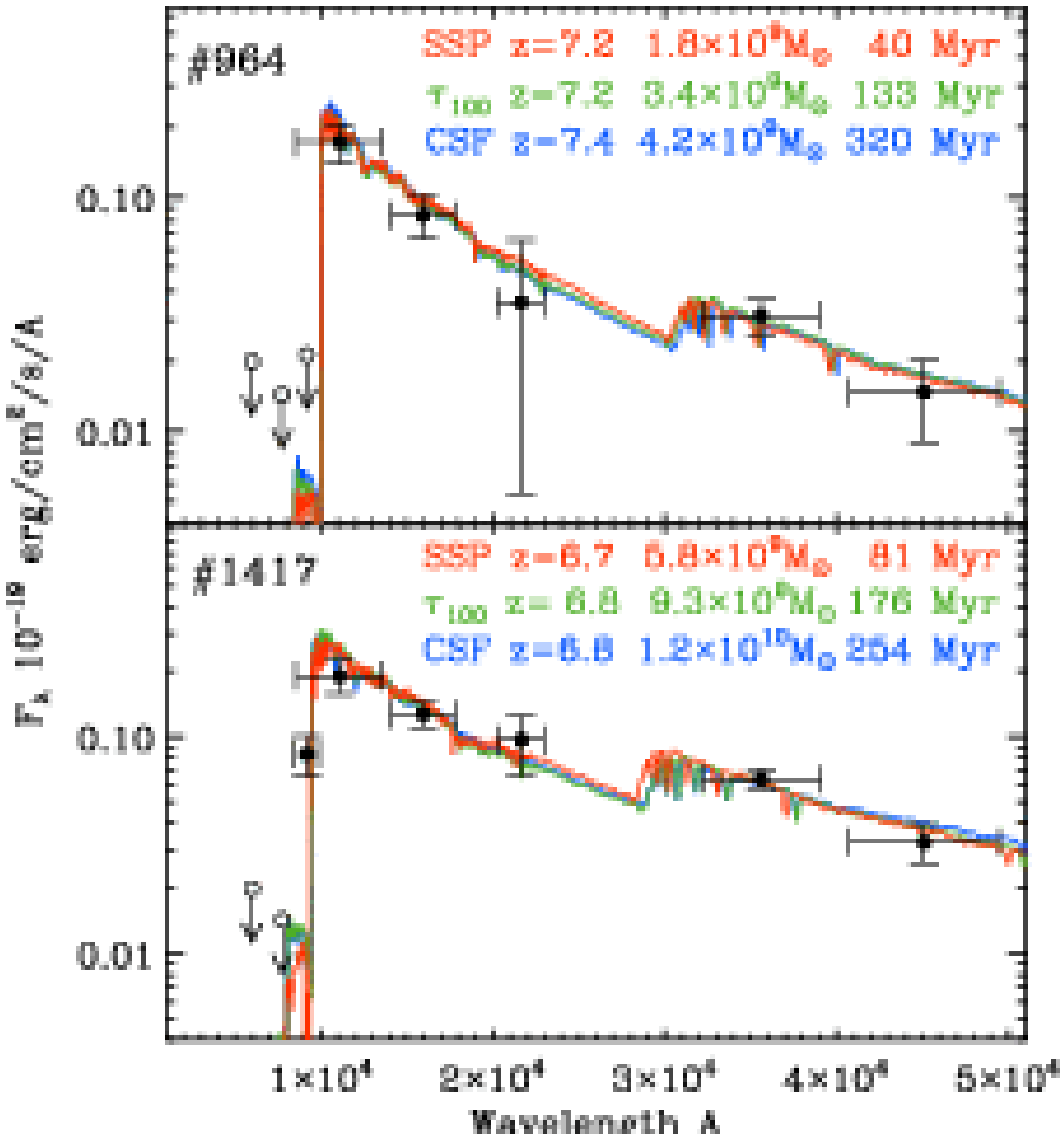
6.6 kpc:
Large Scale Structure:
-1.81 -0.34 1.14 2.62 4.09
0.56 1.33 2.11 2.88 3.66
660 pc:
Protogalaxy:
-1.36 0.78 2.92 5.06 7.20
Temperature
0.71 1.46 2.21 2.96 3.70
Tom Abel
Harvard Smithsonian CfA

Opportunity

- A liquid mirror telescope on the moon offers the opportunity to go super-deep in the IR.
- This is well matched to the study of very-high redshift galaxies and perhaps even the first stars.
  - Must cover down to 1.5 μm or bluer to see Ly alpha dropout.
  - Probably need to reach at least to 4 μm.
  - First objects are very faint: 10 picoJy or less in the continuum.
  - 20-meter telescope could reach early galaxies 100 times smaller than JWST.
  - Should consider spectroscopy of z>10 "JWST" galaxies (few nanoJy).

Why infrared is required – universe opaque below 90 nm wavelength

- We'd like to study galaxies in the rest-frame optical and UV, say 0.12–1 micron, but the light from distant galaxies has its wavelength stretched by the expansion of the Universe.
- At z>7, all of the galaxy's light is in the IR.
  - No light passes shortward of 0.1216(1+z) μm.



Labbe et al. (2006)

Dan Eisenstein tasks

- Gathering the primary science drivers in the various regions of parameter space.
  - First stars/galaxies/supernovae.
  - Imaging vs. Spectroscopy vs. Narrow-band Imaging
  - Beyond objects: can we see fluctuations in the unresolved light from scattered Lyman alpha?
- Paying particular attention to the very high-redshift Universe: first stars and first galaxies.
  - Planning to run cosmological hydro simulations to extend work at z~8 up to higher redshift, leveraging in-house tools and expertise.
  - Study gas aggregation, star formation, and cosmic web as a function of model parameters.

IR limit vs mirror temperature

Maximum wavelength for which observations will be limited by zodiacal sky background, as a function of mirror surface temperature.

Emissivity of 1% by the spinning liquid mirror is assumed

Sky background includes both thermal emission and sunlight scattered from zodiacal particles.

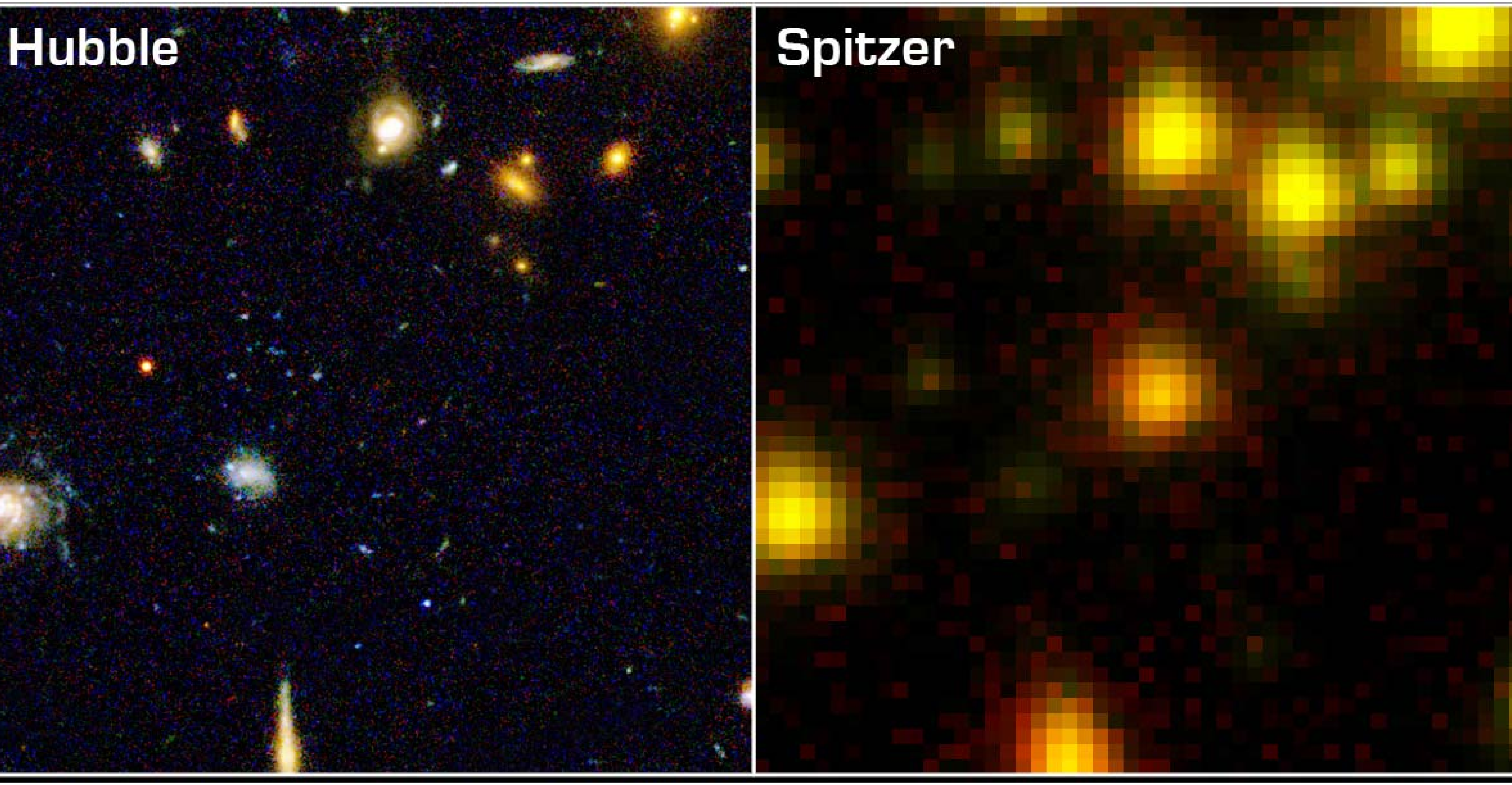
T (K)	λ max (μm)
80	11.0
100	8.0
120	5.8
140	4.7
160	4.0
180	3.5
200	3.1

Target temperature ≤ 150K

Need for very large aperture

- Lunar telescope would go to the next level of sensitivity, beyond HST and JWST
- JWST will be 6.5 m diameter D, cooled infrared telescope at L2, with longest integrations of t~ 1 month
- Lunar telescope should have D > 20 m and integrate for many years
- Sensitivity as D2√t: compared to JWST
  - 20 m for 1 year will be 30 times more sensitive
  - 100 m would be 1000 times more sensitive
  - Virtually impossible by rigid mirror technology

Diffraction limit advantage
20 m at 5 μm = 2.4 m at .6 μm



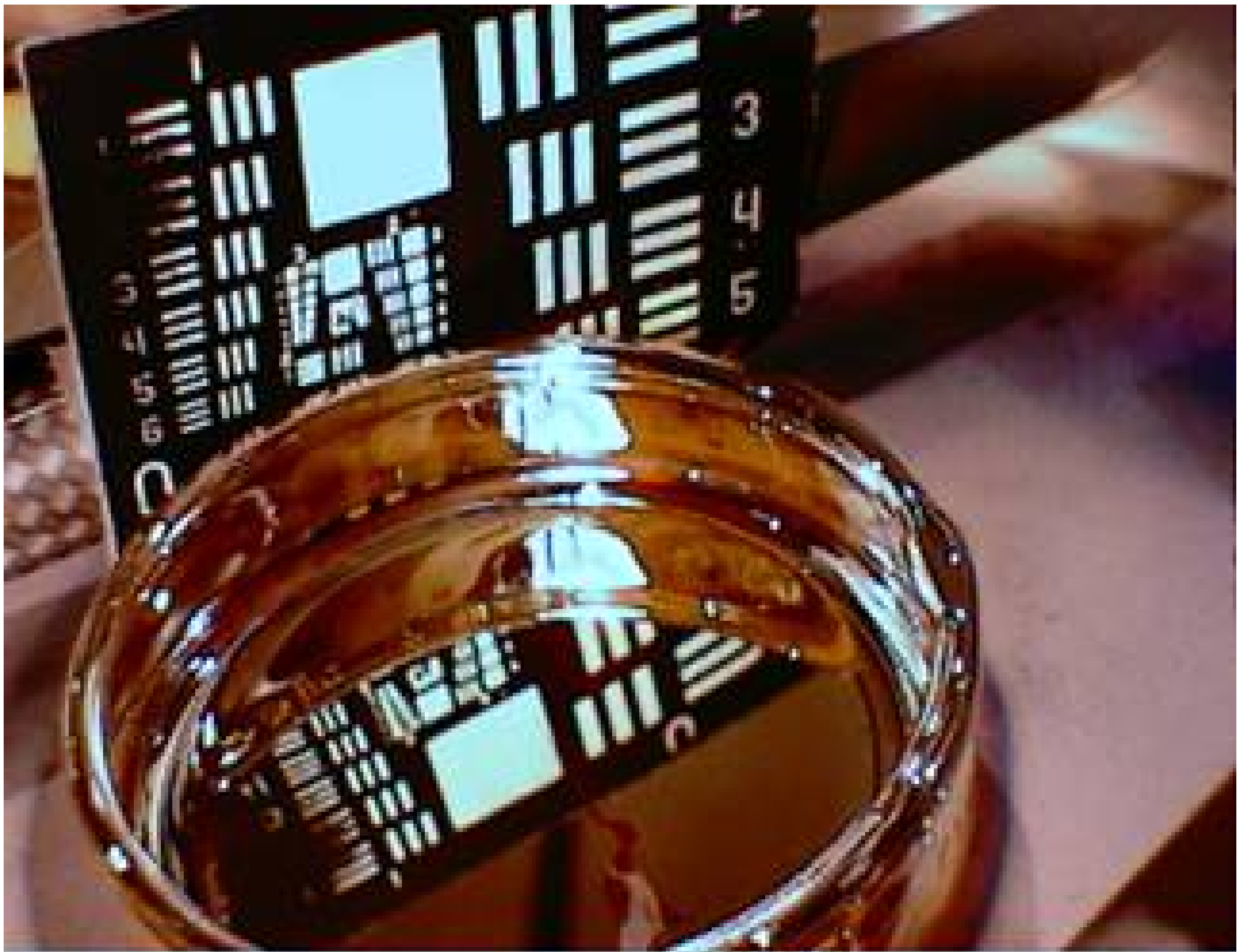
Designs of increasing size

Mirror Diameter (m)	2	20	100
Mirror area (m2)	3	300	7600
Primary mass (tons)		1	50
Total mass (tons)	0.5	3	100
Field	3.1° annulus	15’	3’
Diffraction limit @ 1mm	0.1 “	0.01”	0.002”
Pixels @ 2mm (Nyquist)	18,000/°	45,000	45,000

Cold reflective liquid surface?

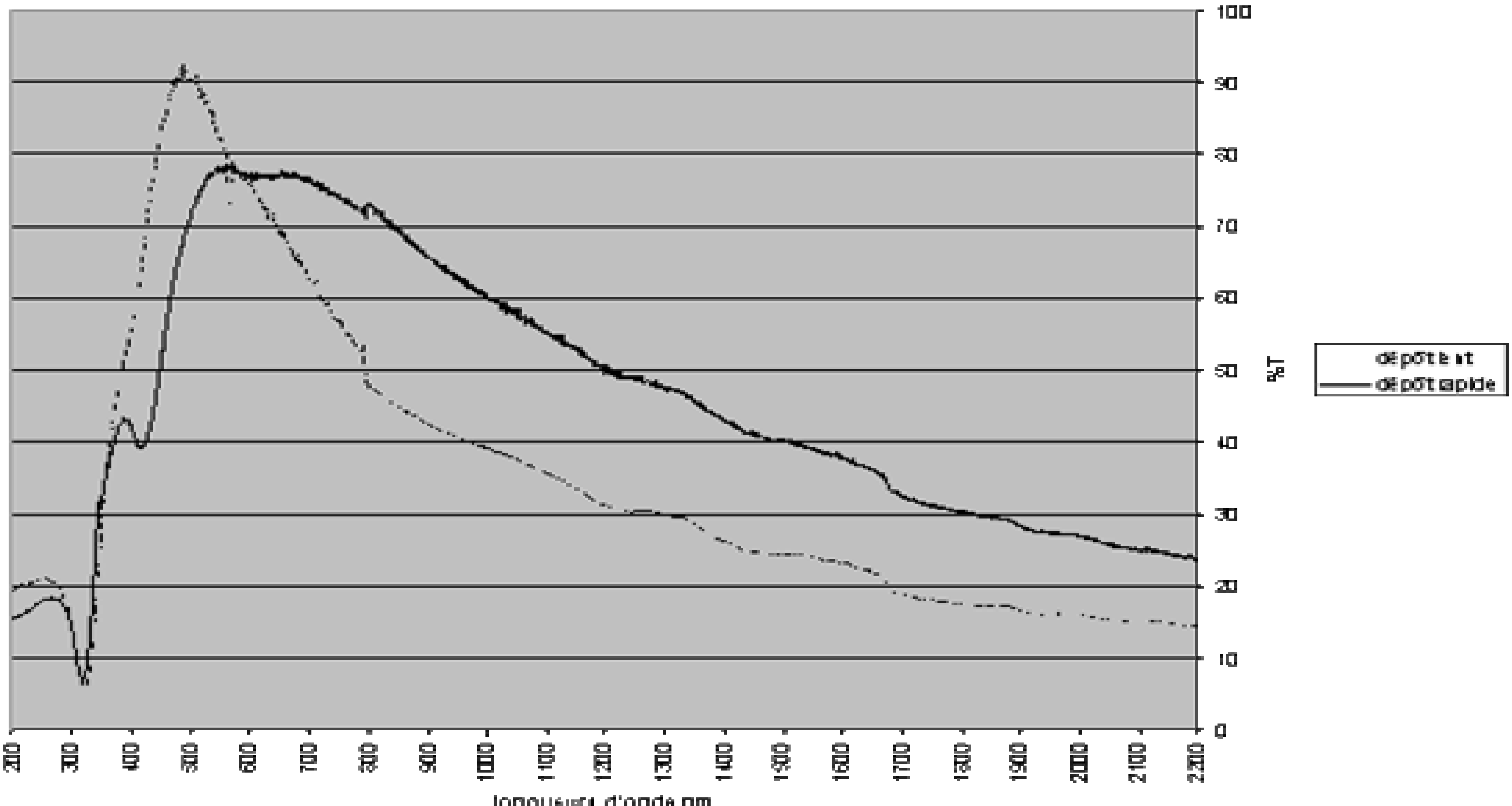
- Critical issue
- Mercury frozen at 150K
- Need to evaporate metal on cryogenic dielectric liquid
- Will this work?

Early try - mirror surface of silver on polypropylene glycol deposited by Borra



Ag on PPG-PEG-PPG

- Increasing deposition speed increases reflectivity in near IR (200 to 2200 nm)

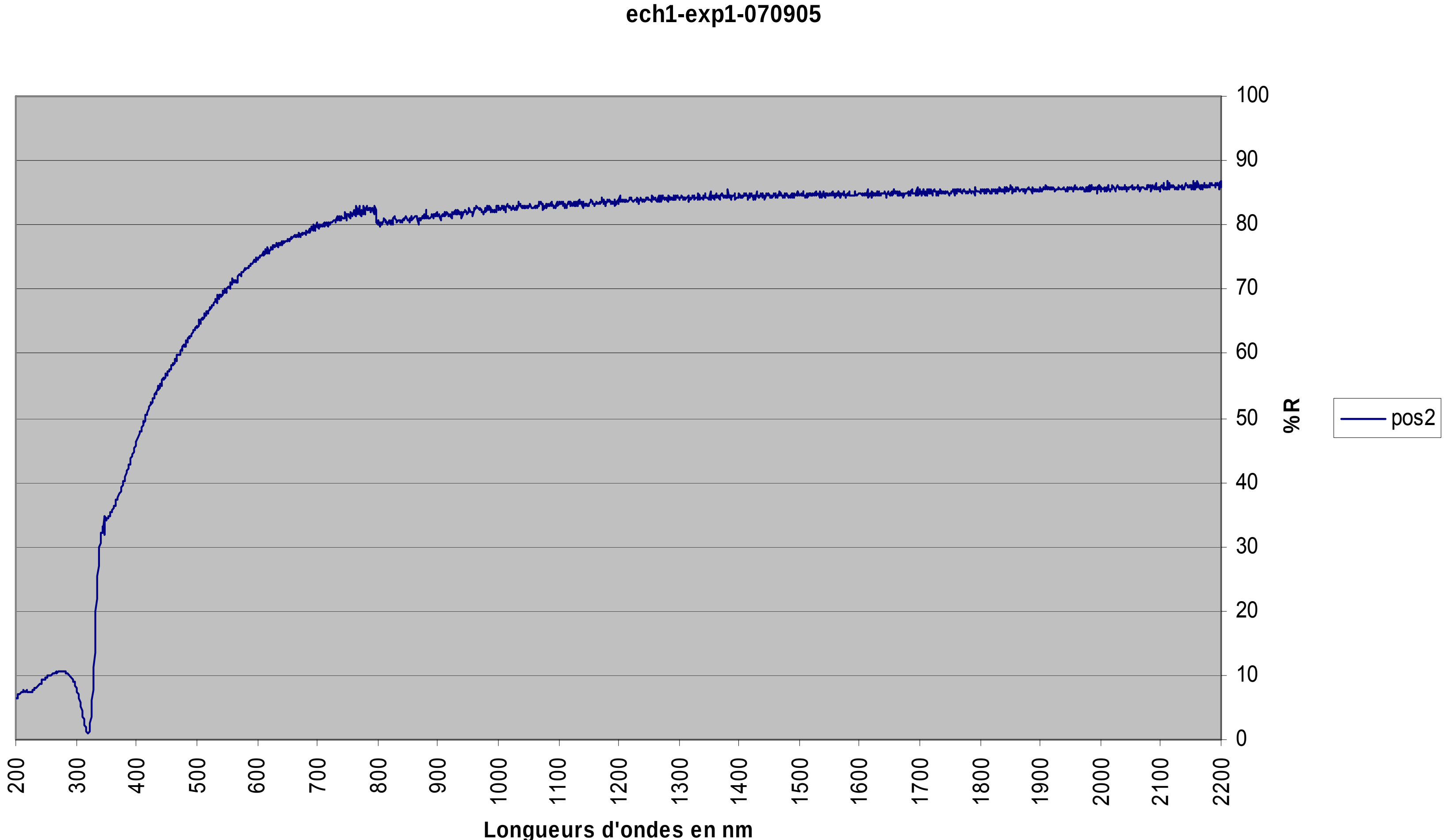


ionic liquids - Prof Ken Seddon

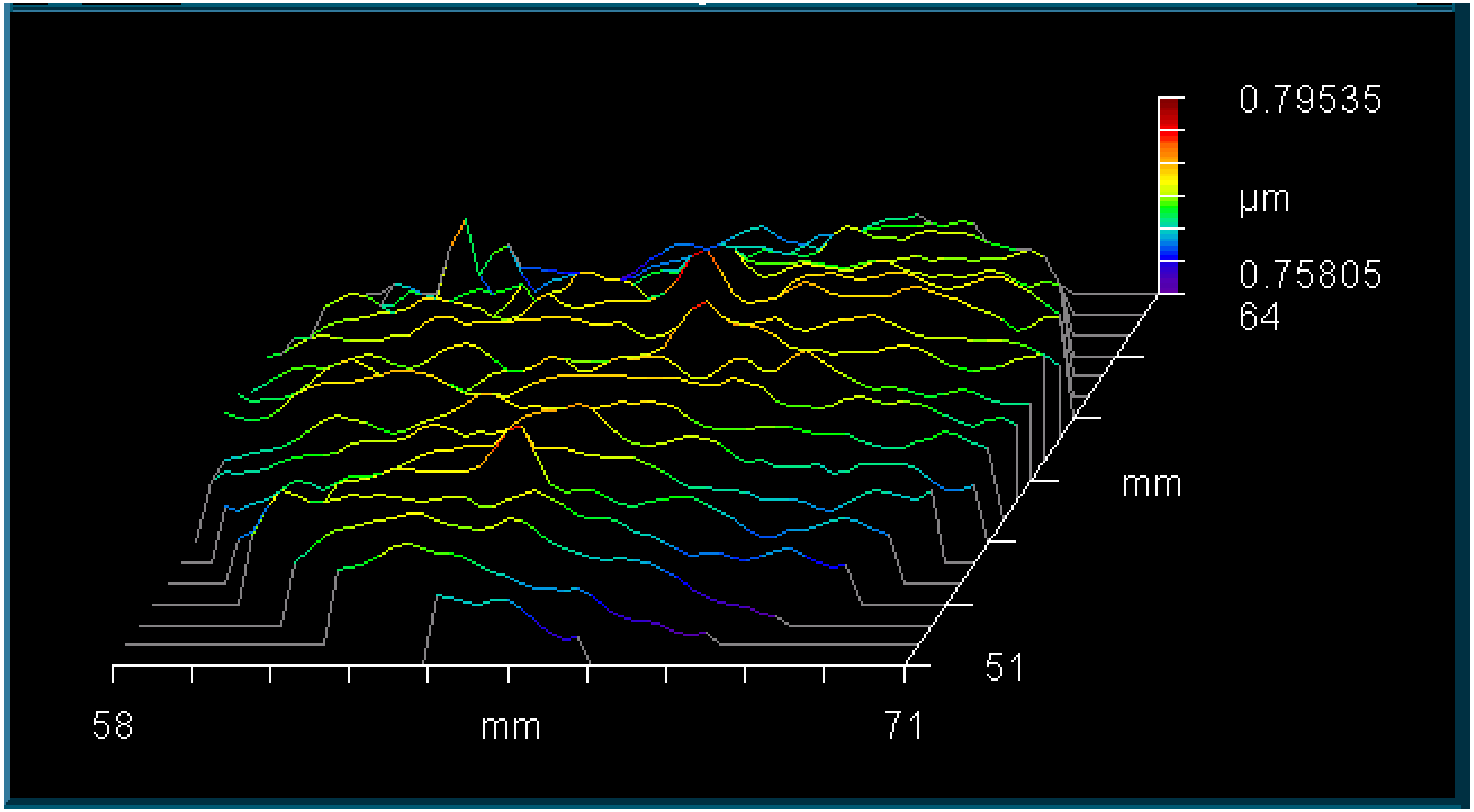
- Ionic fluids preferred
  - Low vapor pressure
  - Low melting T < - 100 C
- Very active field of research
  - Like liquid salt, except anions and cations big and organic
  - Application for vapor free solvents in chemical manufacture (Change physical properties by changing anions and cations: huge number of possible liquids (Billions!)

Take silver well
Borra results for Ag on ECOENG212

Best reflectivity in near IR for Ag



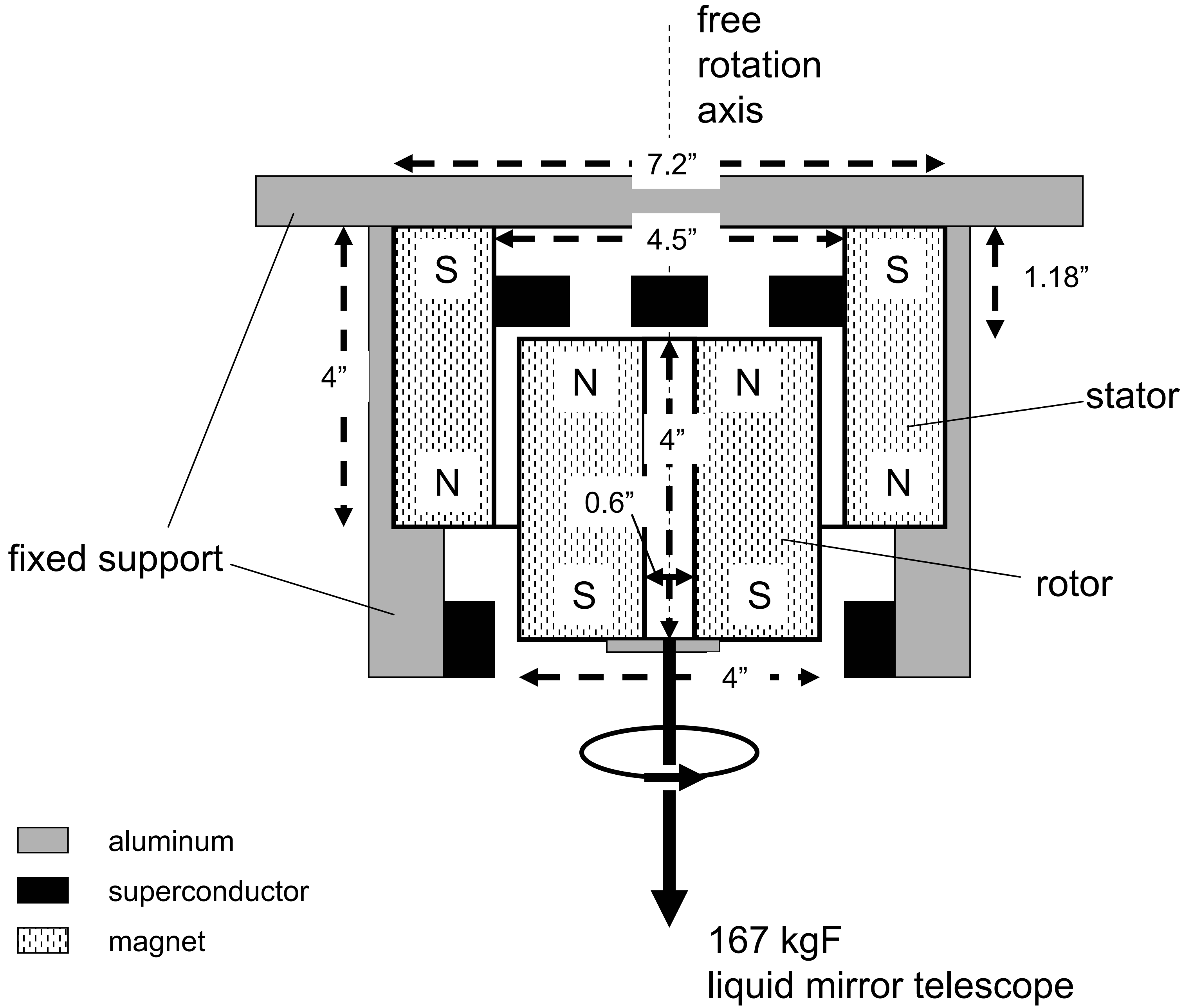
Interferometry (P-V = 0.04 microns)



Superconducting bearing- not disturbed by dust

- model with spinning liquid mirror on a superconducting bearing by Professor Ma. (a) shows the bearing, with a nitrogen-cooled YBCO superconductor in the upper cup, and a neodymium magnet in the inverted cup below. The gap is ~ 3 mm. Hanging on 3 strings below (b) is a 20 cm spinning dish of black soy sauce with ~ 8” focal length. The lettering is the reflection of a screen above


free
rotation
axis
7.2”
4.5”
1.18”
S
S
4”
N
N
N
N
4”
stator
N
N
0.6”
fixed support
S
S
rotor
4”
aluminum
superconductor
magnet
167 kgF
liquid mirror telescope

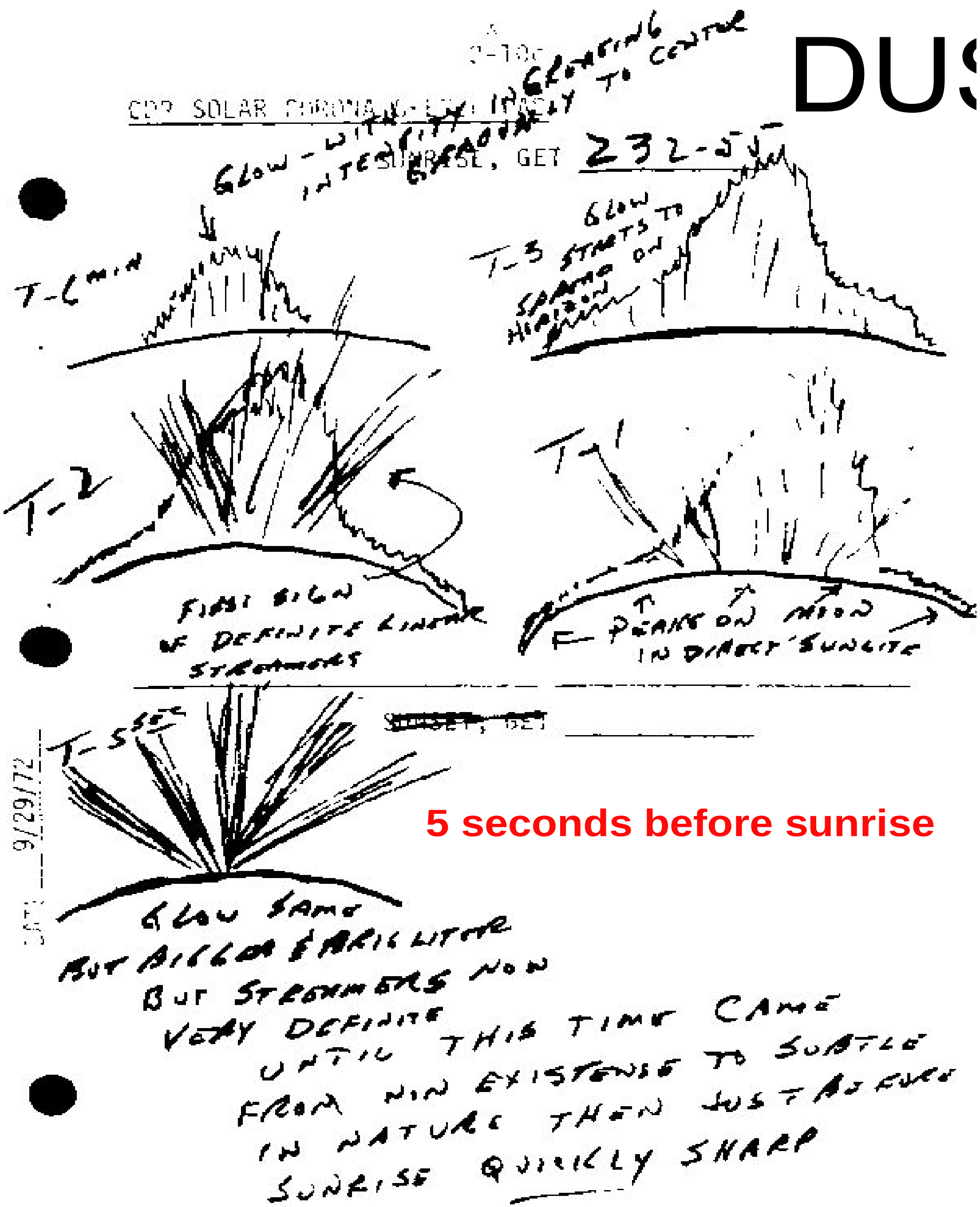
Superconducting bearing design (Prof Ki Ma)

	model	Simple scale up	Optimized design
Mirror diameter	0.2 m	20 m	
mirror mass	0.18 kg	1000 kg	
Mirror weight	0.18 kgF	167 kgF	
YBCO diameter	25 mm	0.75 m	1 m
YBCO thickness	12 mm	0.36 m	0.025 m
superconductor mass	0.055 kg	1.53 tons	0.2 tons
Total bearing mass	0.085 kg	2.4 tons	0.3 tons

Will dust be a problem?

- Dust levitated ~ 1 meter by electrostatic force, well established from surface measurements
- Dust to ~ 10 km?
  - Atmospheric glow seen occasionally from Apollo command module
  - Not confirmed by Clementine

DUS



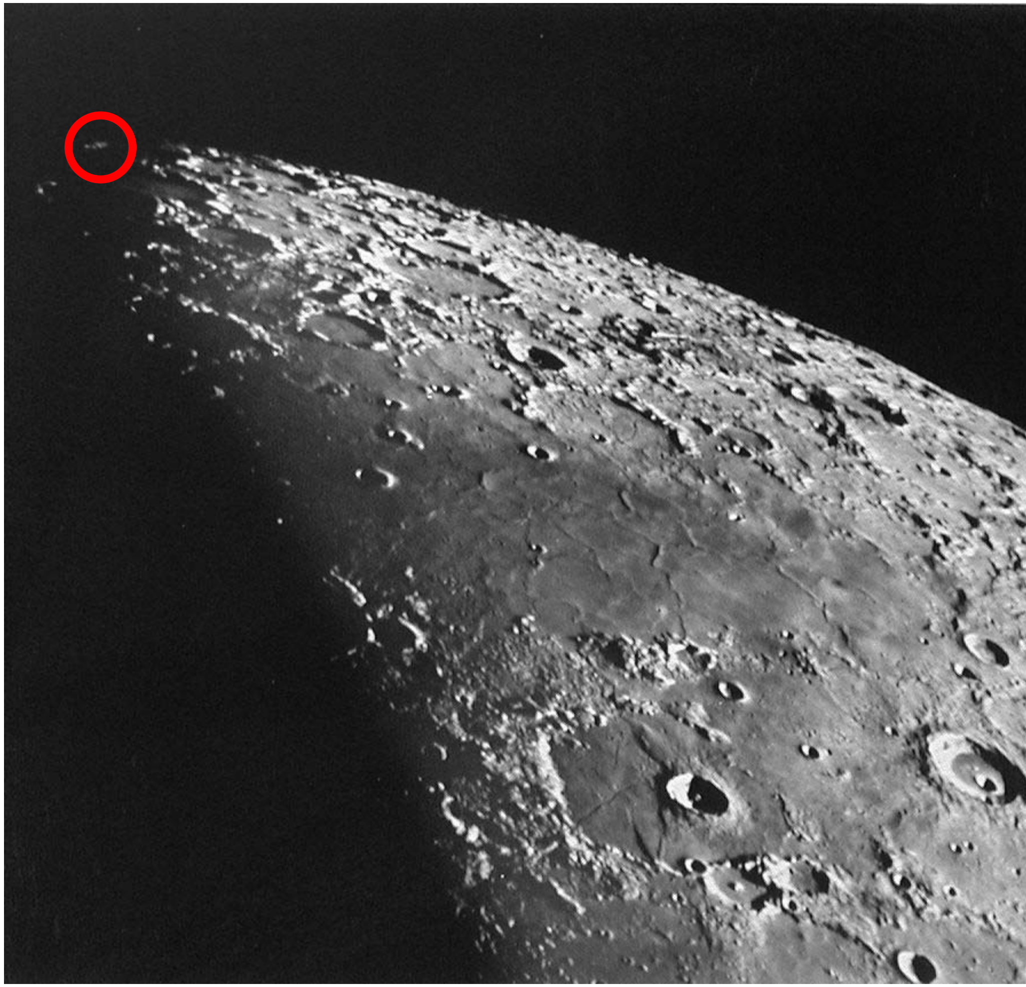
5 seconds before sunrise

Sketch by Apollo 17 captain Cernan

Best seen with back illumination - Small angle scattering illustrated by Monet

Sivanandam planning ground-based adaptive optics imaging

- Require guide star for wavefront measurements. Use high illuminated peaks on the dark side
- Image small 30” region above the polar surface in the 1.6 micron band and of the polar region itself in 5 micron band.
- 100s of meter resolution imaging
- Will attempt this measurement later this year

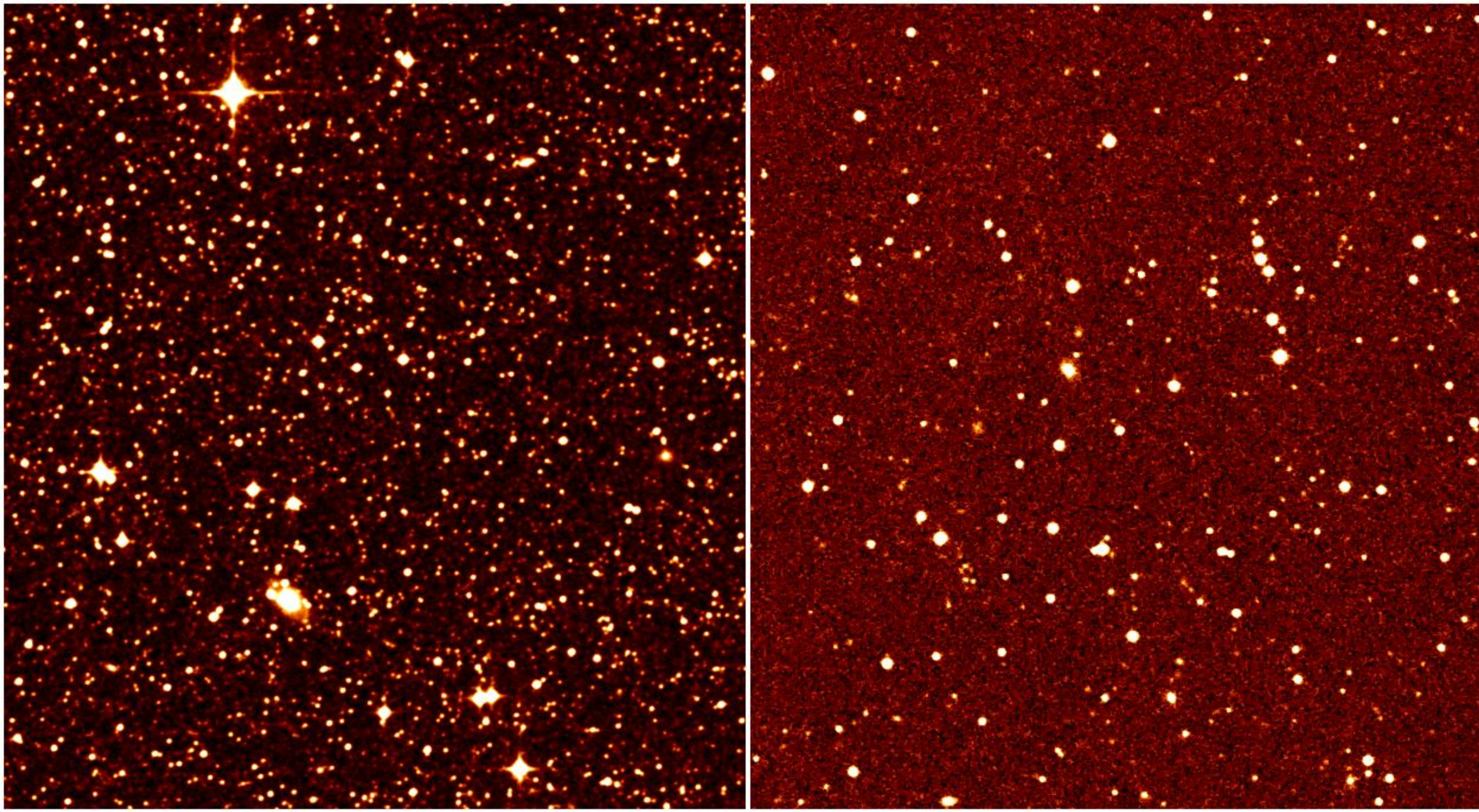


8.66 micron image of Moon [Lawson et al. 2003]

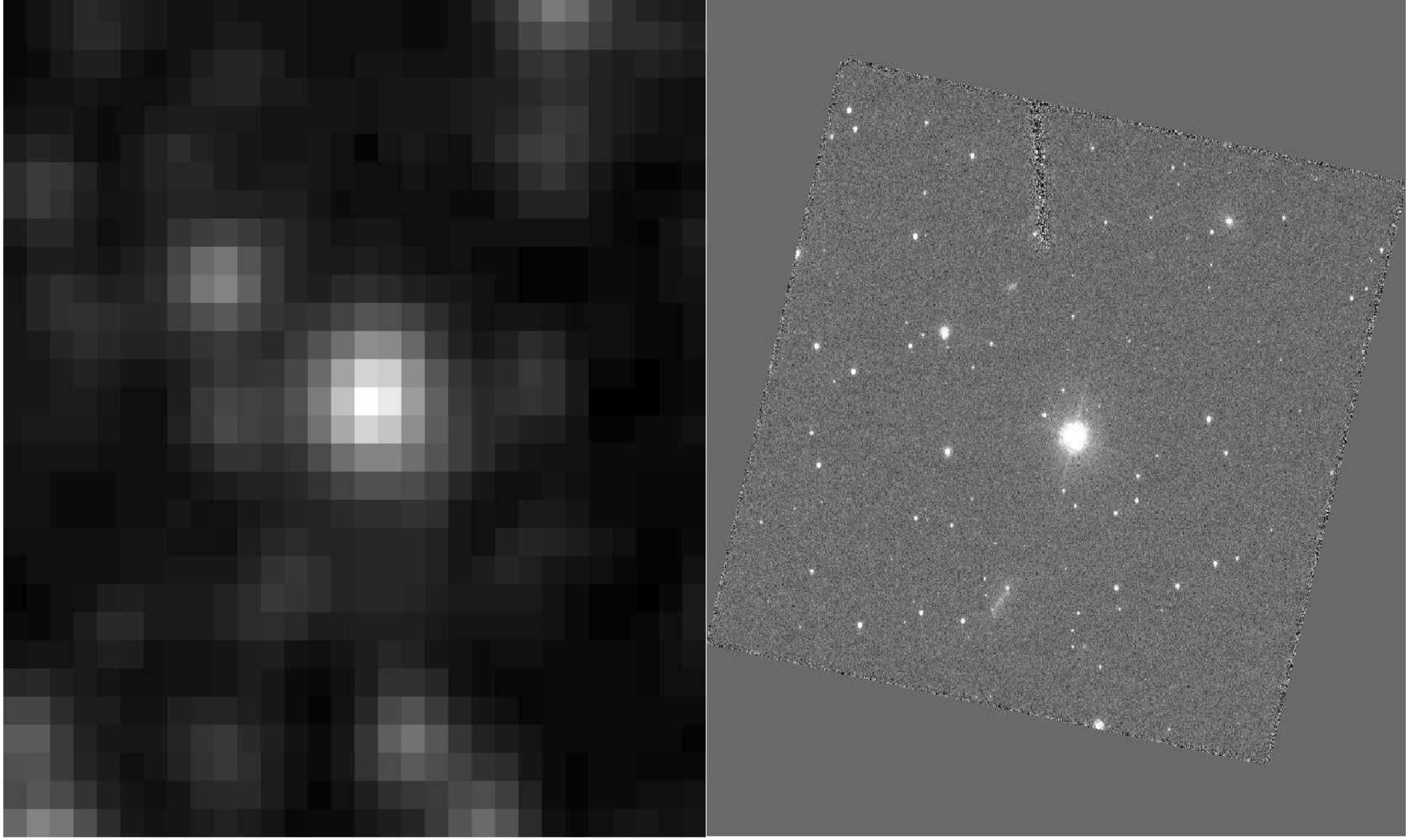
Location – near lunar pole

- Zenith view fixed on sky along spin axis
- Deep integration with no steering
- Strong radiative cooling for high infrared sensitivity possible
  - Use cylindrical radiation shield
  - Shields from sun always on horizon

Comparison of N and S ecliptic poles

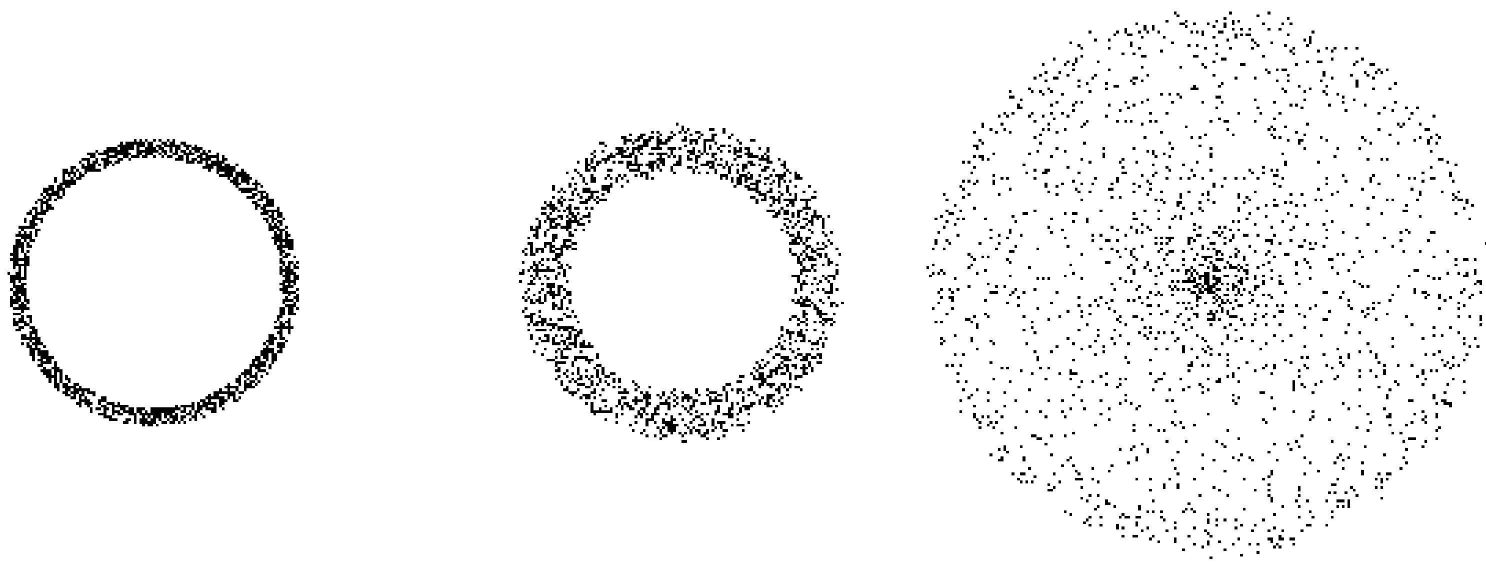


Schmidt survey photographic R-band images: Left – South Pole view; Right – North Pole view. R_{limit} = 21; FWHM = 2”; FOV = 12’×12’.

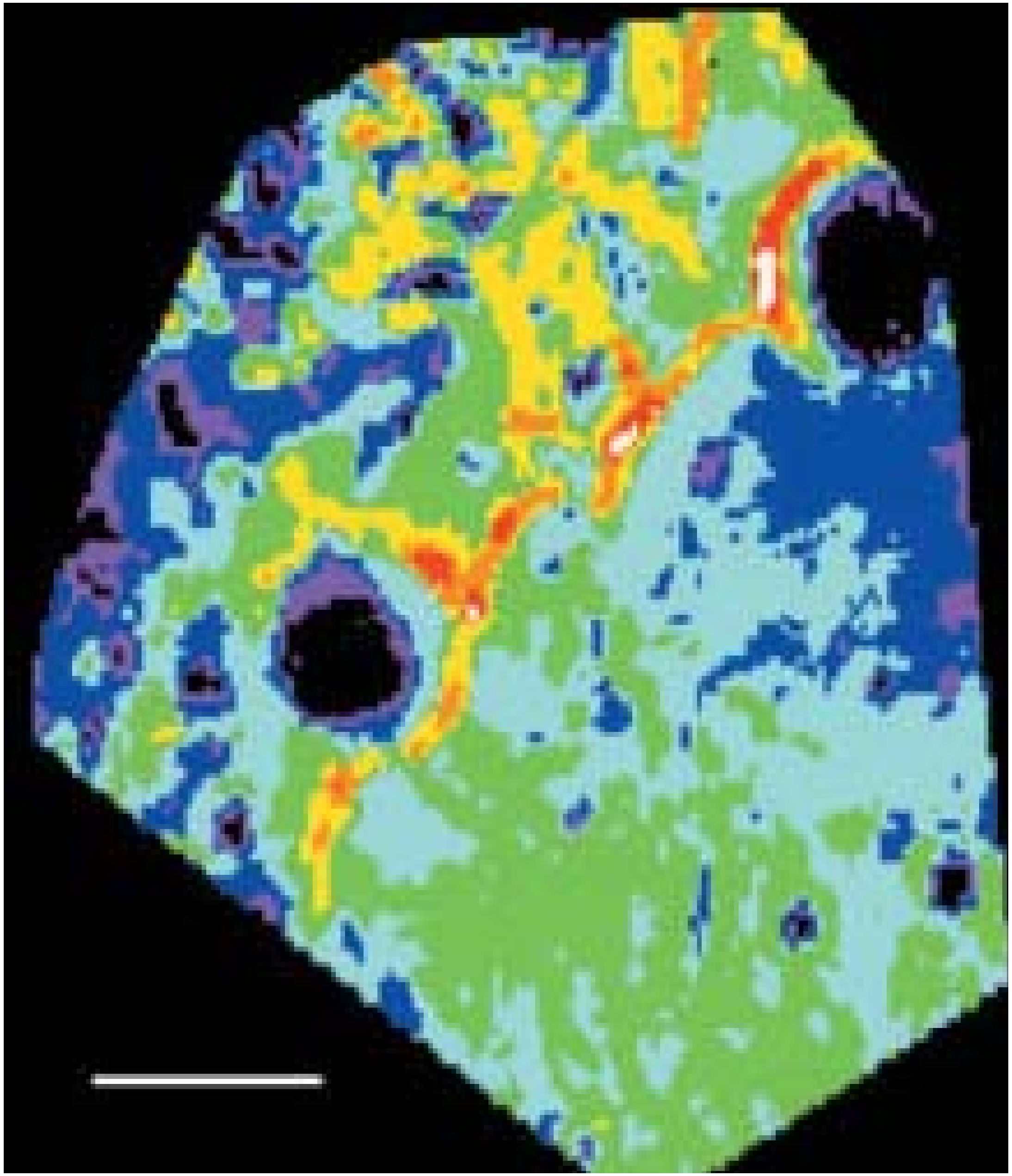


Detailed images of a field (30”×30” in size) close to the South ecliptic pole. Left: Schmidt survey image of field. Right: HST image of the same field, with stars resolved out at limit of V=26.

Effect of location on sky access for a zenith-pointed telescope with 0.2° field, 18 yr exposure



Left – at the pole, annulus 3.1 ° diameter centered on the ecliptic pole, 5 months on any one spot.
Center – 0.2° from the pole, the field sweeps ½ ° annulus each month, covering any one spot every month for a year
Right – 1.55° from the pole. Each month the field sweeps a 3.1° annulus, covering any spot for about 15 hours. Ecliptic pole seen each month, for total integration of 5 months over 18 years.

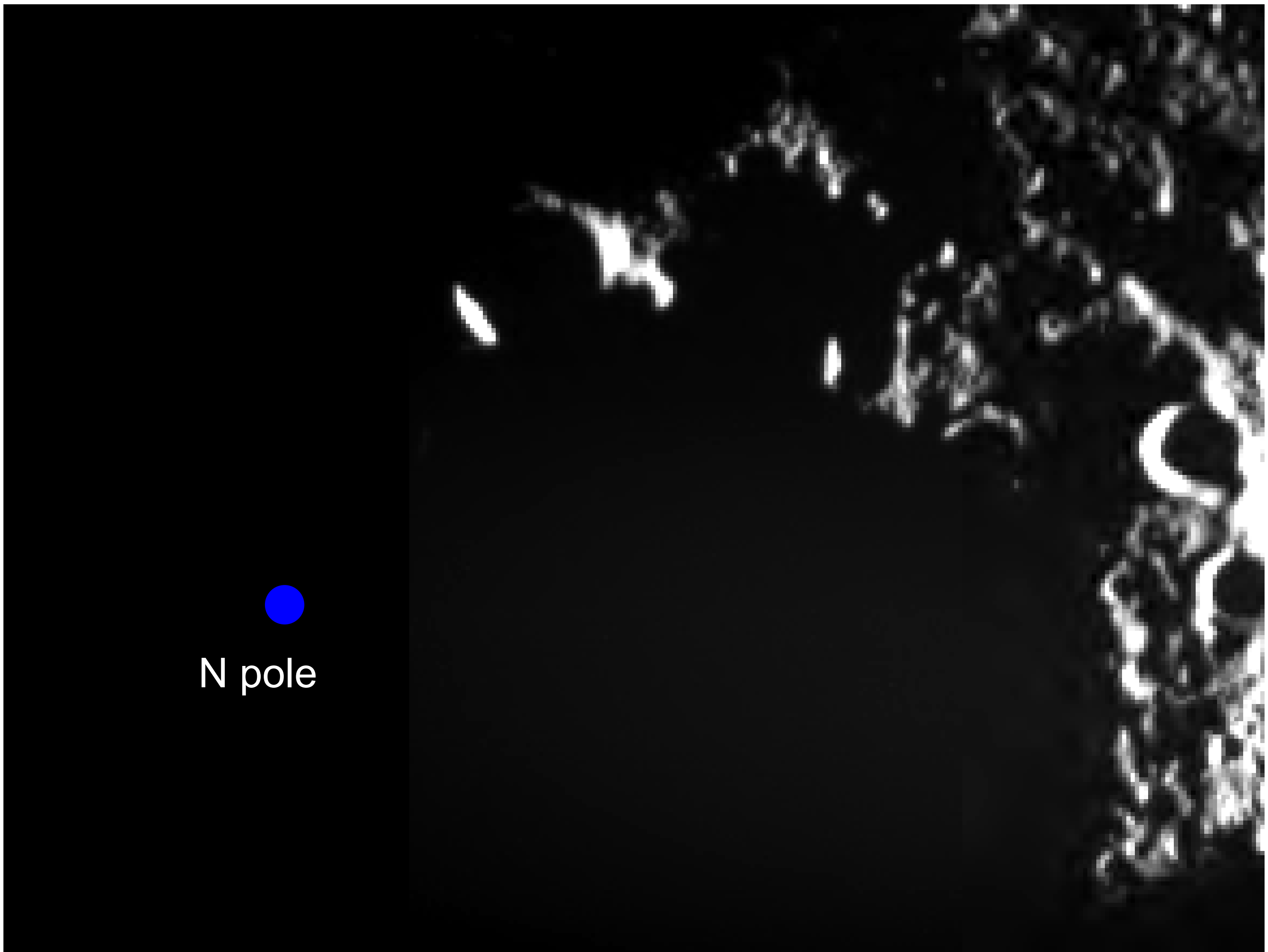


Summertime illumination map generated from Clementine data of the North Pole

The crater located near the 90°E meridian is the encircled crater shown in the SMART-1 image. scale bar on the left is 15 km in length

SMART-1 AMIE image of N pole in mid-winter

the nearest illuminated crater is 15 km distant with 100% summer illumination.



Possible sequence

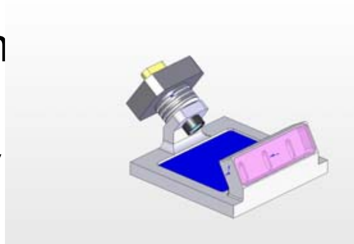
- Micro site survey
- 1.7 m robotic wide field survey
  - Complements Spitzer and JWST
- 20 m
  - Follow up spectroscopy of JWST candidates
- 100 m
  - Completely unique

Planning a small site survey mission – Millenium Space (Tom Svitek)

- Mission objective
  - Collect in-situ data to confirm feasibility of large lunar telescopes
  - Identify any possible compromises or impacts on seeing conditions (primarily dust)
- Mission constraint
  - Lowest possible in-situ dust survey for potential lunar polar telescope site
- Land on polar crater rim that is permanently illuminated
- Nominal mission duration of 1 year (assumes continuous sunlight)
- Payload mass allocation of <10 kg
- Average payload power allocation less than 10 W

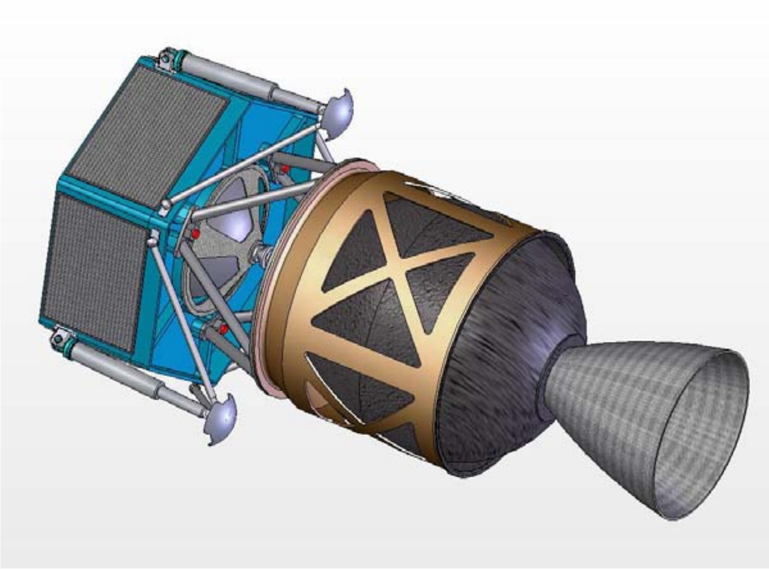
Lunar Site Survey Lander Payload

- **Infrared survey camera (2 kg)**
  - Primary mirror <15 cm, passively cooled optics and FPA (~50 K)
  - 3-5 um, zenith viewing, ~90 deg FOV, no moving parts, 30 cm



- **Visible survey cameras (0.1 kg each)**
  - Full azimuth coverage of horizon w/3 cameras (120 deg FOV
  - IFOV ~1 mrad (?), tolerates continuous solar exposure
- **Liquid coating test plate (2 kg)**
  - Flat horizontal plate, ~100 cm^2 (needs to leveled after landing ?)
  - Assess quality of coating and gradual degradation due to vacuum and dust
  - One-time liquid dispenser
  - Scattered light sensor and optical interferometer (?)
  - Protected by solar panels top edge at 60 cm (TBR) above ground
- **Dust detector at 3 azimuth locations levels and varying height above ground (0.2 kg)**
  - Standard space heritage dust detector design (impact-sensing polymer)
- **Electrostatic potential analyzer (Langmuir probe) (1.5 kg)**
  - Standad technique to measure surrounding electrostatic field intentsity as function of sun elevation and azimuth

Millenium Site Survey Lander Configuration



Lander system after separation from Falcon-1 upper stage

Dust survey payload is integrated on top equipment shelf

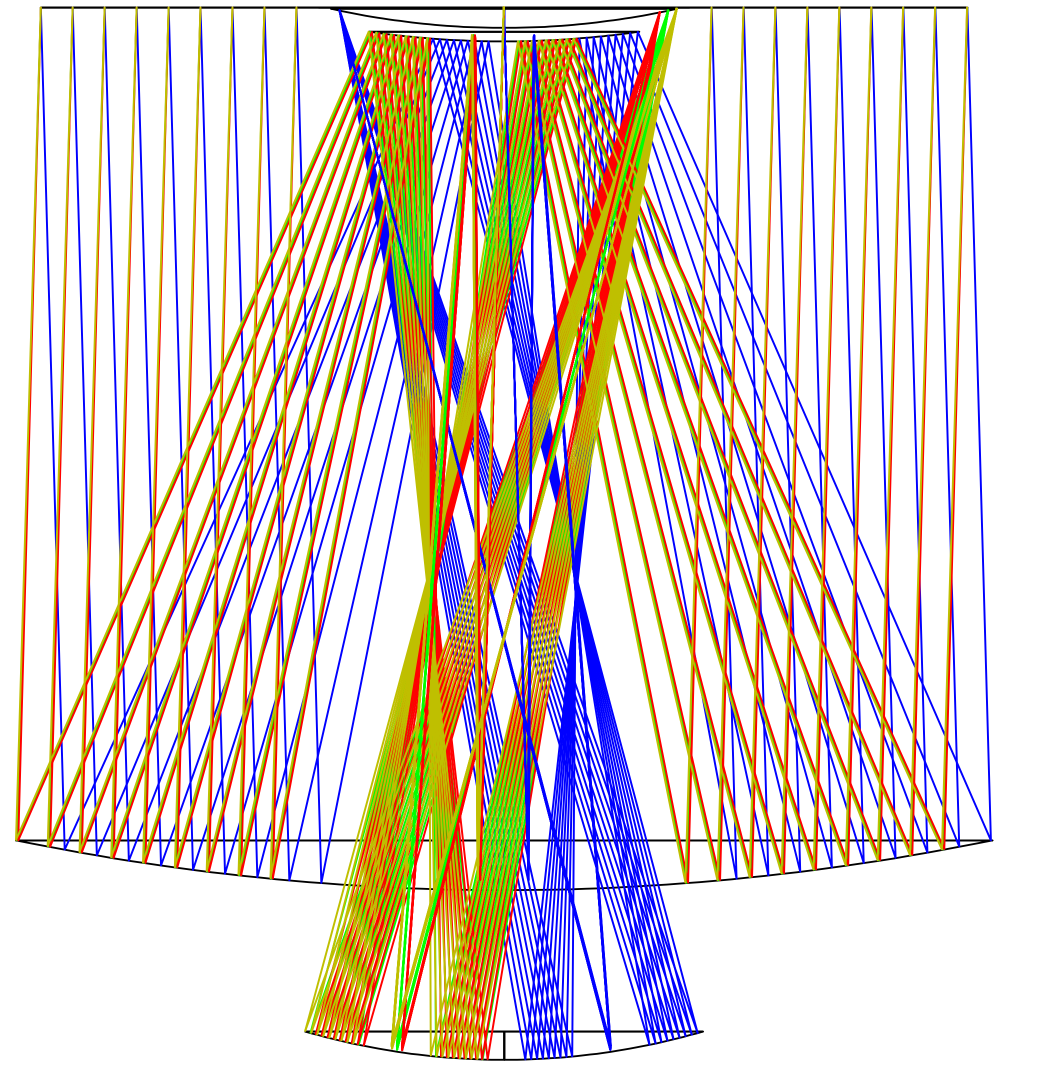
Preliminary Budget

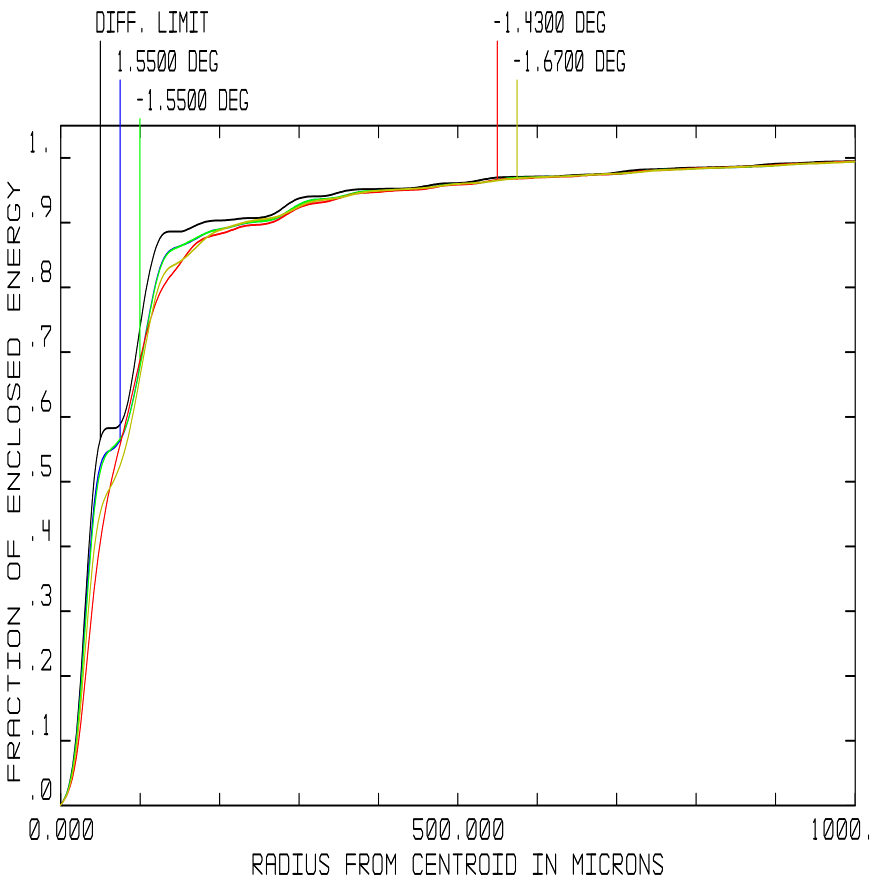
WBS	DESCRIPTION	TOTAL $M
1.0	Lander management	3.5
2.0	Systems engineering	5.8
3.0	Propulsion	11.2
4.0	Lander avionics	12.2
5.0	Lander mechanical	8.3
6.0	Payload	5.0
7.0	Lander I&T	2.1
8.0	Mission operations	1.0
9.0	Launch vehicle	7.0
	Average labor (FTE)	23.7
	Materials totals	33.6
	Grand total	**52.6**

Next mission – wide field survey with 2 m class telescope

3-mirror design for 1.55º annular field

Field angle 1.43 – 1.67°





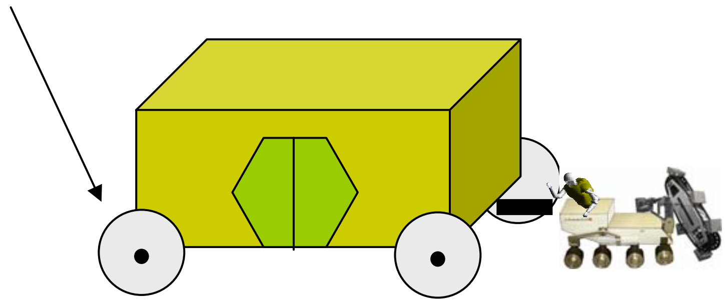
Encircled energy at 2.5 μm (1.7 m)

1.7 m precursor details

- Diffraction limited resolution
  - 0.3 arcsec at 2.5 μm
  - 0.6 arcsec at 5 μm
- 3 degree annular field, 14 minute wide
  - 2 square degrees
  - 4096 x 0.2 arcsec pixels wide
  - 30 square degrees covered during 18 yr precession
- 18 year mission
  - average 2 years integration on typical field point
  - ~2 weeks on each of 40 differently filtered detectors in ring
  - Limiting sensitivity as D2√t, 25x Spitzer in same broad bands (4 of the 40 slots) i.e. 20 nJy at 3.5 μm.

20 m telescope – construction sequence by Paul Susante

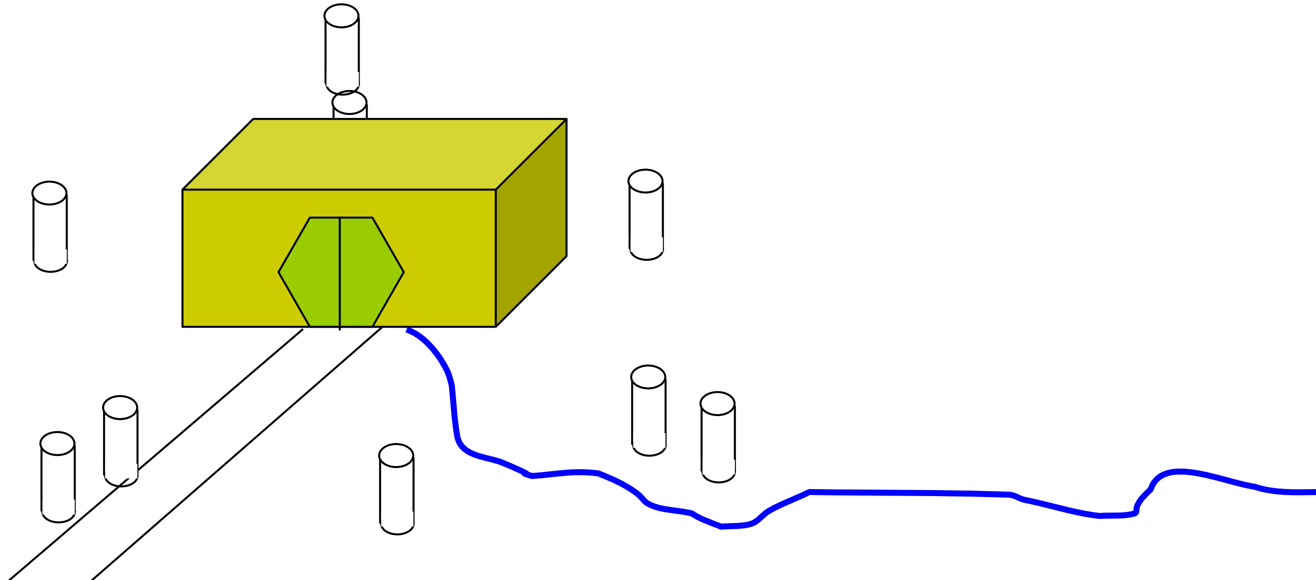
Inflatable wheels

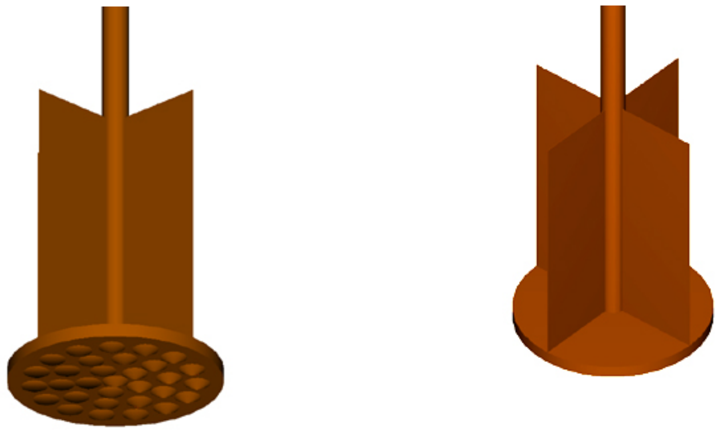


Removal of preloading

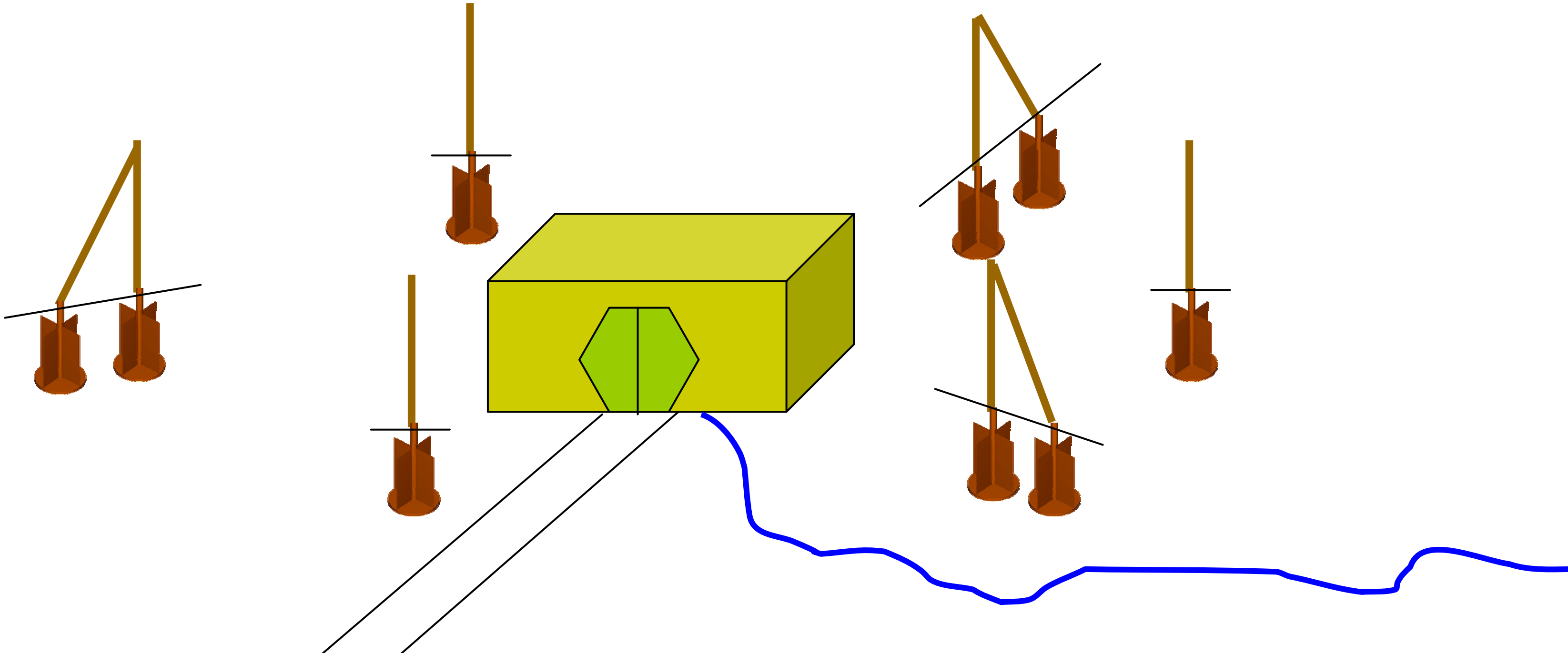
Placement of Instrument housing and telescope base

Connection of power and communication lines





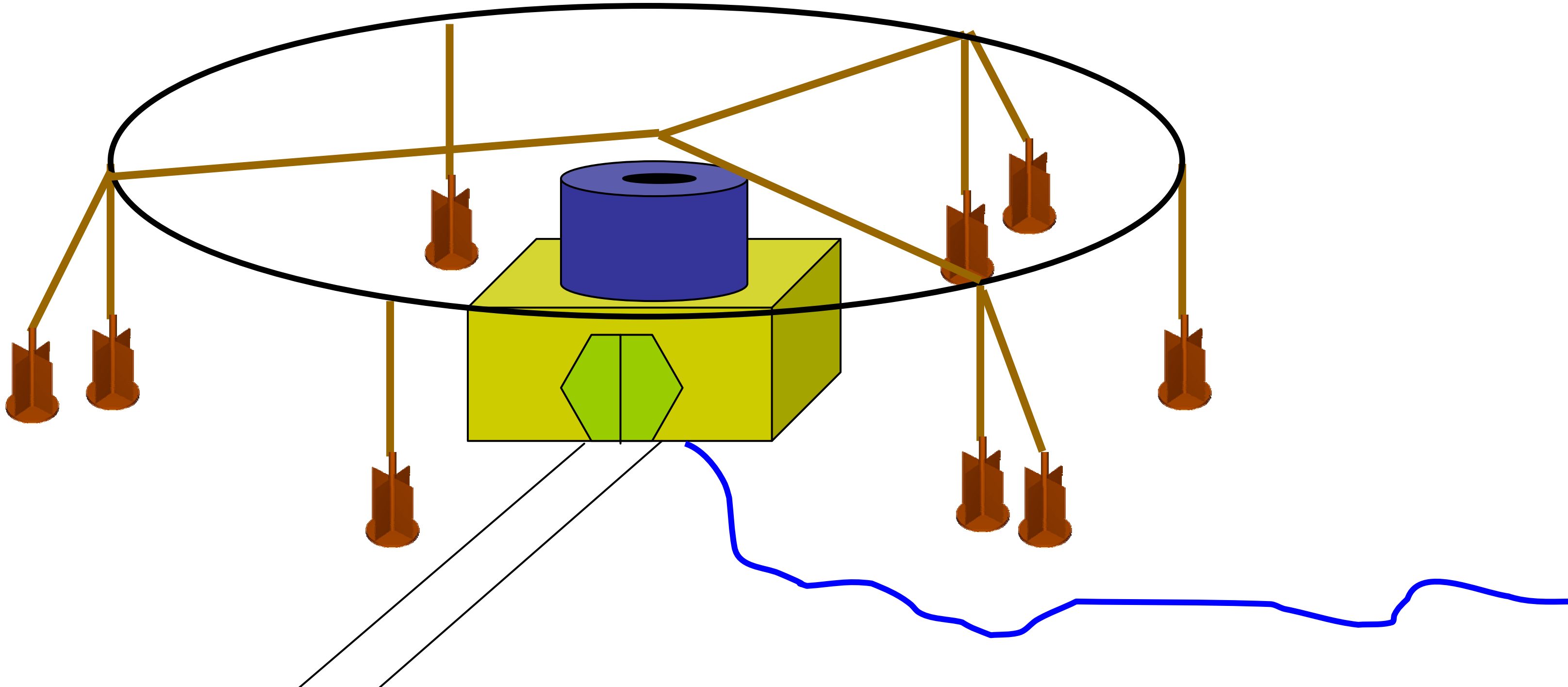
Placement of foundation piles



Placement of shield lower ring supports

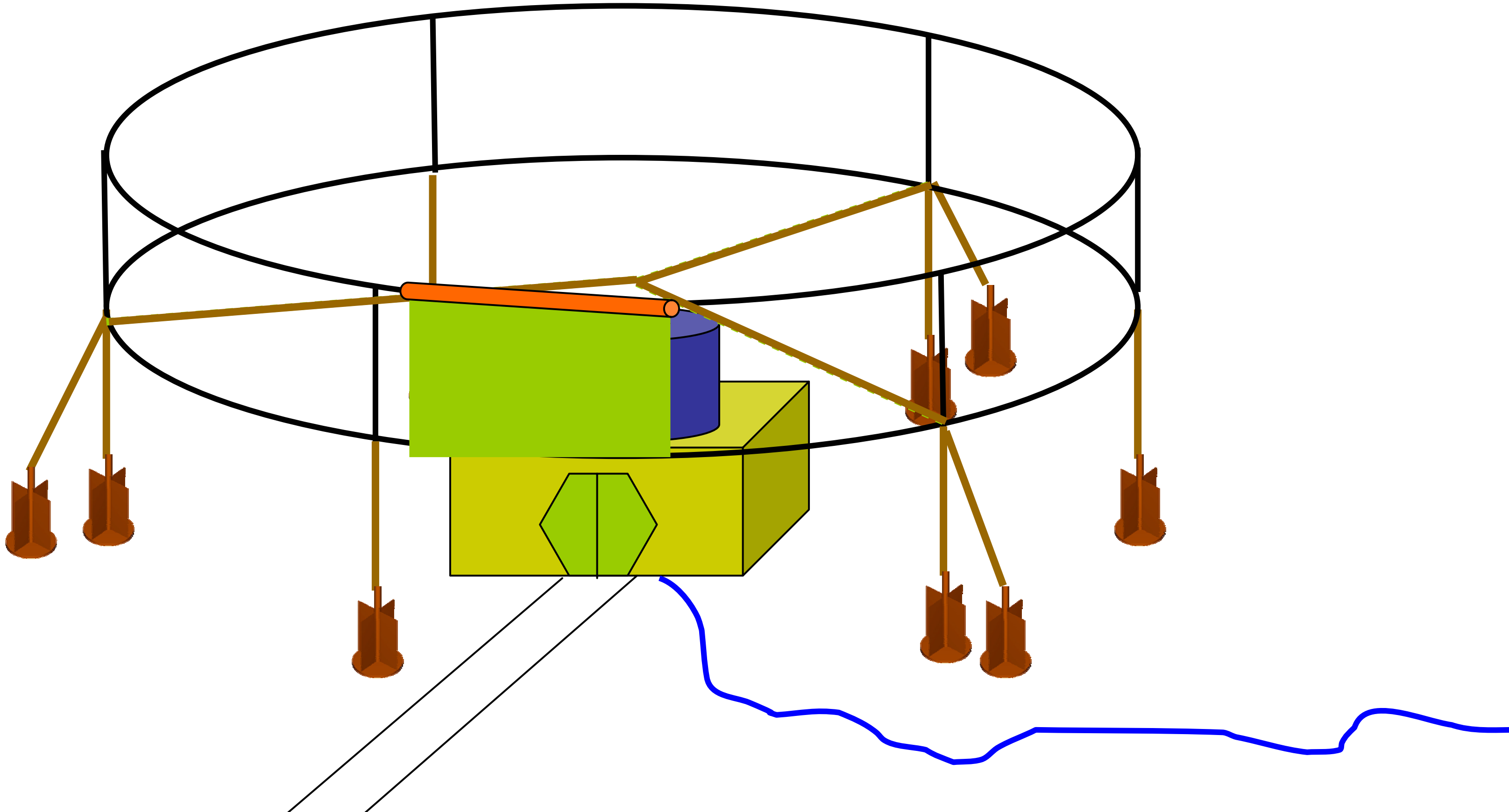
Placement and deployment of telescopic secondary mirror supports

Installation of the superconducting magnetic bearing and housing

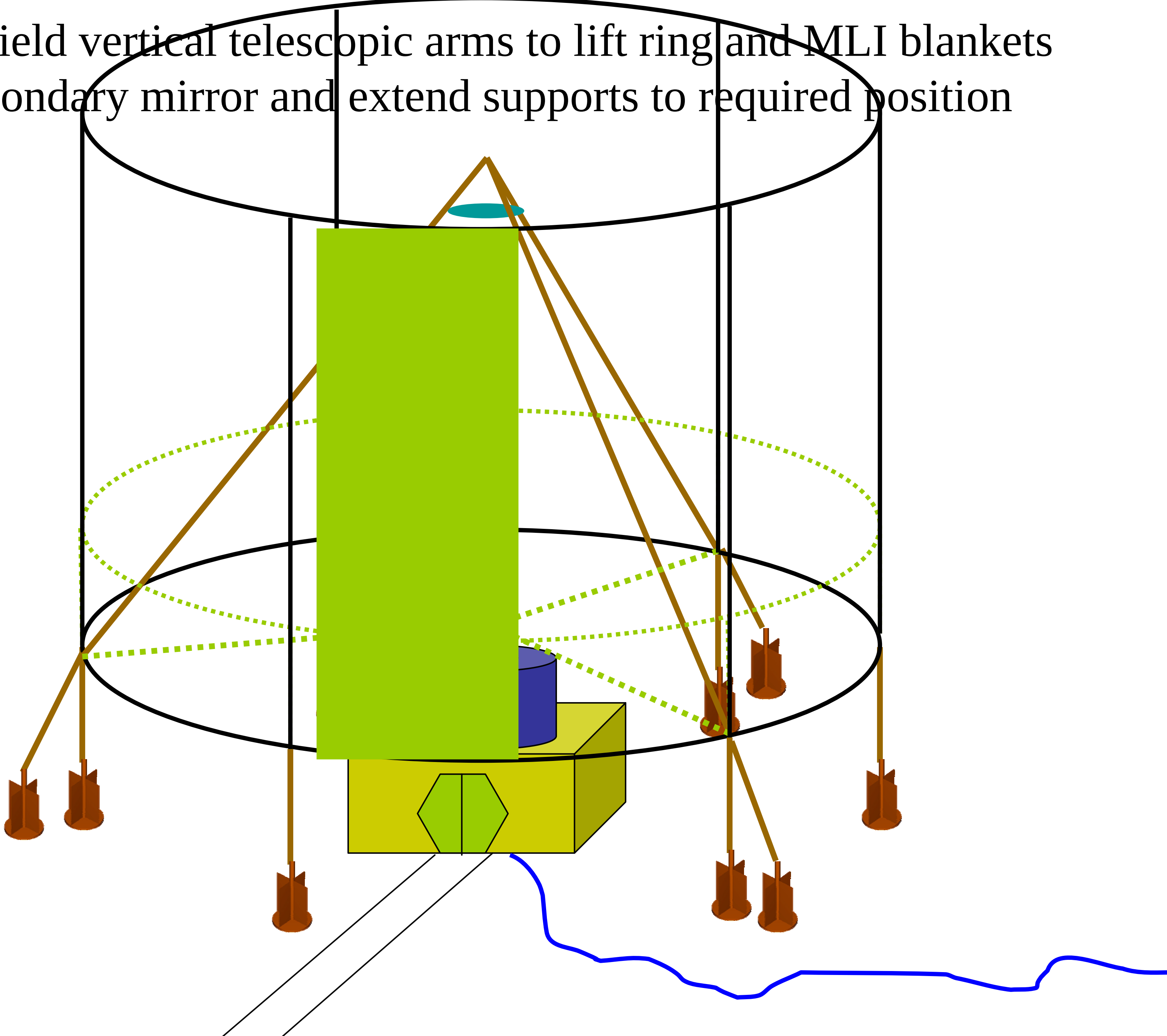


Install vertical telescopic shield supports and top ring
MLI blankets hang from top ring like a curtain, seal connections between blankets

27 rolls of blankets on top



Extend shield vertical telescopic arms to lift ring and MLI blankets
Install secondary mirror and extend supports to required position

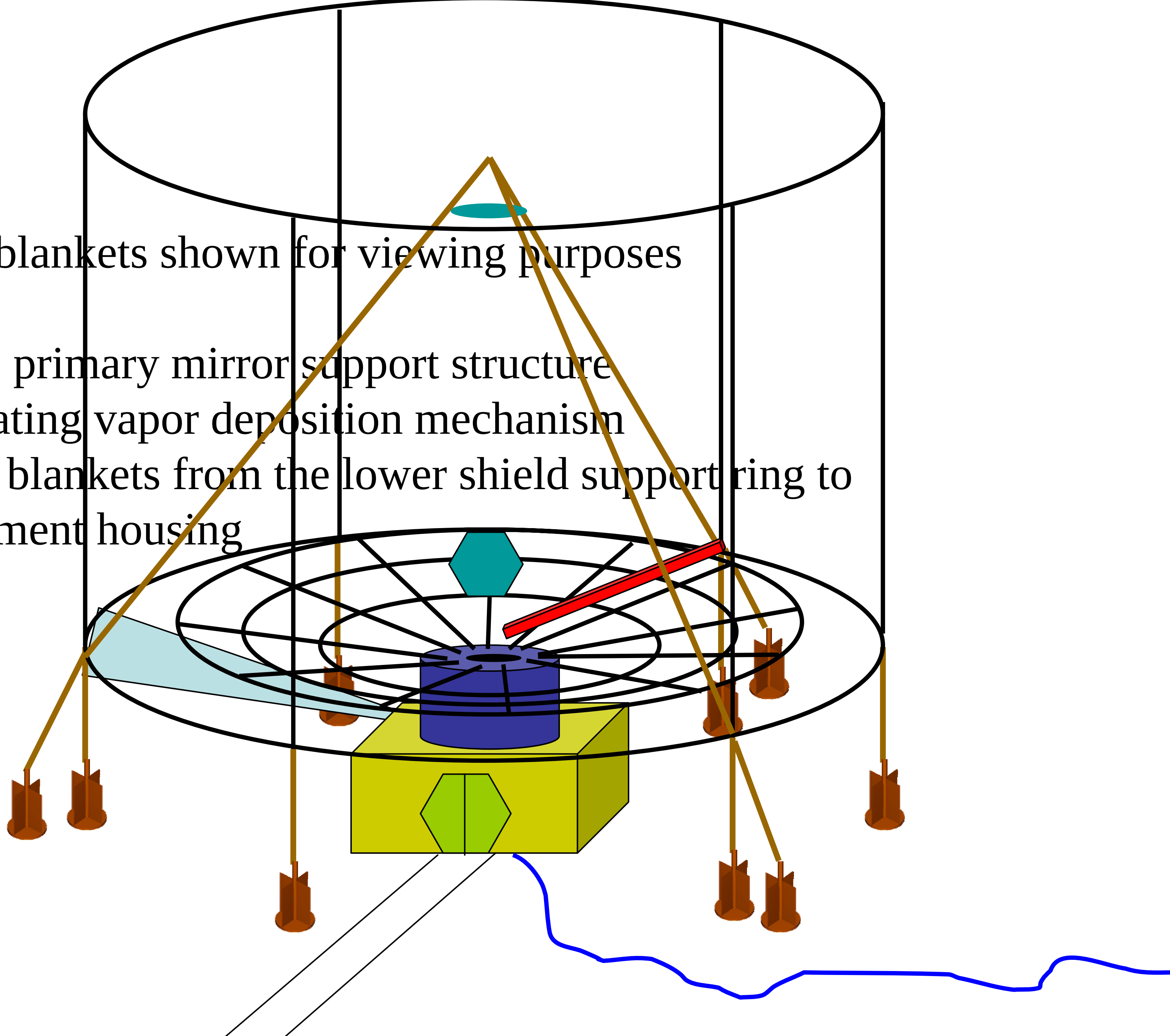


NO MLI blankets shown for viewing purposes

Assemble primary mirror support structure

Install coating vapor deposition mechanism

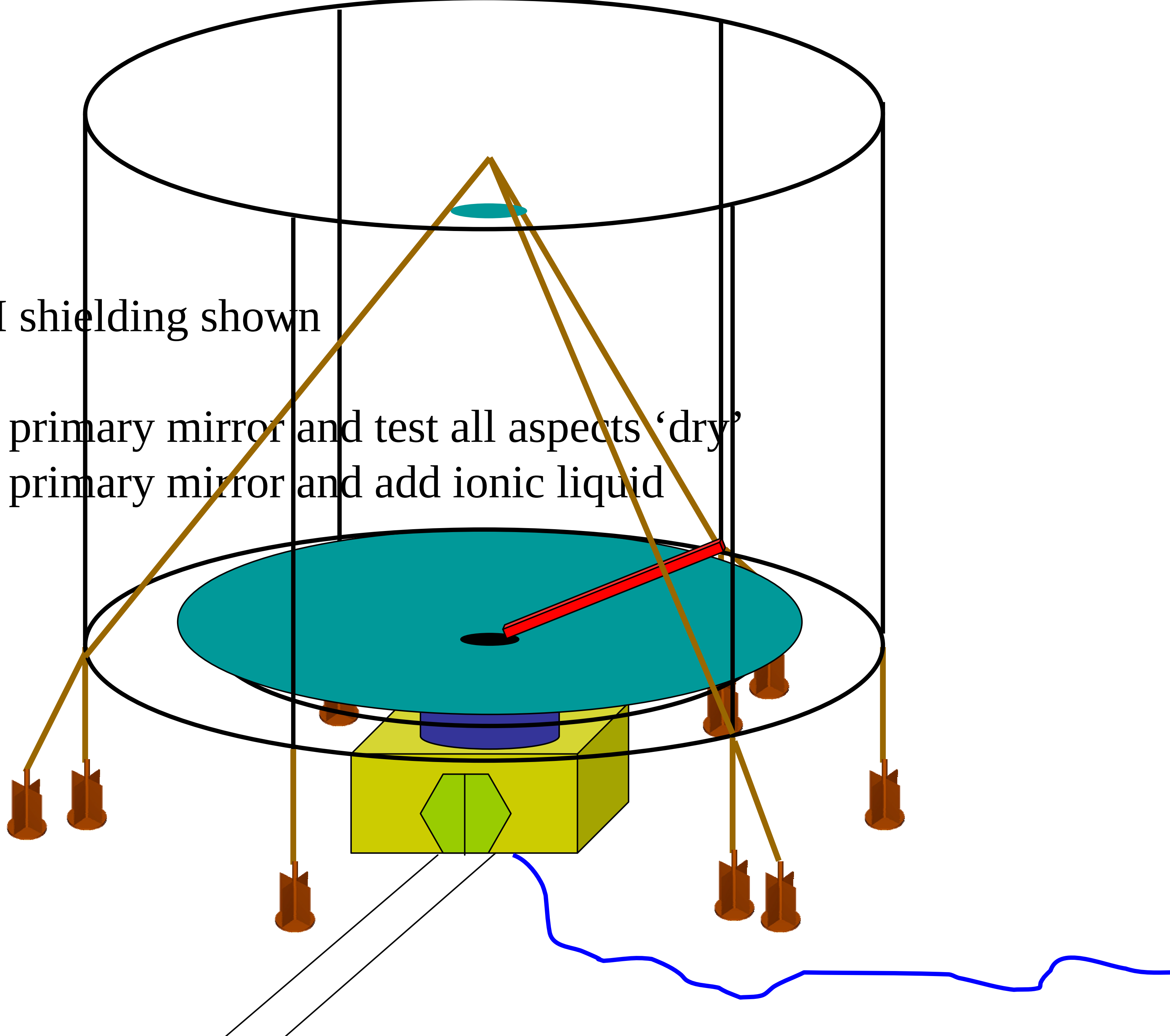
Add MLI blankets from the lower shield support ring to the instrument housing

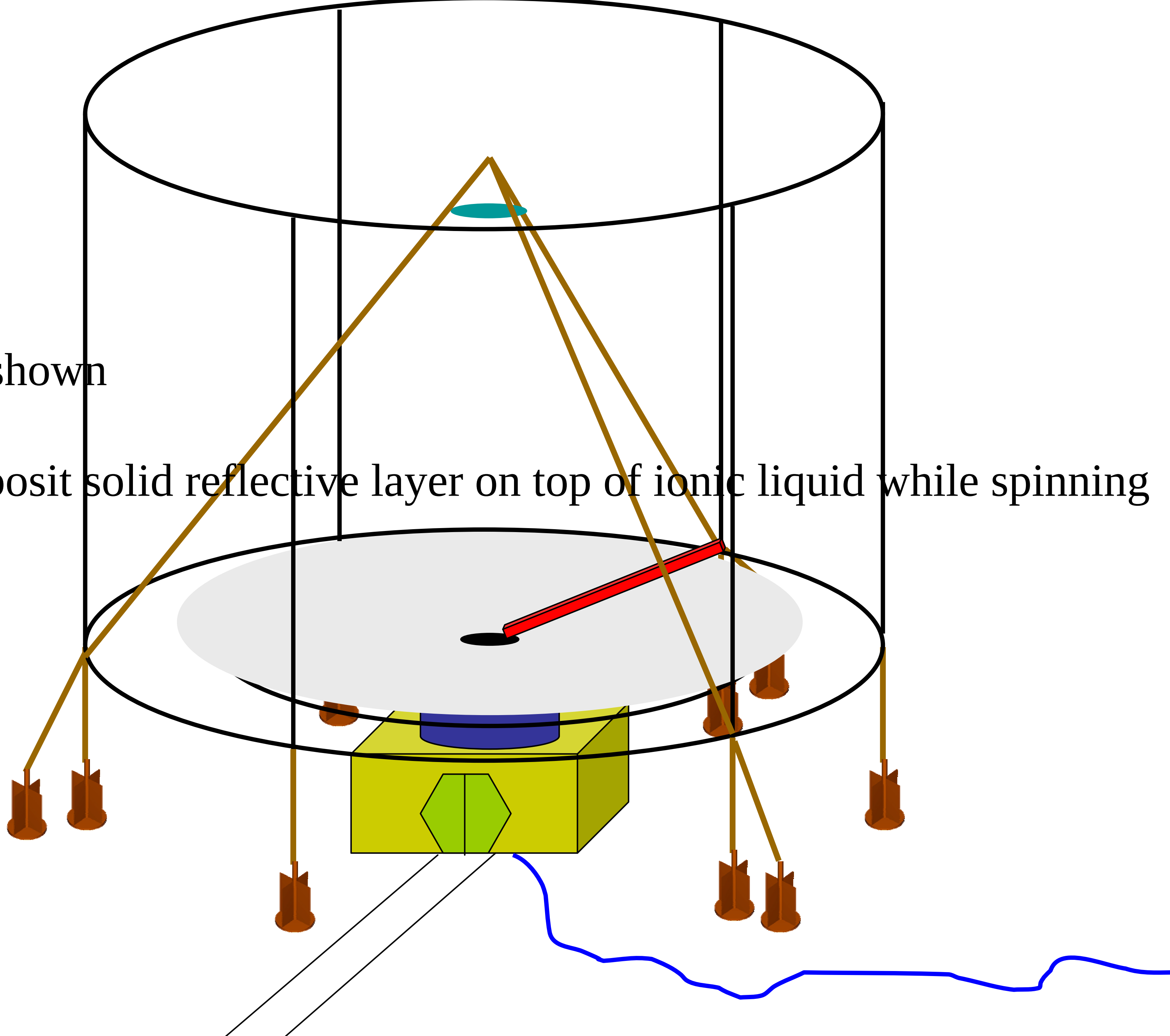


NO MLI shielding shown

Spin the primary mirror and test all aspects ‘dry’

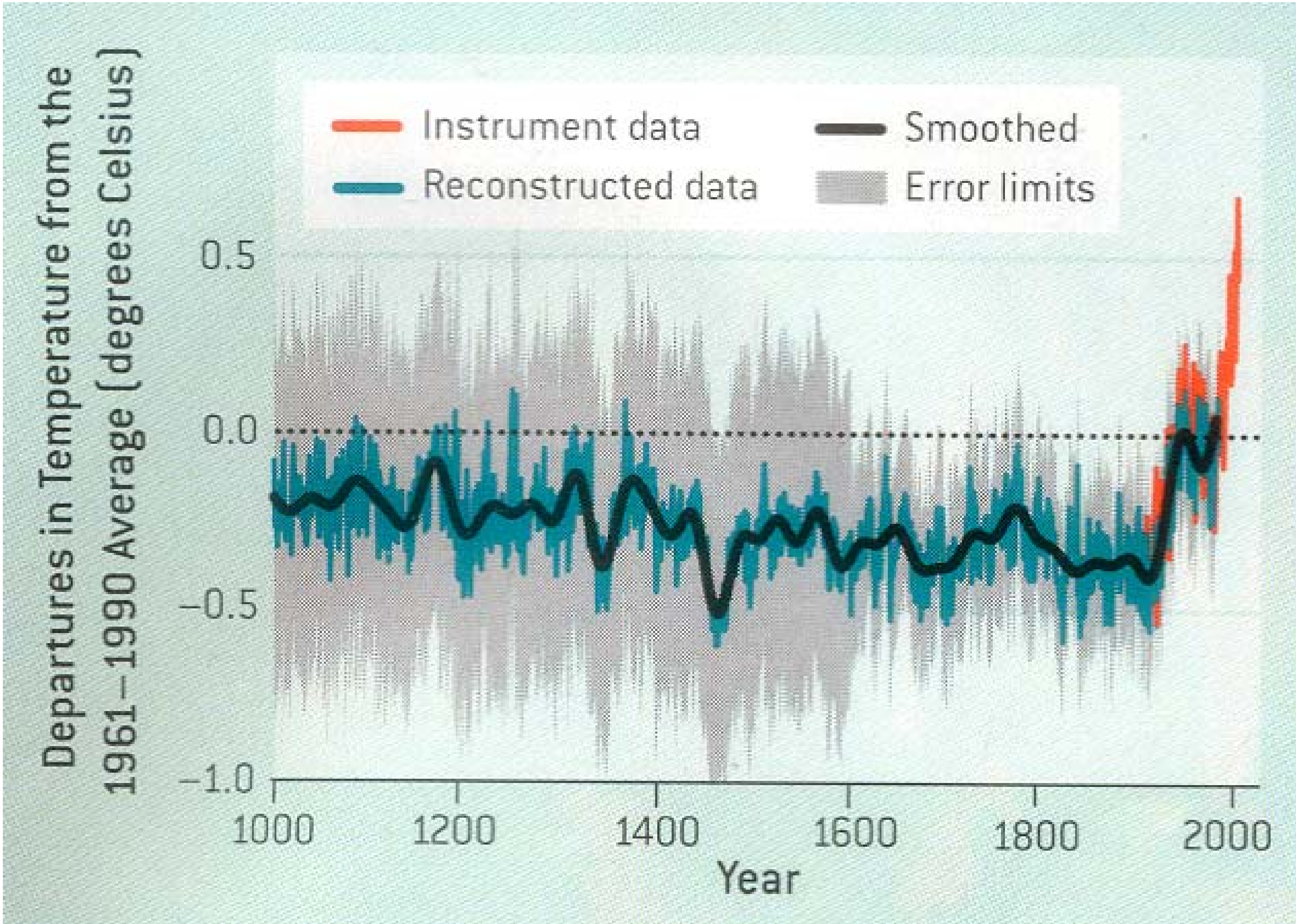
Spin the primary mirror and add ionic liquid



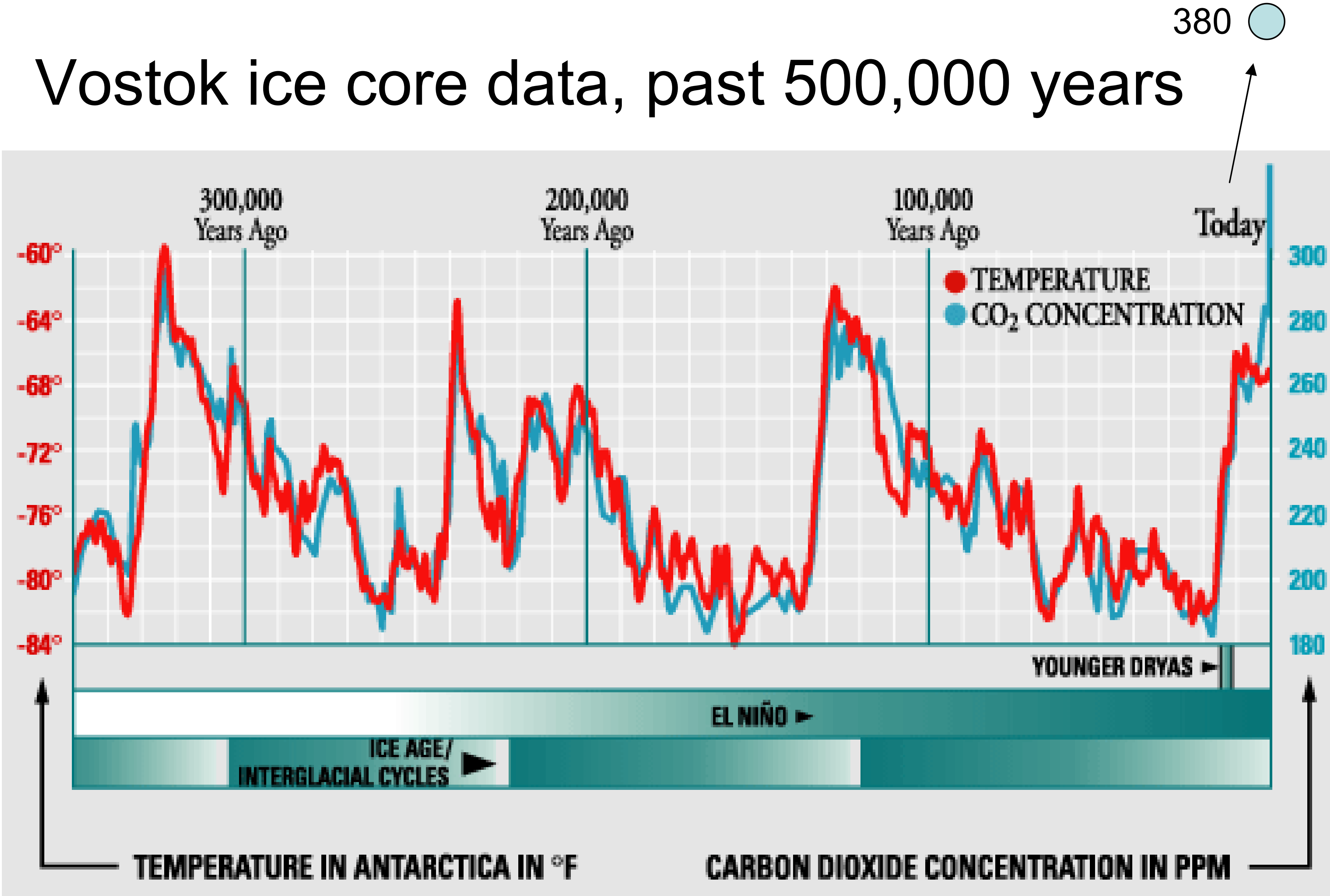

NO MLI shown
Vapor deposit solid reflective layer on top of ionic liquid while spinning

Conclusion

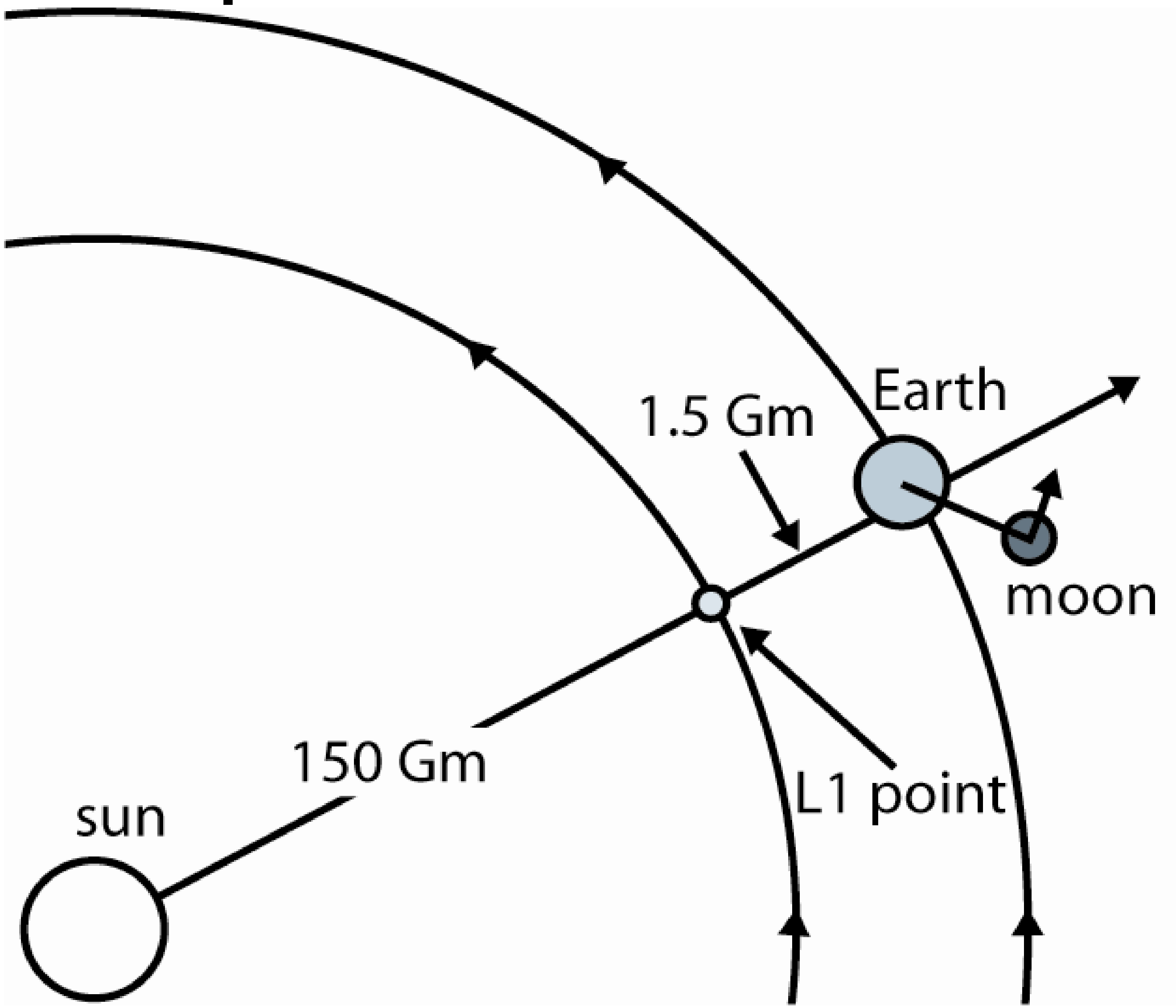
- Excellent scientific potential
- No tall tent poleson technical side
- 20 m class telescope will depend on lunar exploration program
- Could validate program, as Hubble did for Shuttle

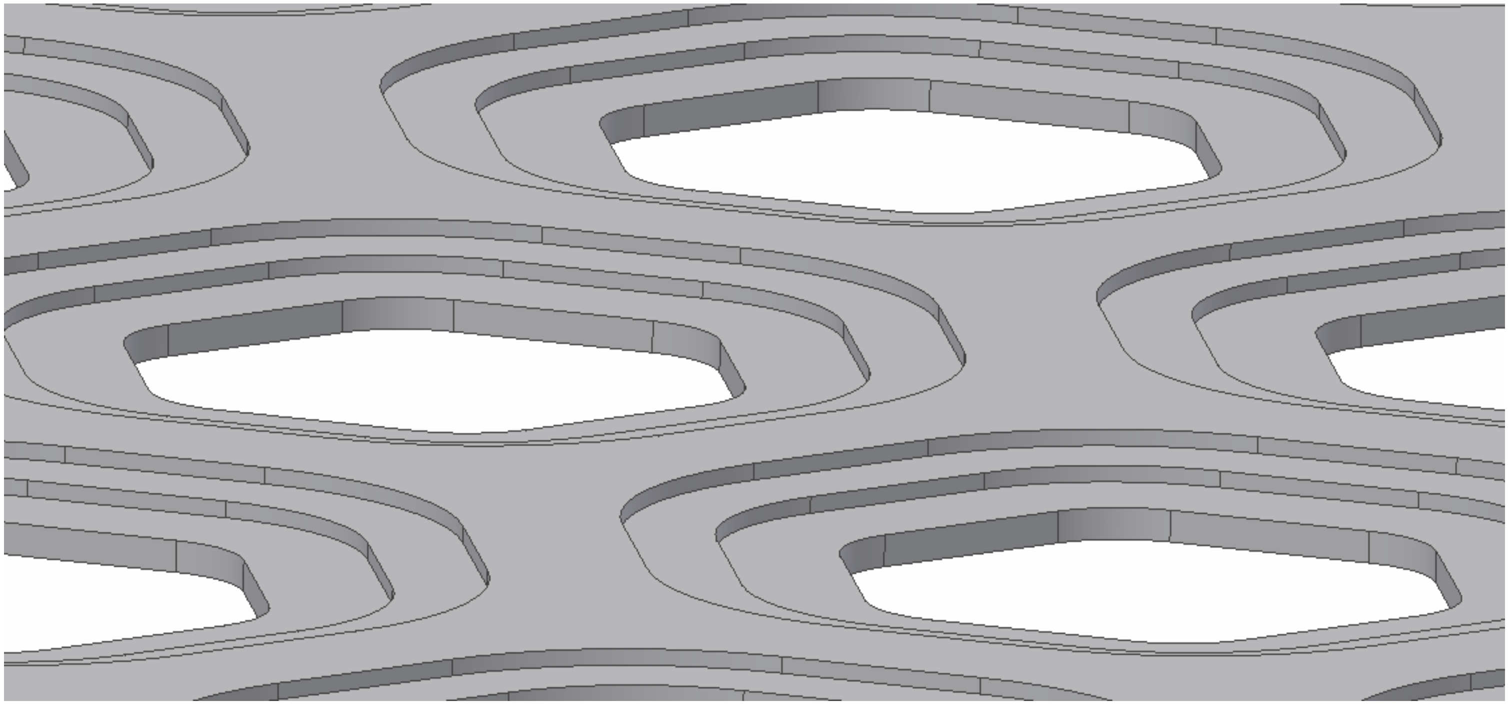

Instrument data
Smoothed
Reconstructed data
Error limits
Departures in Temperature from the 1961–1990 Average (degrees Celsius)
0.5
0.0
−0.5
−1.0
1000
1200
1400
1600
1800
2000
Year

Vostok ice core data, past 500,000 years



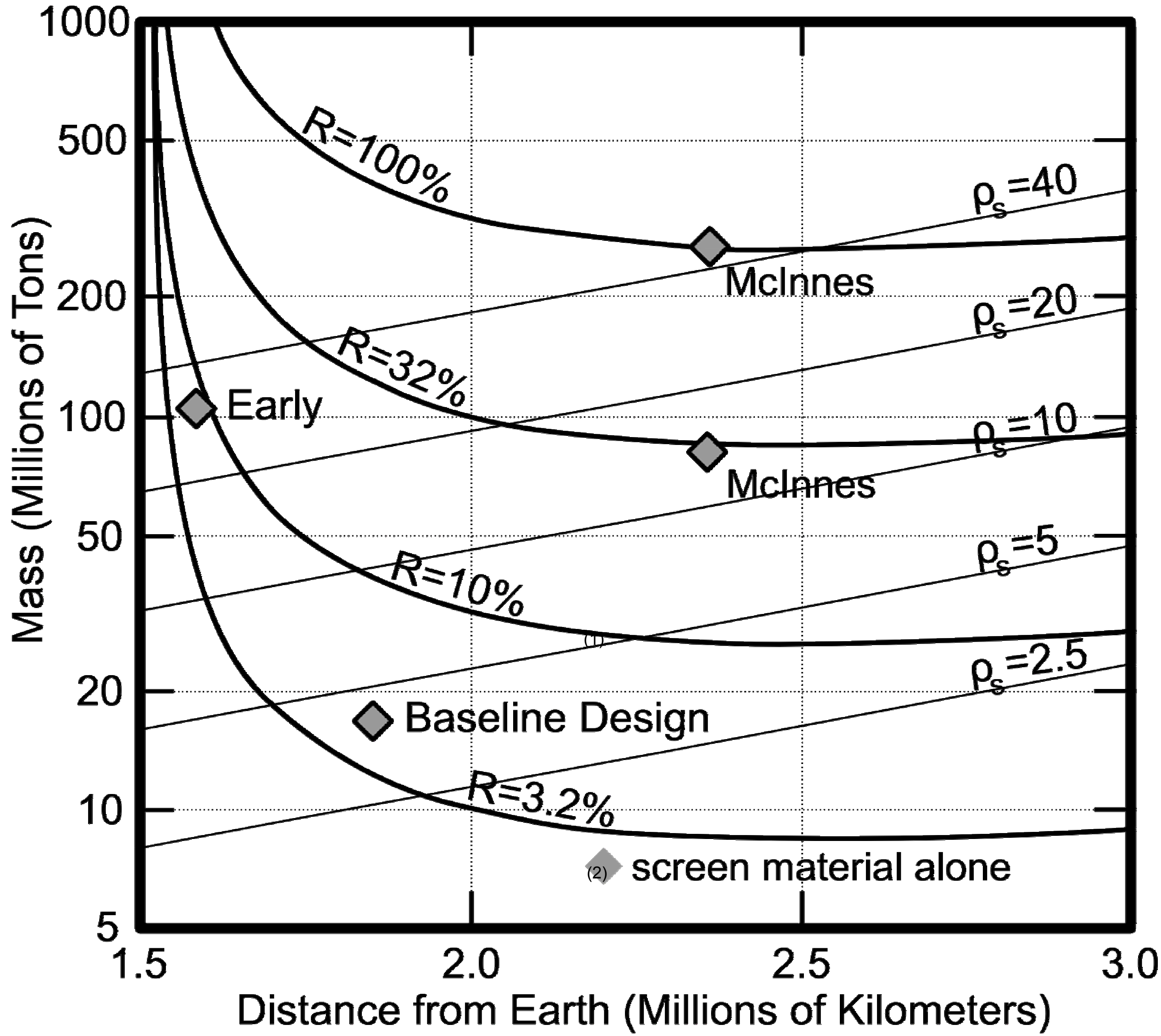
Space sunshade location





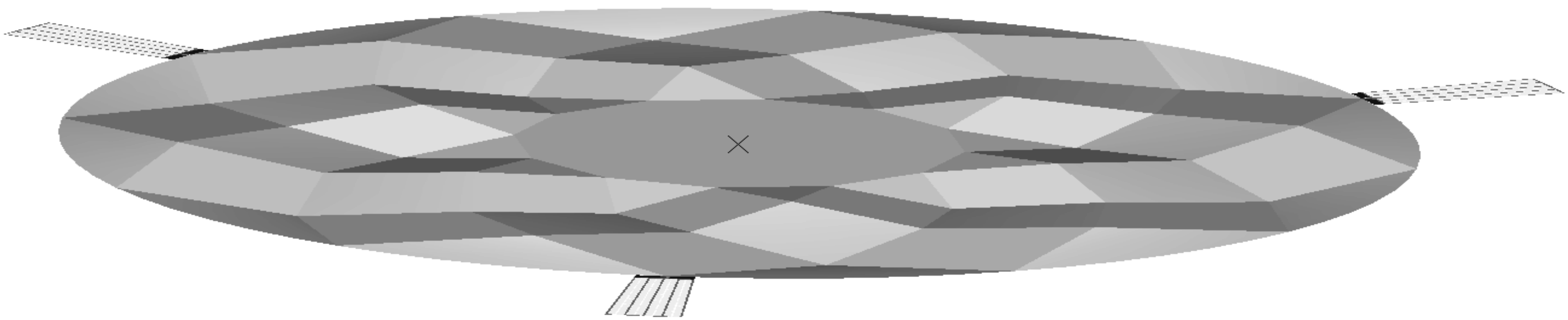
Detail of the refractive screen. The holes are on 15 μm centers, and the maximum thickness t_{max} = 1.06 μm.

T=10% for full solar spectrum



1000
500
200
100
50
20
10
5
Mass (Millions of Tons)
1.5
2.0
2.5
3.0
Distance from Earth (Millions of Kilometers)
R=100%
R=32%
R=10%
R=3.2%
ρs=40
ρs=20
ρs=10
ρs=5
ρs=2.5
McInnes
McInnes
Early
Baseline Design
(1)
(2)
screen material alone

Flyers randomly located in cloud 6000 km diameter and 100,000 long



- Screen 0.6 m diameter
- Ears stick out 0.1 m
  - Mems mirrors for radiation pressure control
  - Small cameras, solar cells and computers
- Thickness 5 μm screen, 100 μm ears
- Mass 1.2 g each, 16 trillion required
- Launched in stacks of 800,000 weighing 1 ton, 4 m high
- Each vehicle has its own destacker robot