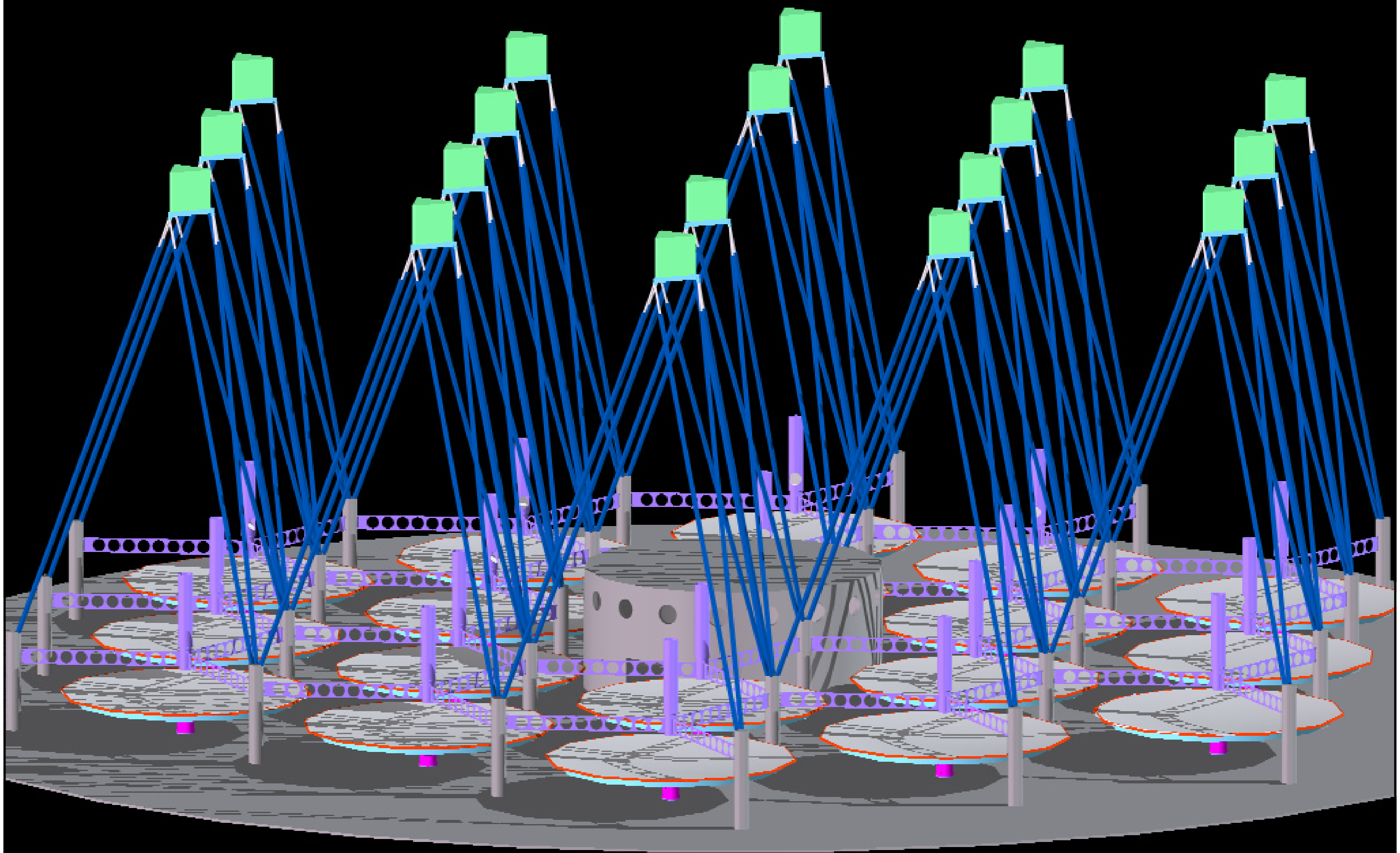
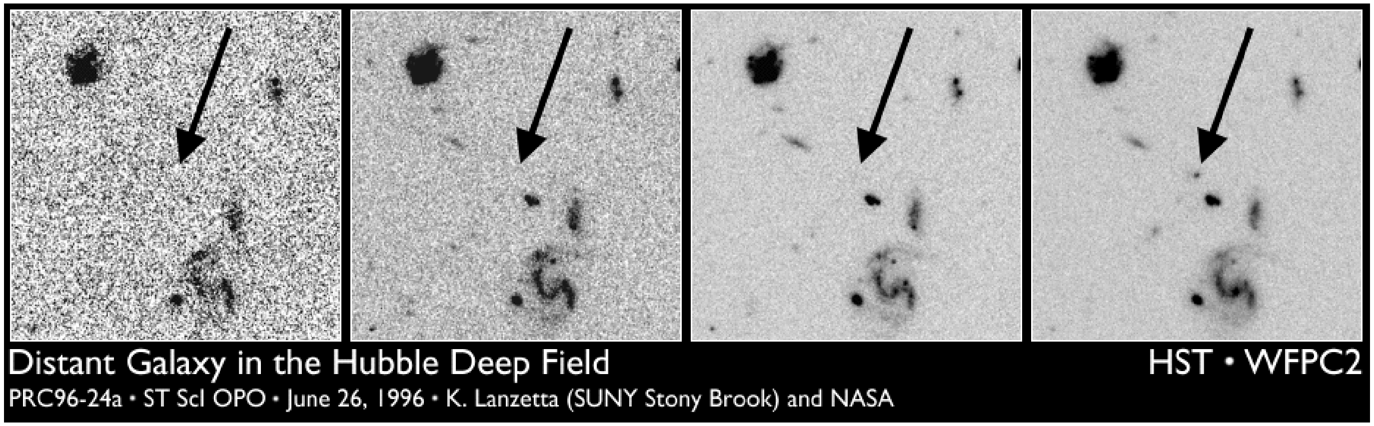
Large-Aperture Mirror Array



Paul Hickson, Dept of Physics & Astronomy, University of British Columbia

Finding the first luminous objects

- Wavelength range 0.4 < λ < 2.5 um
- Lyman-a visible to z = 19.6
- Sub-nanoJansky sensitivity required (1 Jy = 10^{-26} W m^{-2} Hz^{-1})



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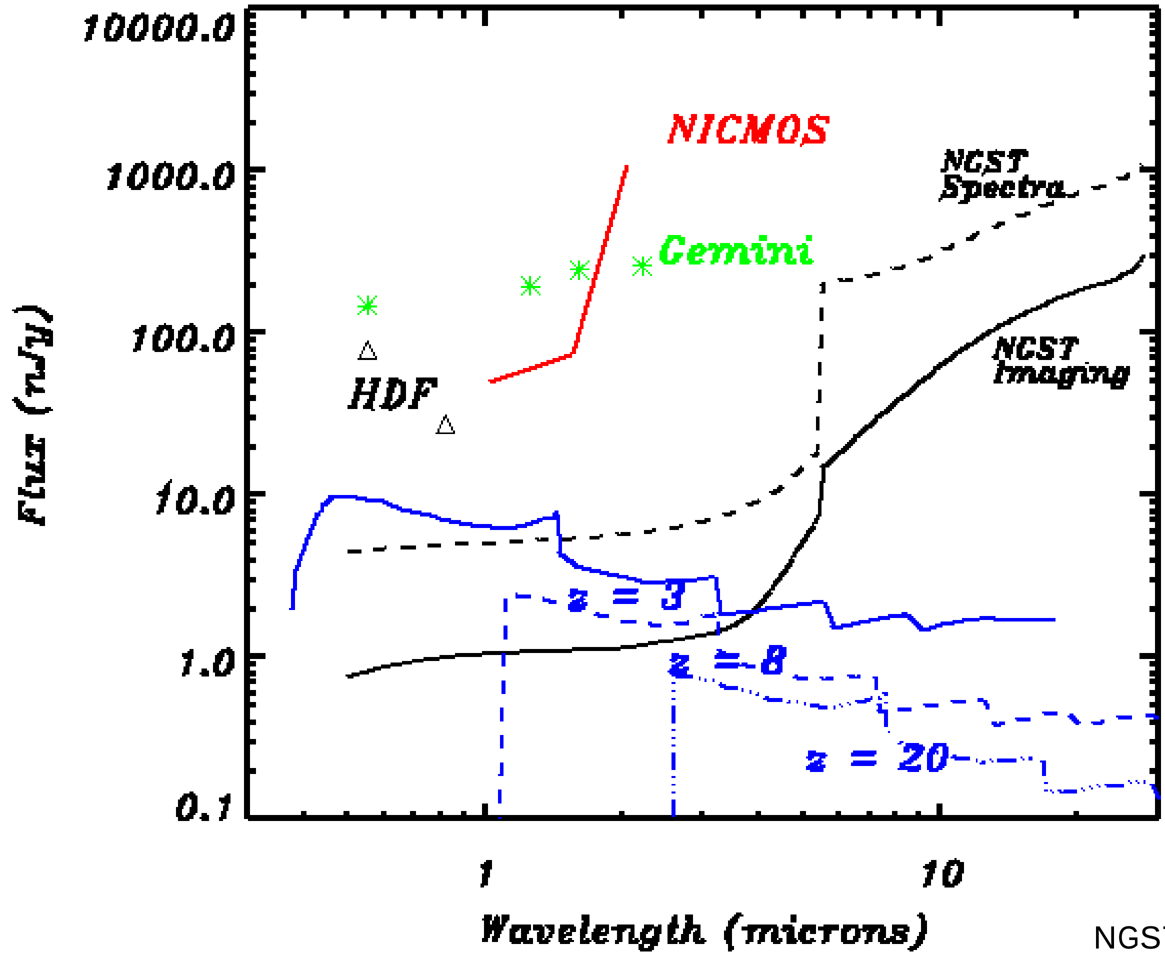
NASA

First star clusters



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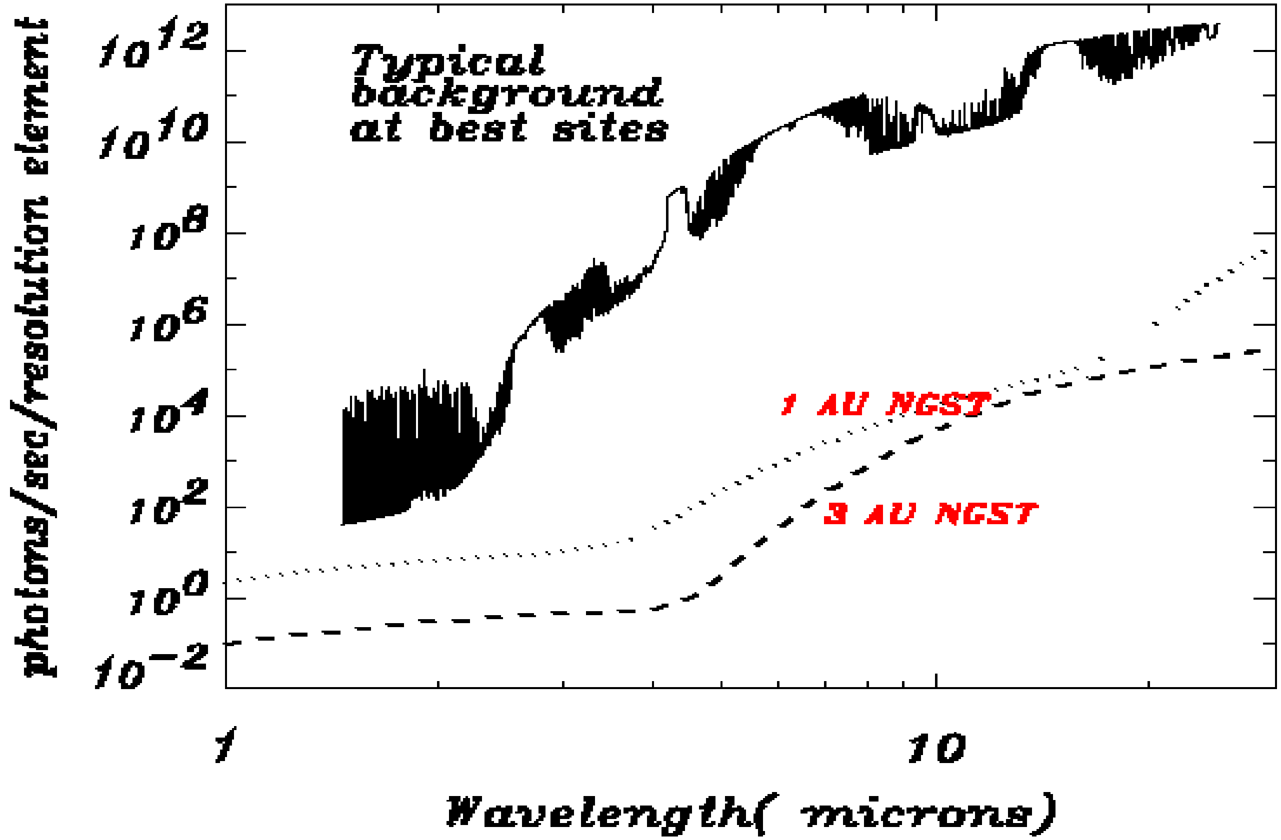
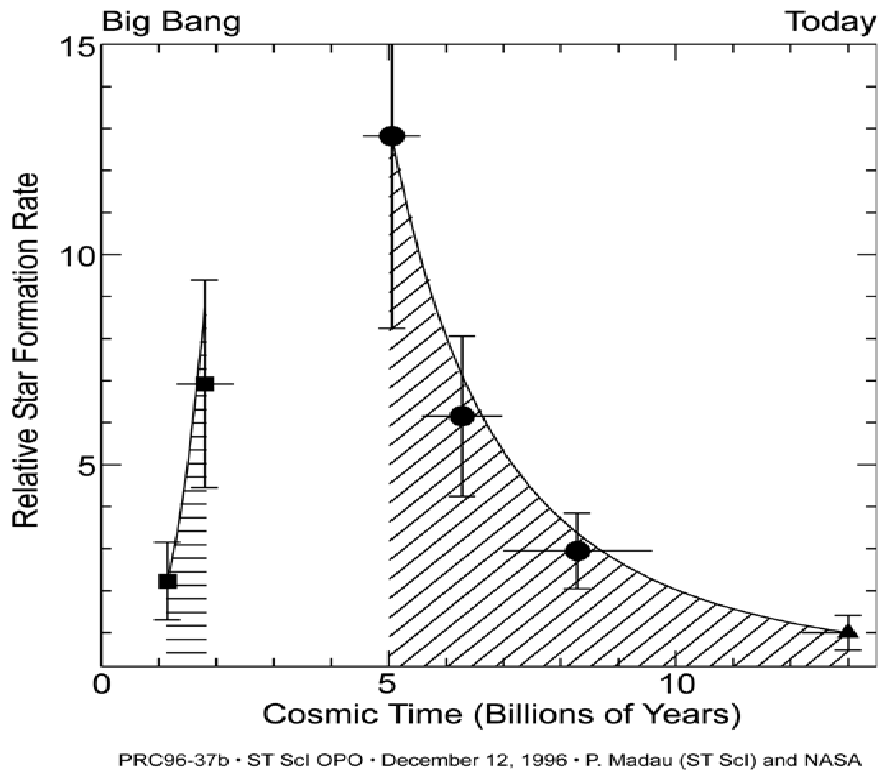
NGST Project

Background Light



Star-formation history of the Universe?

- UV luminosity is related to star formation rate, but suffers from…
  - incompleteness
  - dust obscuration
- Better to use type II supernovae
- These can be detected to z > 10 with a 30-m telescope



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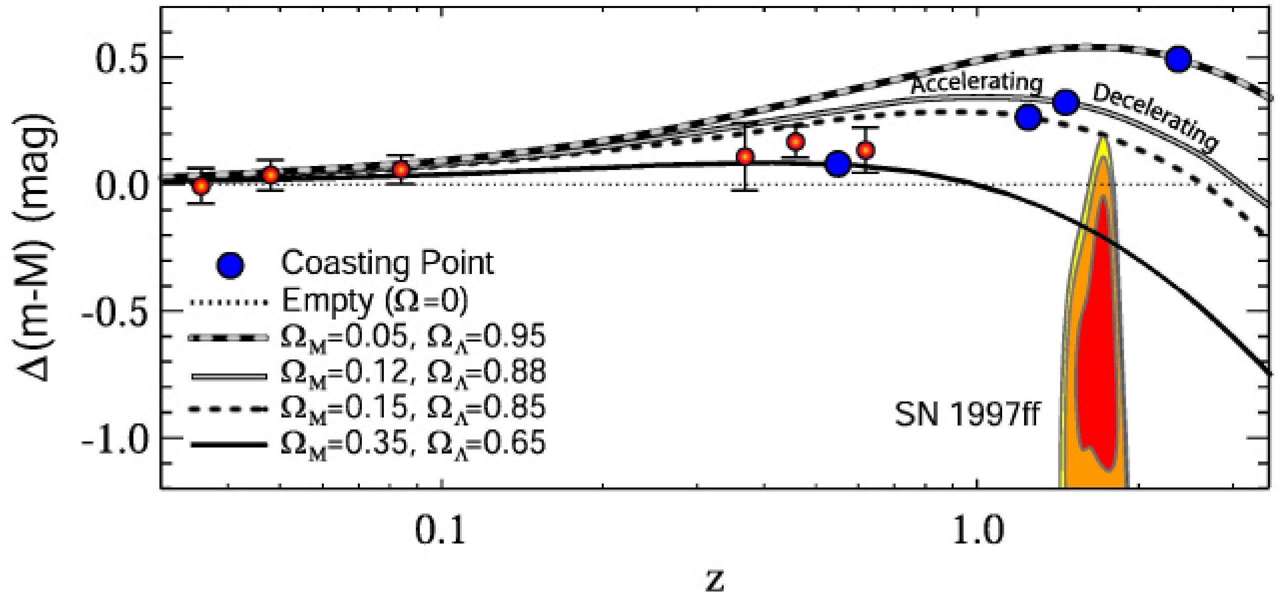
NASA

Probing dark energy

- The history of acceleration of the universe depends on the quantity and nature of the dark energy
- This can be probed using supenovae with redshift z > 1
- Systematic effects?



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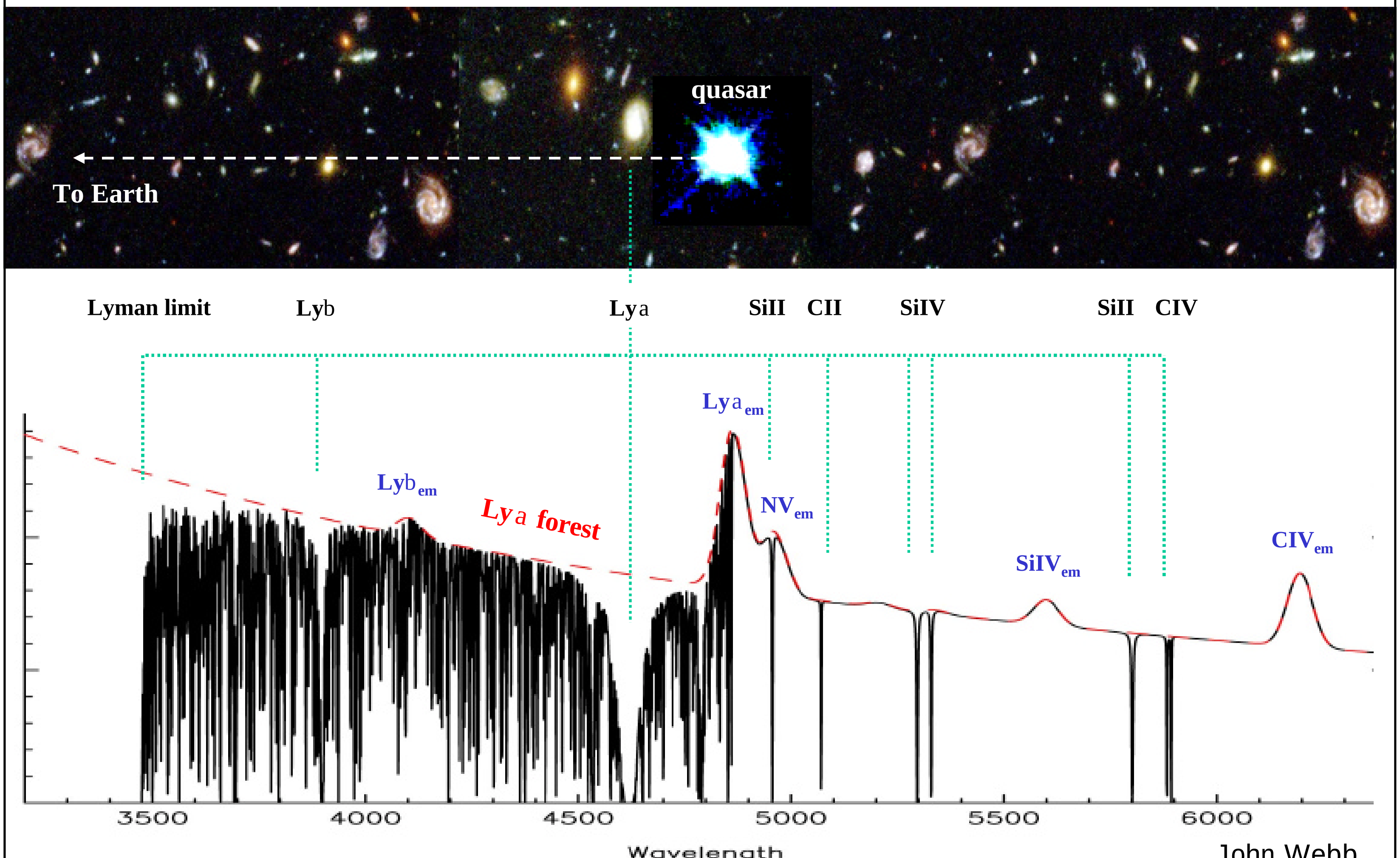
Riess et al. 2001, ApJ

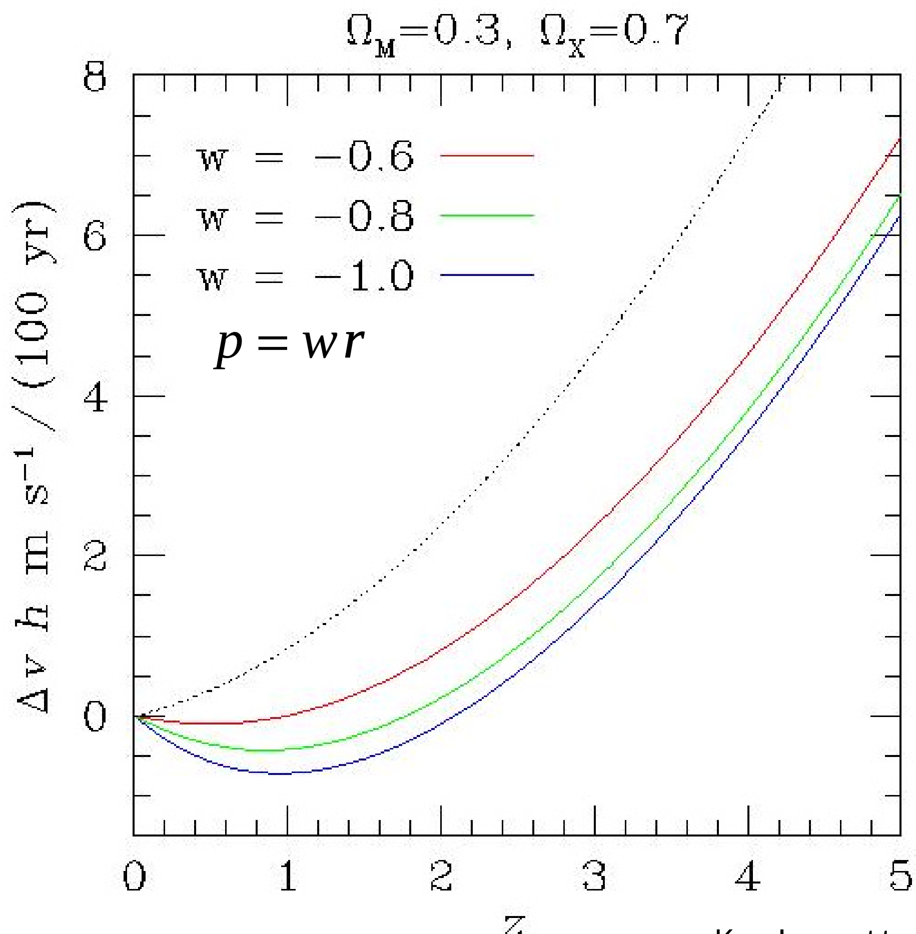
Quasars: Probing early-Universe physics



John Webb

Direct measurement of cosmic deceleration

- Measure secular variation of redshifts of Lyman-α forest lines
- $\Delta\lambda/\lambda \sim 10^{-10}$/yr
- Requires high s/n high-resolution spectra of ~ 100 QSOs
- Requires 30+ metre aperture



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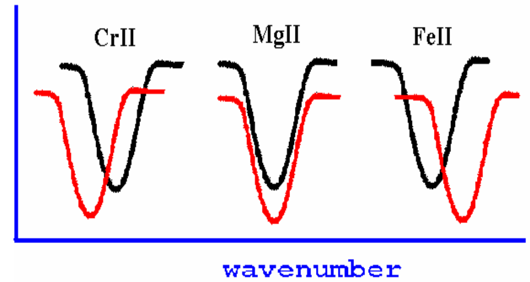
Ken Lanzetta

Do physical constants vary?

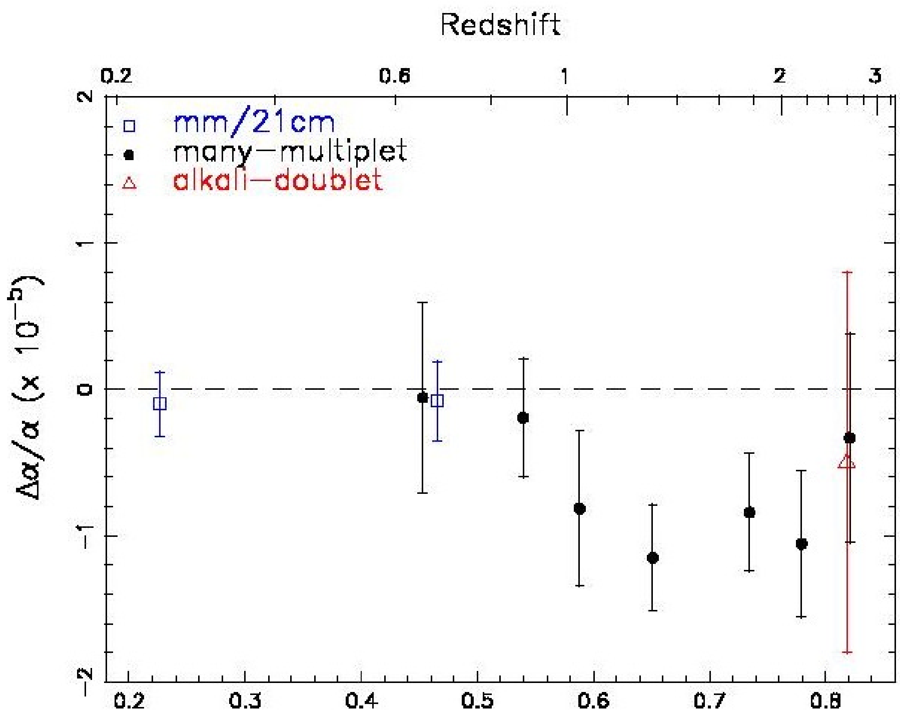


- Variation of the fine structure constant

  $$a = e^2 / \hbar c$$

  would cause small but measurable shift in the wavelengths of QSO absorption lines

- Requires high-resolution spectra of ~ 100 QSOs



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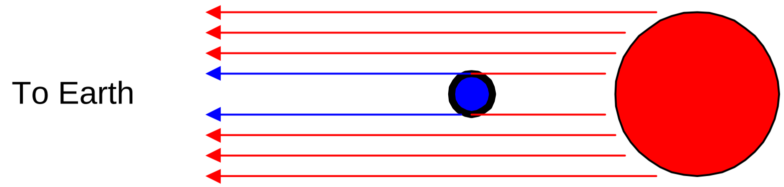
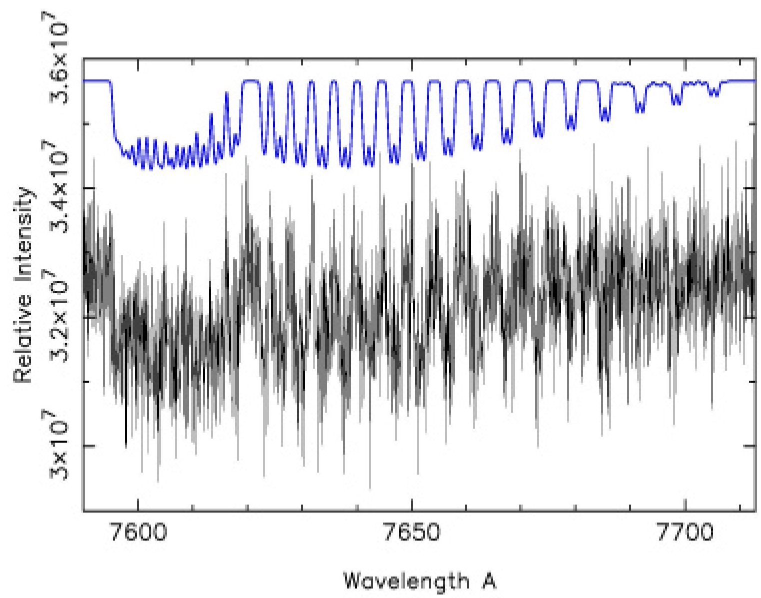
John Webb

Discovering oxygen on other planets?

- If a planet passes in front of its parent star, some light from the star will pass through the atmosphere of the planet.
- In principle one could detect O_2 absorption lines in the spectrum of the star at that time.
- Requires a 30+ metre telescope to collect sufficient light





Webb & Wormleaton 2001

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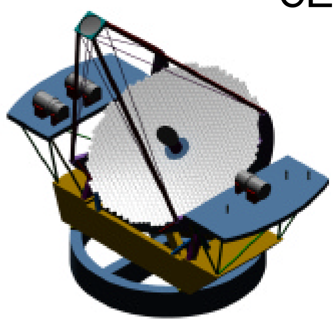
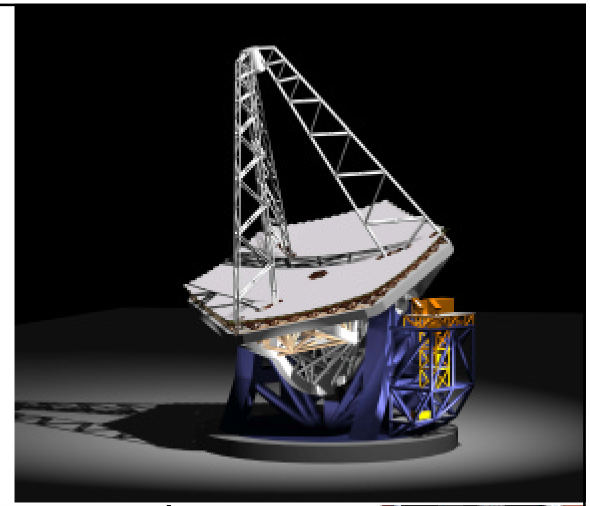
Large telescope projects

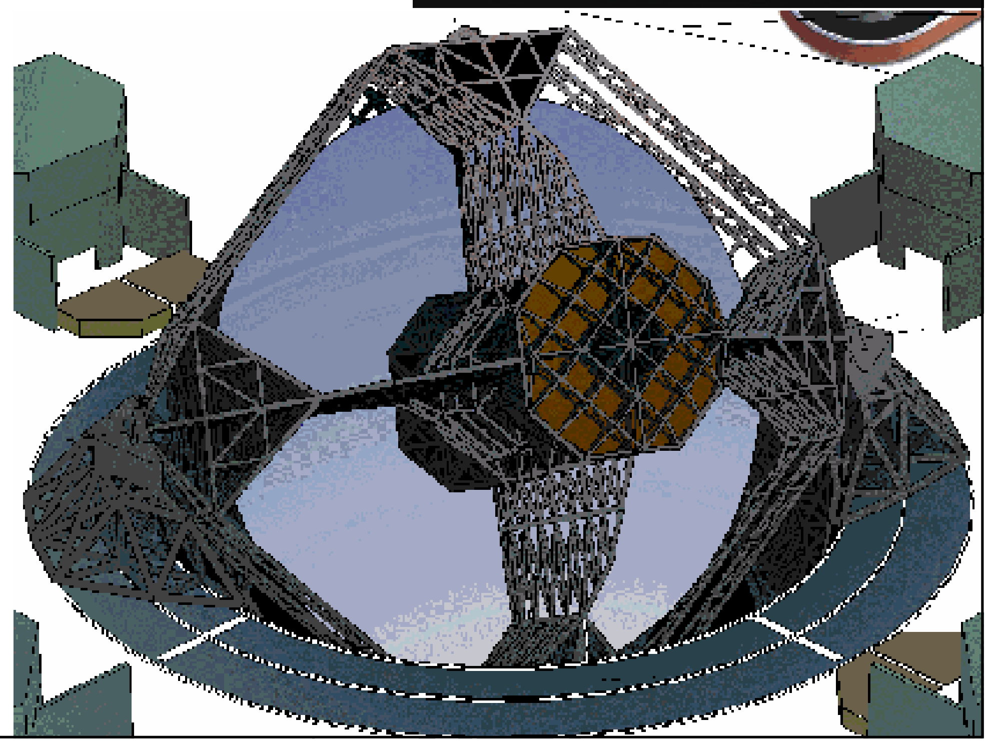
CELT 30m



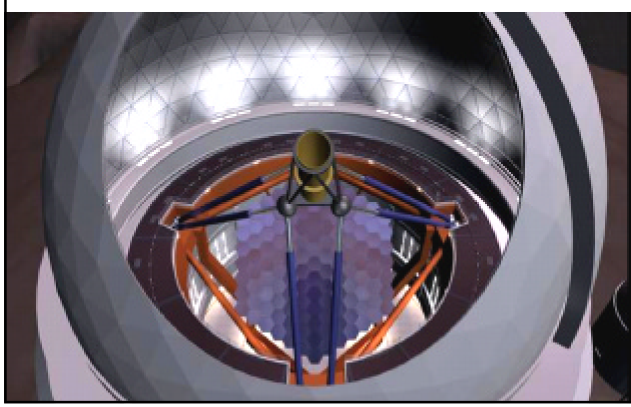
EURO50 50m



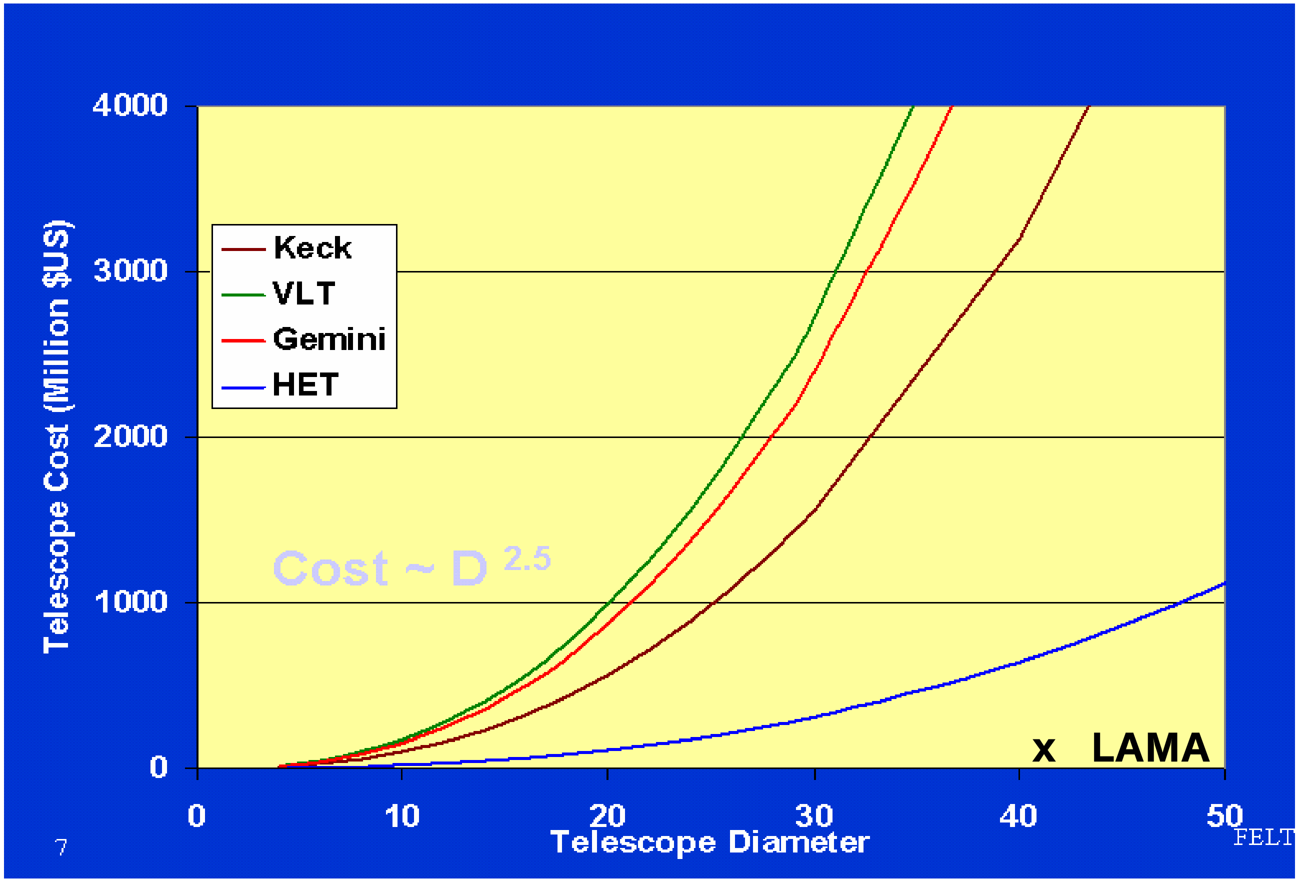
OWL 100m



FELT 30m



Cost scaling of conventional telescopes



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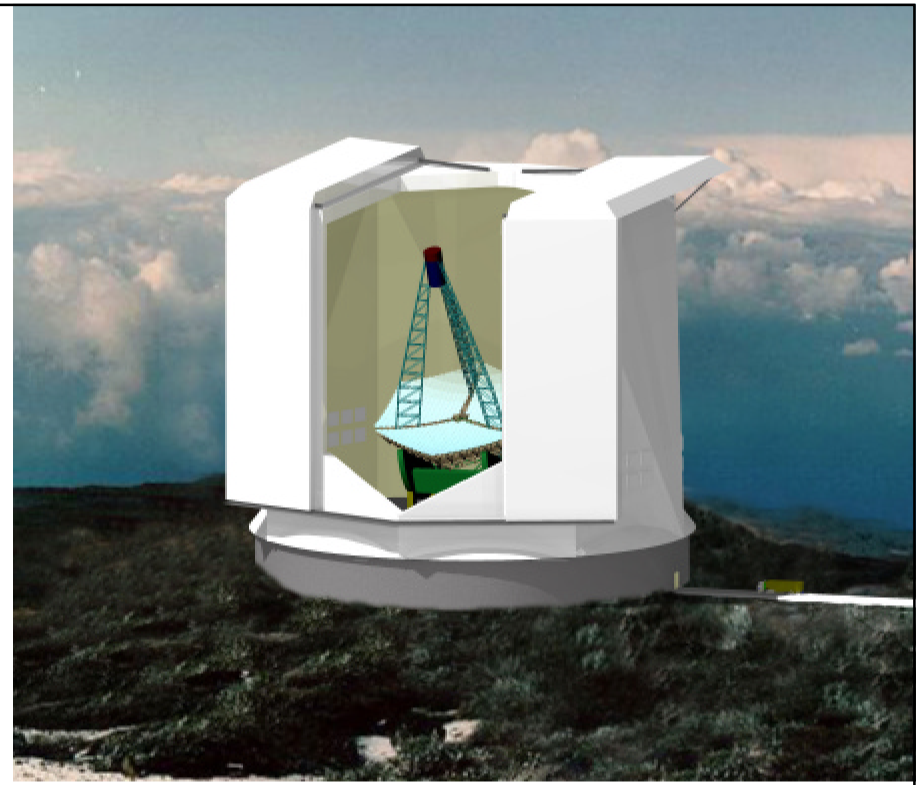
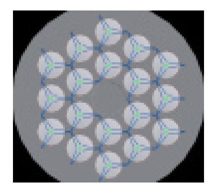
FELT project

Advantages of an array

- Demonstrated technology
- Versatility
- Redundancy
- Cost
  - monolithic ~ $A^{1.3}$
  - array ~ A
  - smaller enclosure
  - economy of scale



EURO50



LAMA

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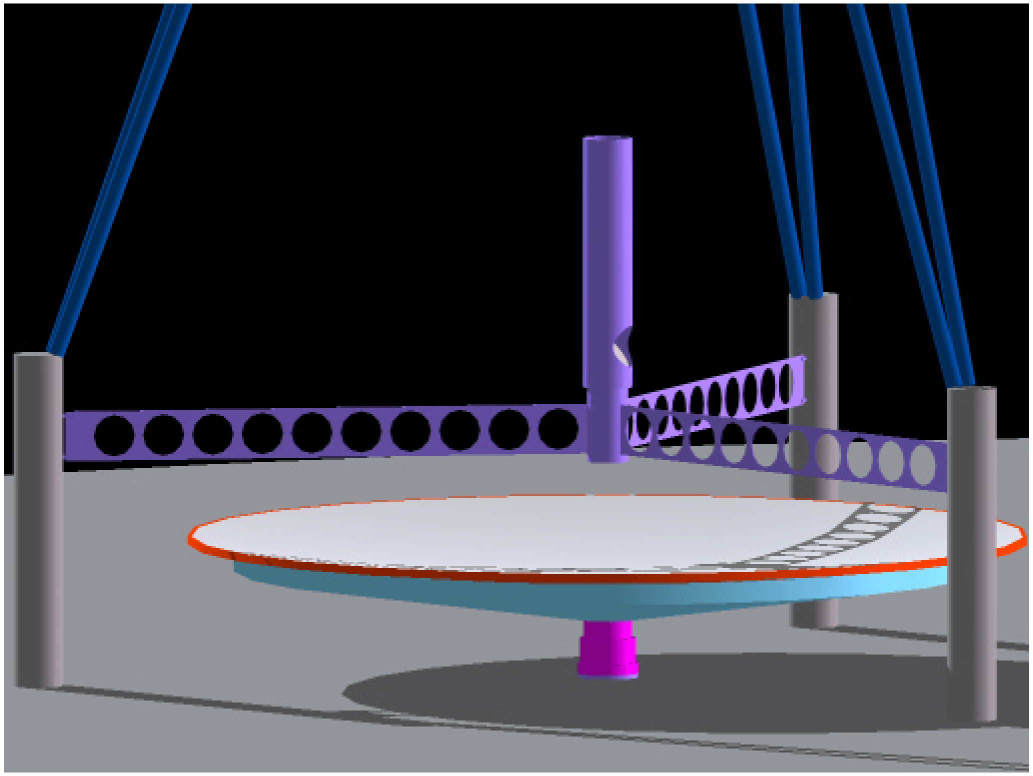
LAMA concept

- Array of fixed mirrors
- Near-zenith pointing and tracking
- Incoherent and coherent modes
- Multiband optical/IR imaging camera
- High-resolution spectrograph



LAMA technologies

- Adaptive optics
- Tracking optics
- Optical interferometry
- Liquid mirrors

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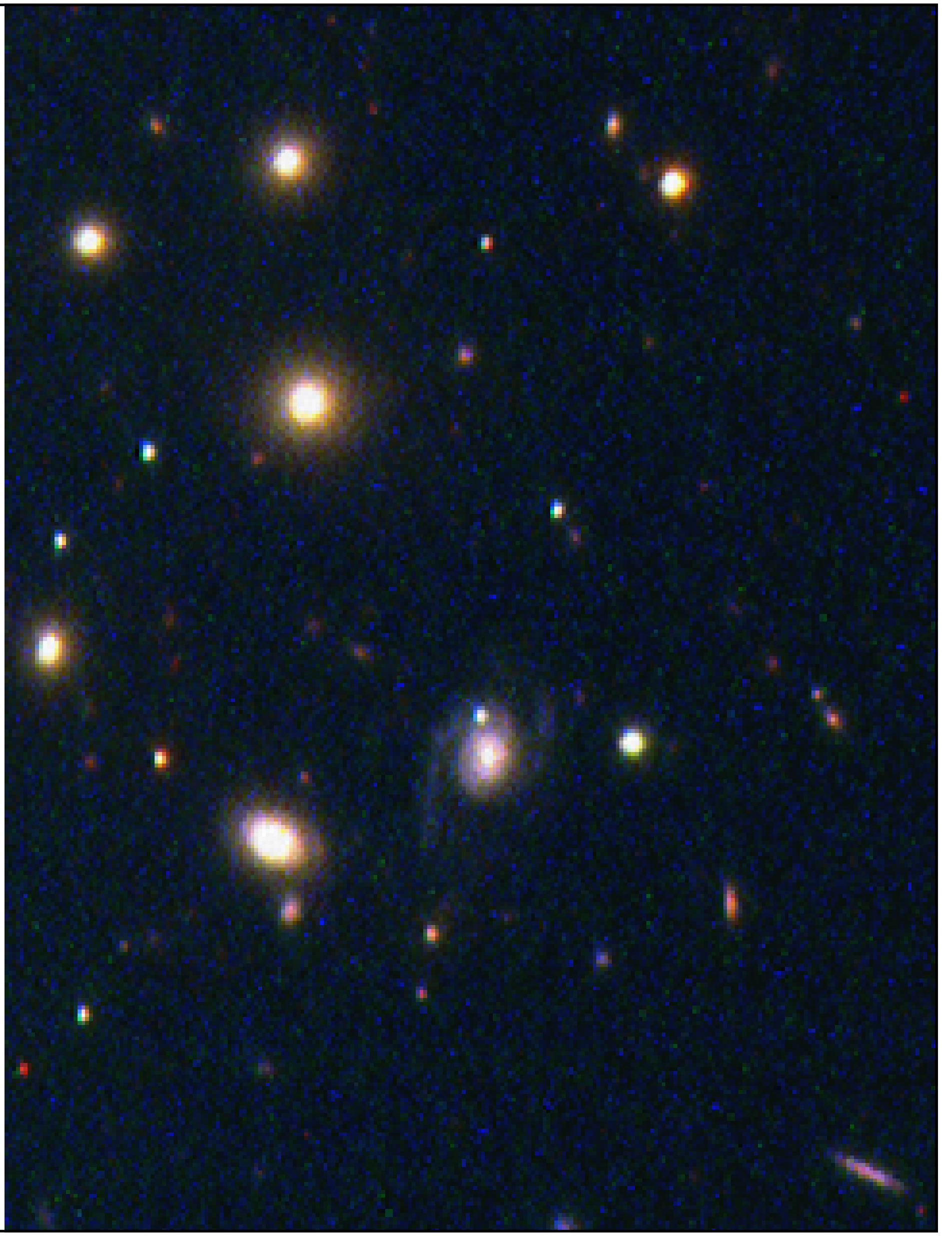
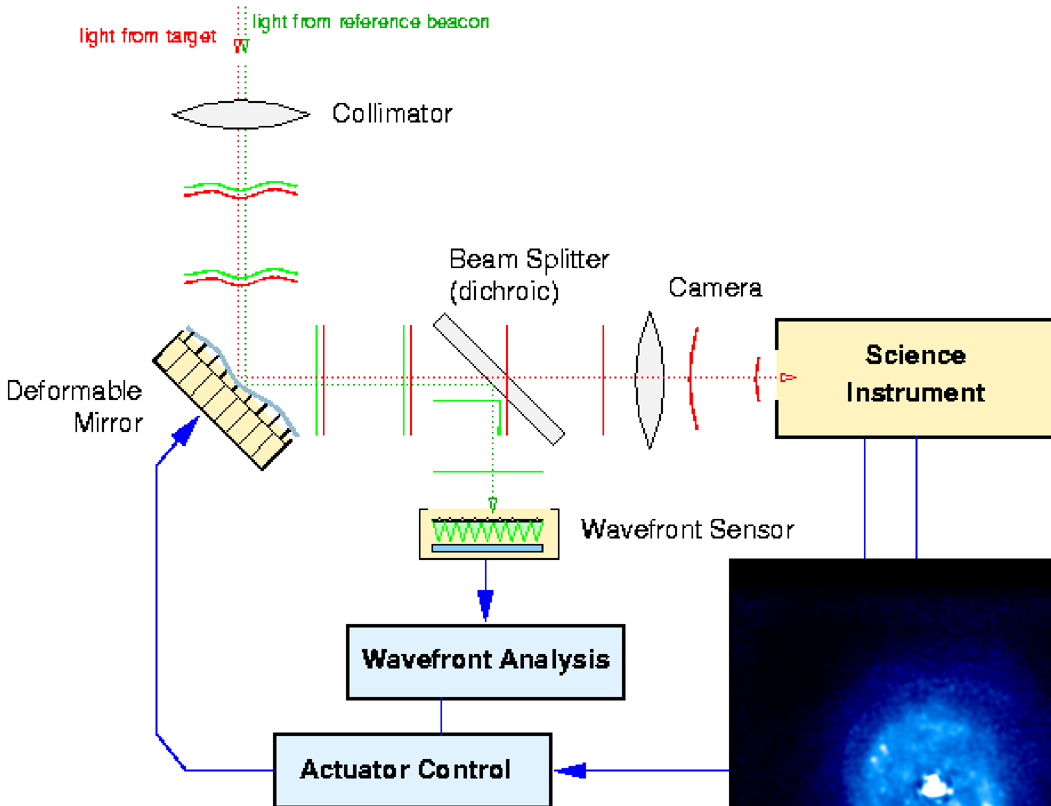
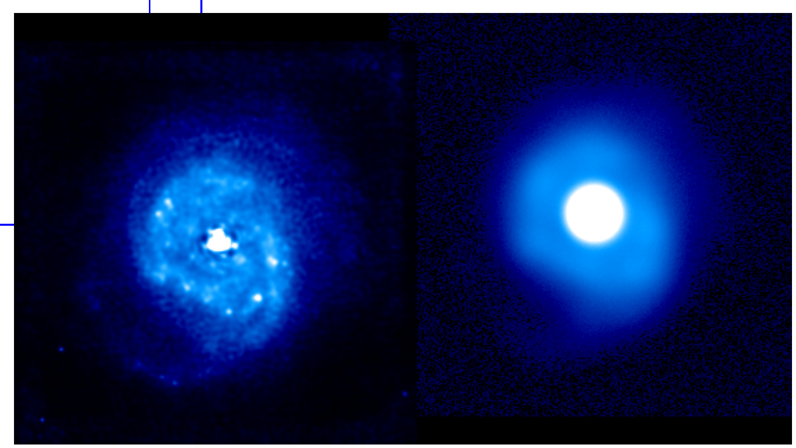
NASA 3m LMT



Adaptive optics



Hokupa'a AO system on the Canada-France-Hawaii 3.6m telescope



Center for Adaptive Optics

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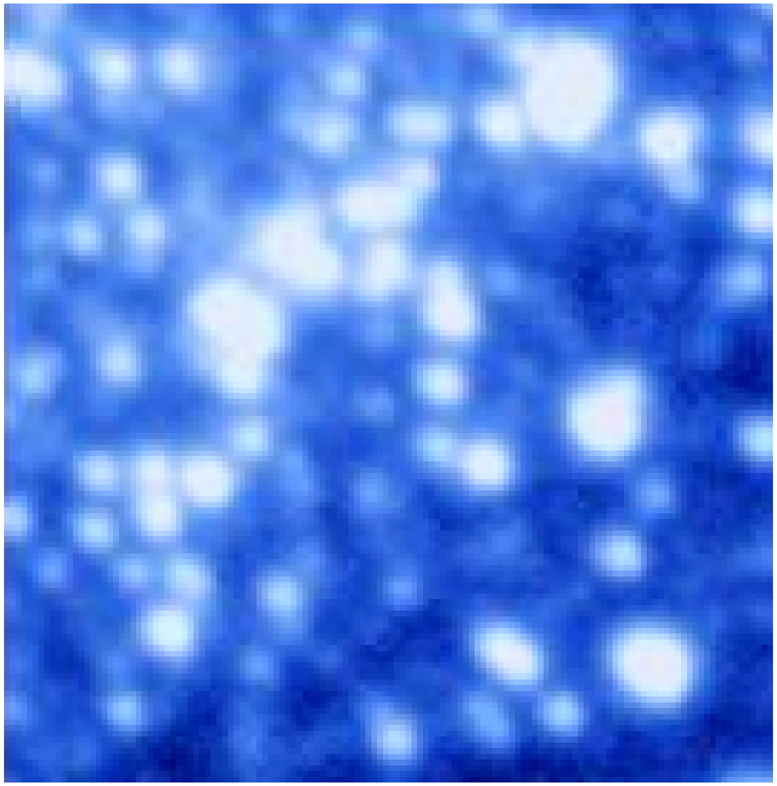
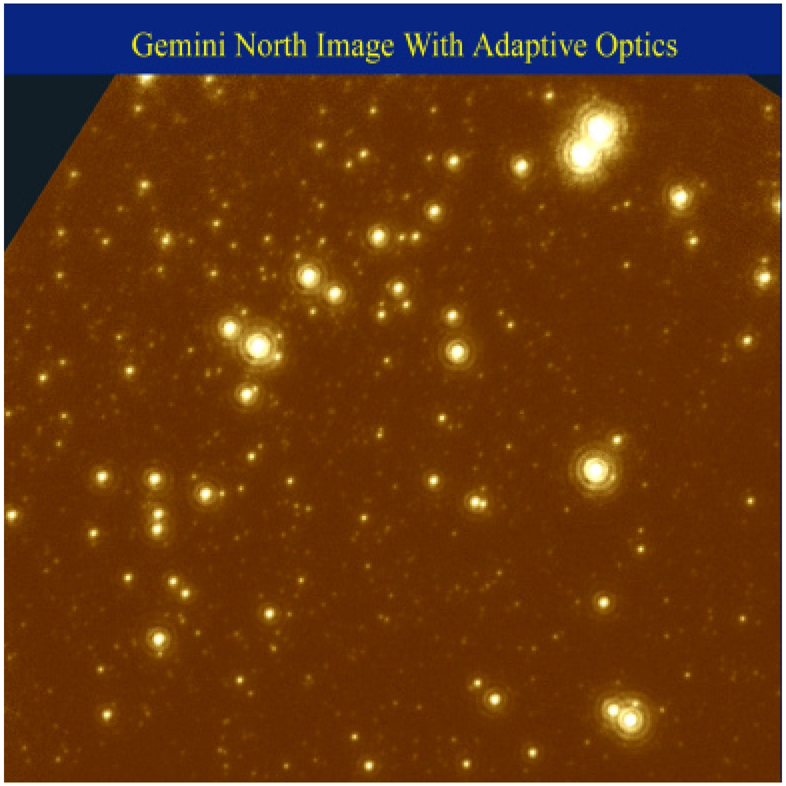
Gemini adaptive optics (8-m telescope)

Without AO
FWHM = 0.8 arcsec

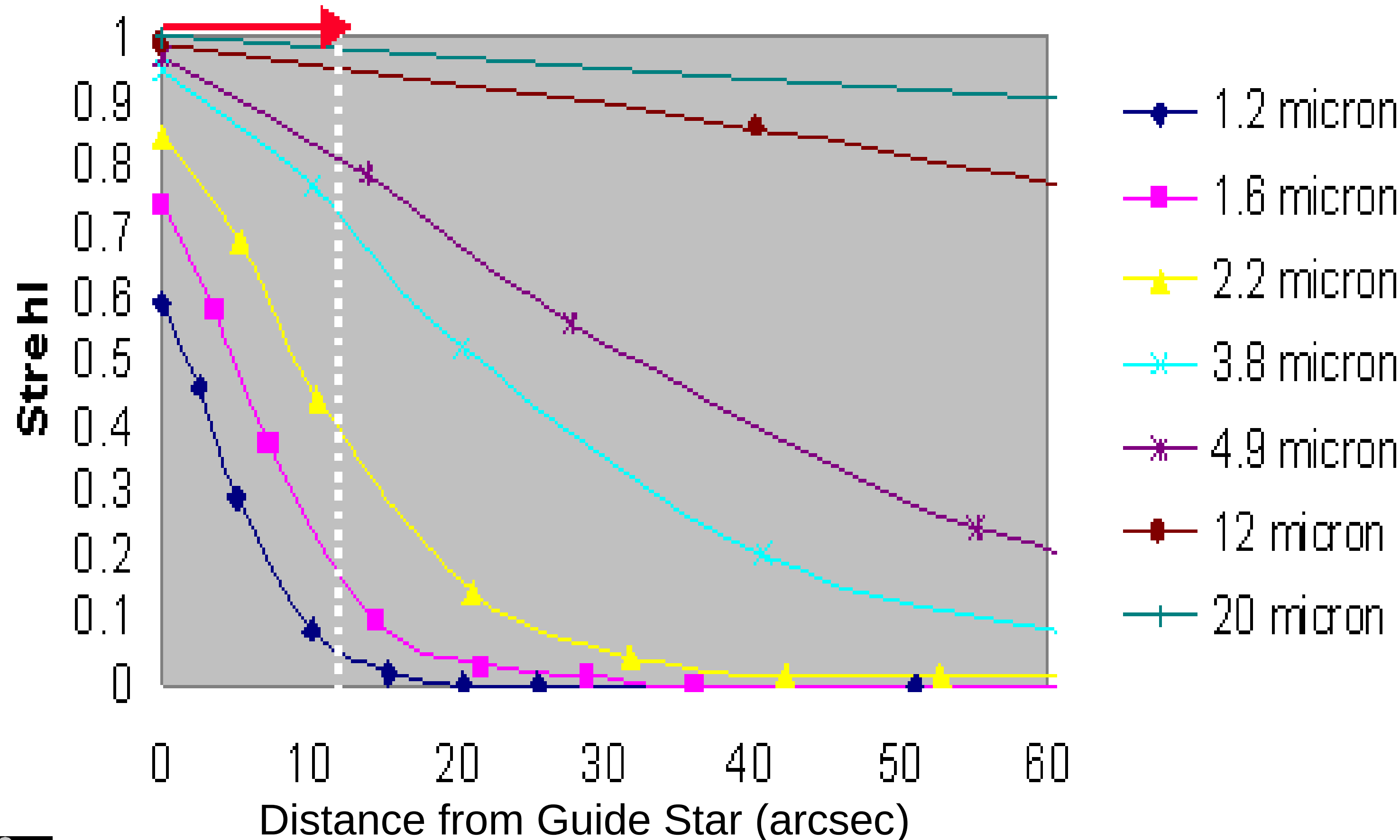


With AO
0.08 arcsec

Gemini Project



Adaptive optics performance



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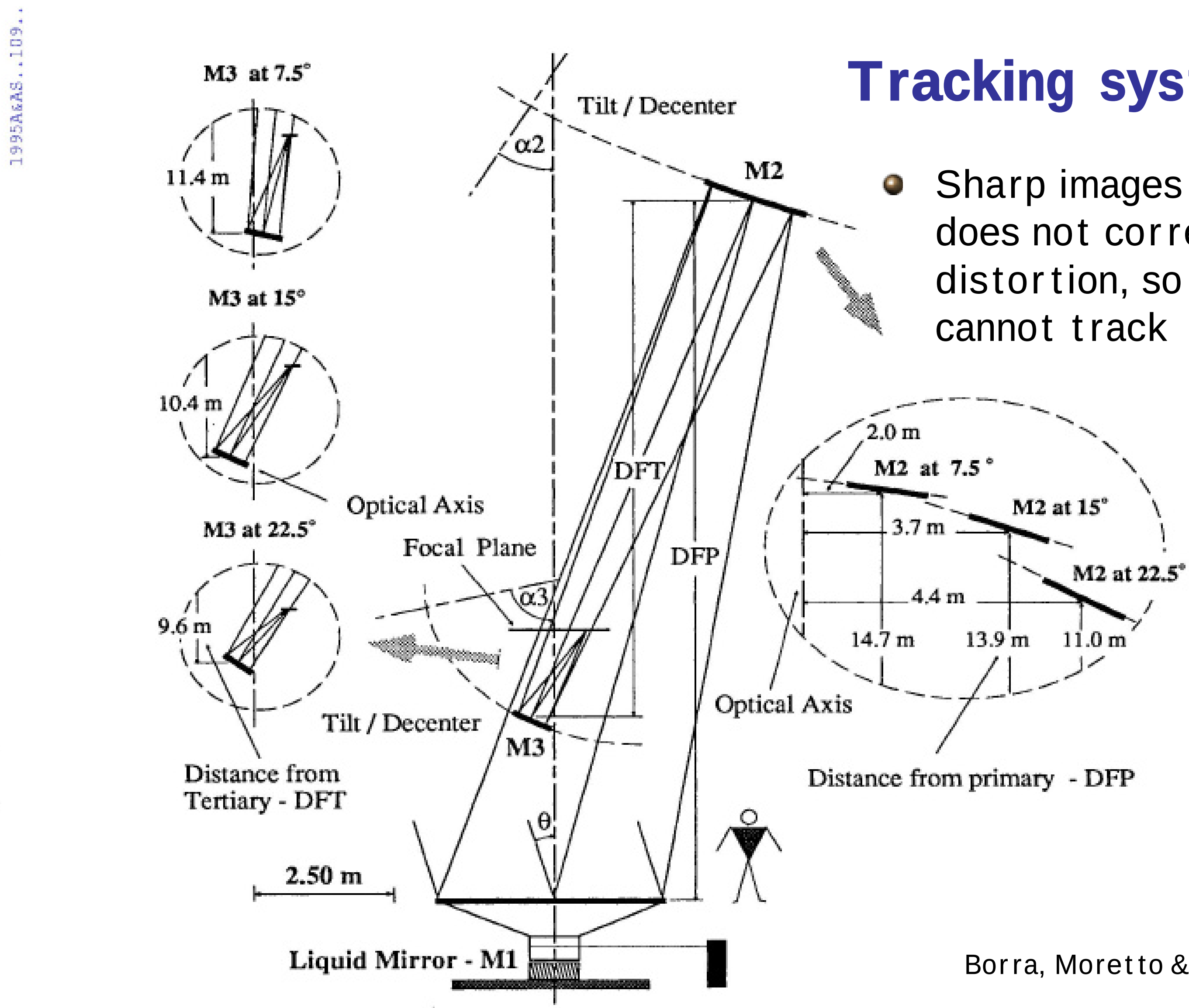
Gemini Project

Tracking system?

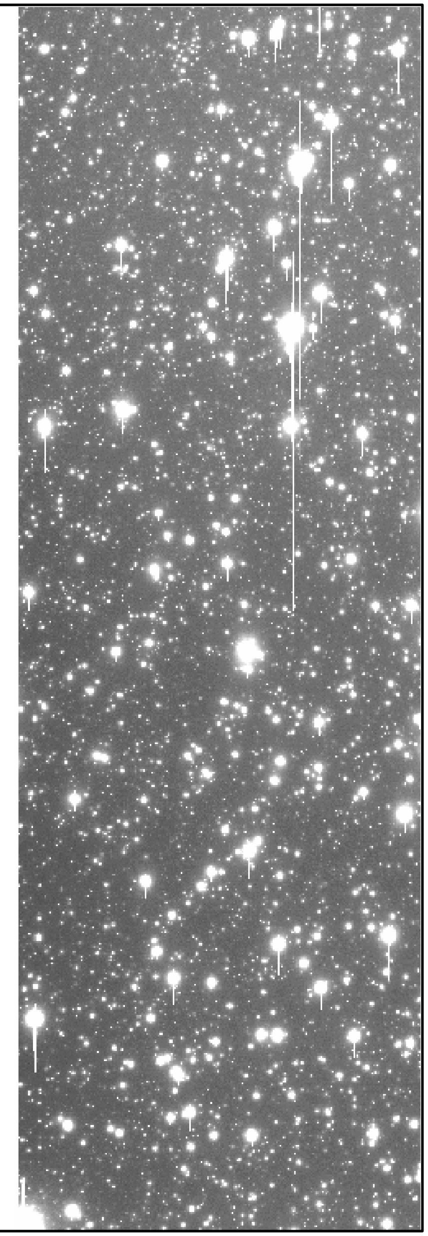
- Sharp images but… does not correct distortion, so cannot track



Borra, Moretto & Wang 1995

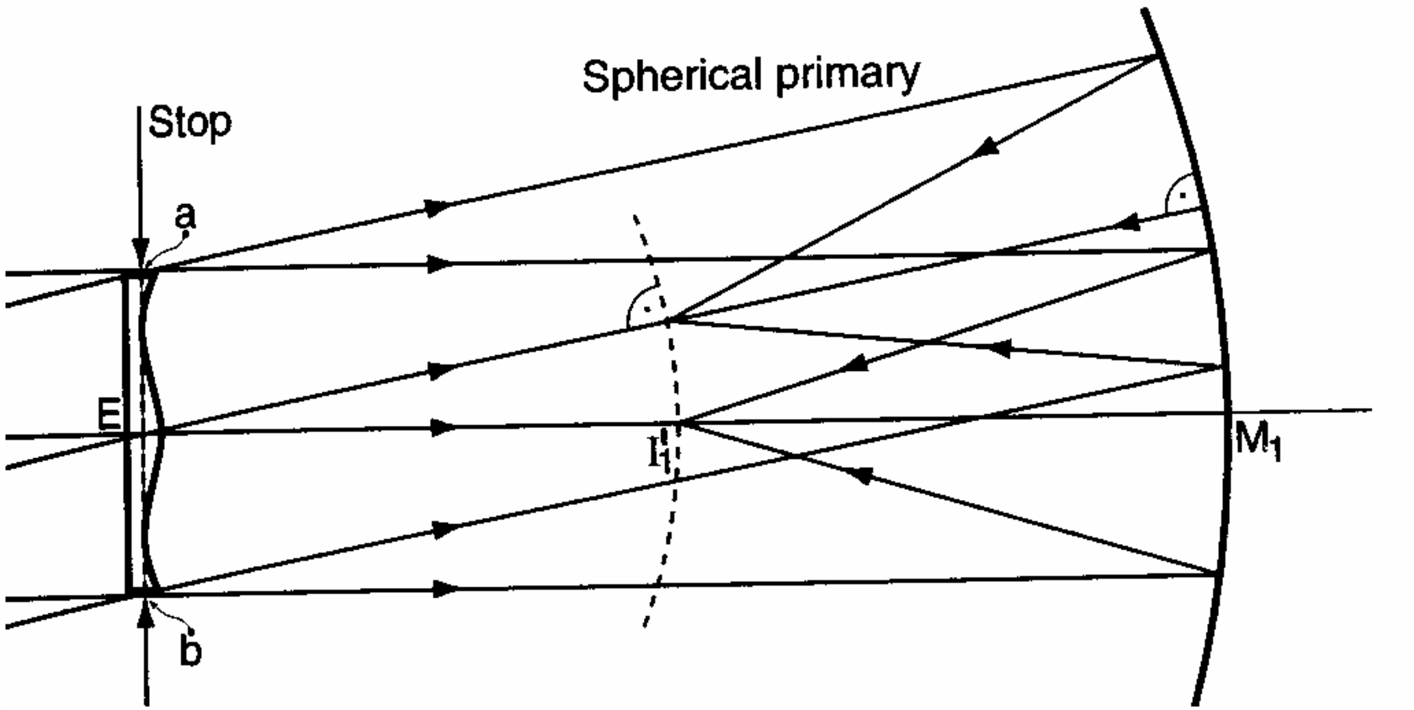
Tracking optics requirements

- Point and track with fixed parabolic primary mirror
- Access several degrees from zenith
- Tracking time ~ 0.5 hr
- Field of view ~ 1 arcmin (limited by atmosphere)
- Deliver collimated beam to a fixed location
- Diffraction-limited image quality
- Achromatic
- No distortion, field curvature or focal-plane tilt



Schmidt - Telescope Principle

- A sphere has no axis -> no coma, astigmatism or distortion



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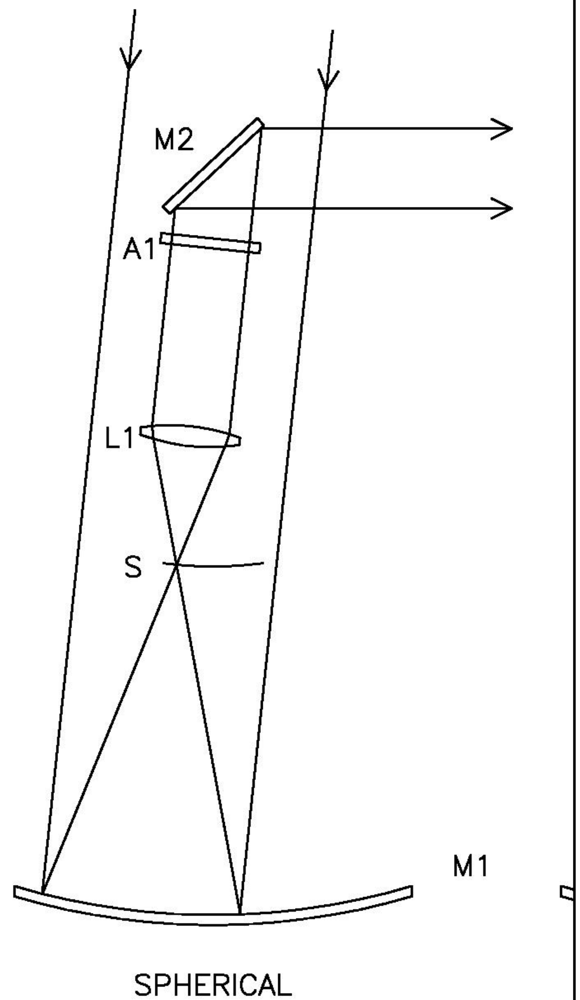
Spherical primary mirror

- M1 is a fixed spherical mirror
  - No-distortion condition satisfied
- Tracking system axis passes through the centre of curvature of M1
  - No-focus-tilt condition satisfied
- Spherical aberration removed by aspheric corrector A1 which moves with tracking system
- No zenith angle limitation – full sky coverage is possible if M1 is sufficiently large



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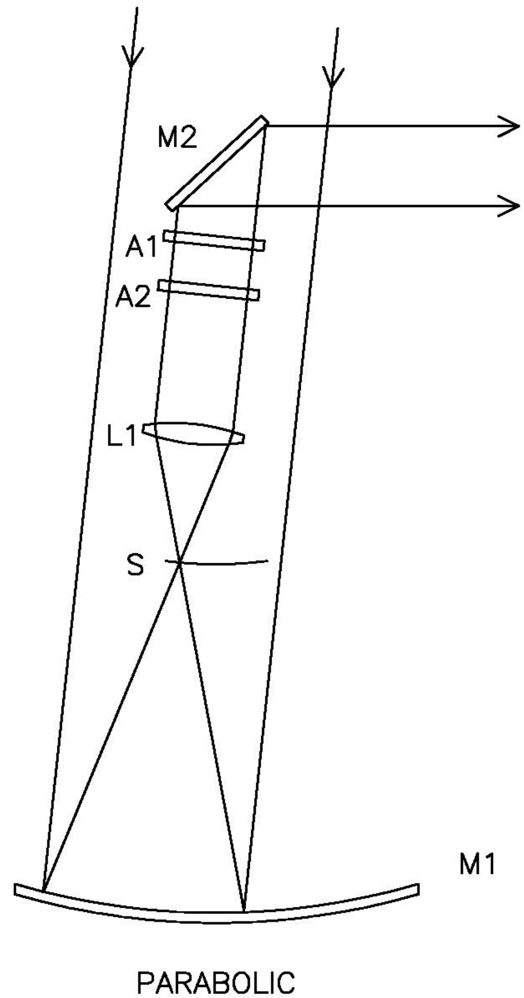
Parabolic primary mirror

- Add aspheric corrector A2, located conjugate to primary mirror M1
- A2 effectively converts the primary mirror to a spherical mirror
- A2 must move transversely, relative to the tracking system, in order to remain conjugate to M1. This does not introduce any distortion or focal plane tilt because A2 has no optical power
- With A2, the system performs like the spherical case, but with a zenith-angle limited by vignetting effects



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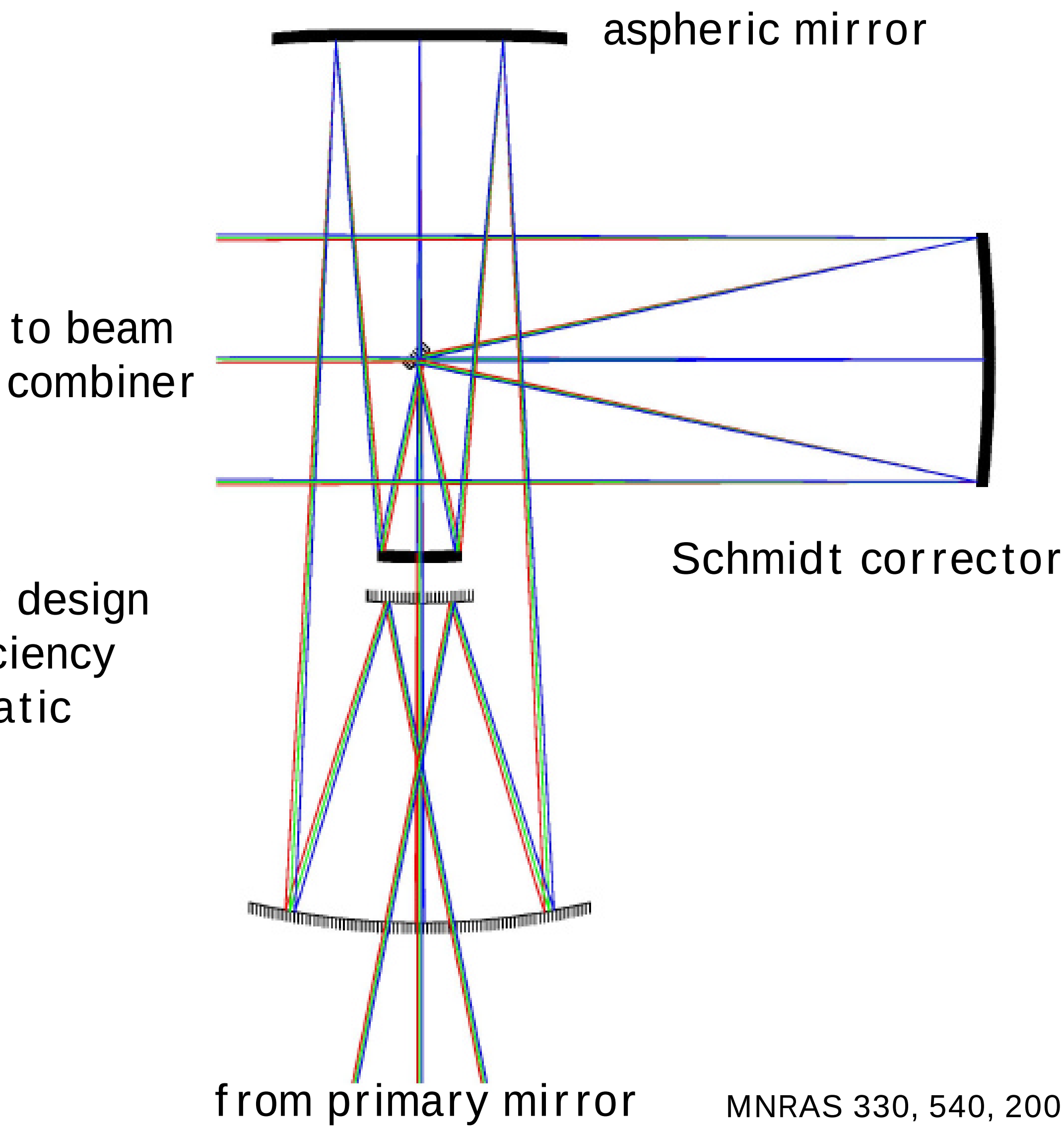
LAMA tracking optics



- All-reflecting design has high efficiency and no chromatic aberration

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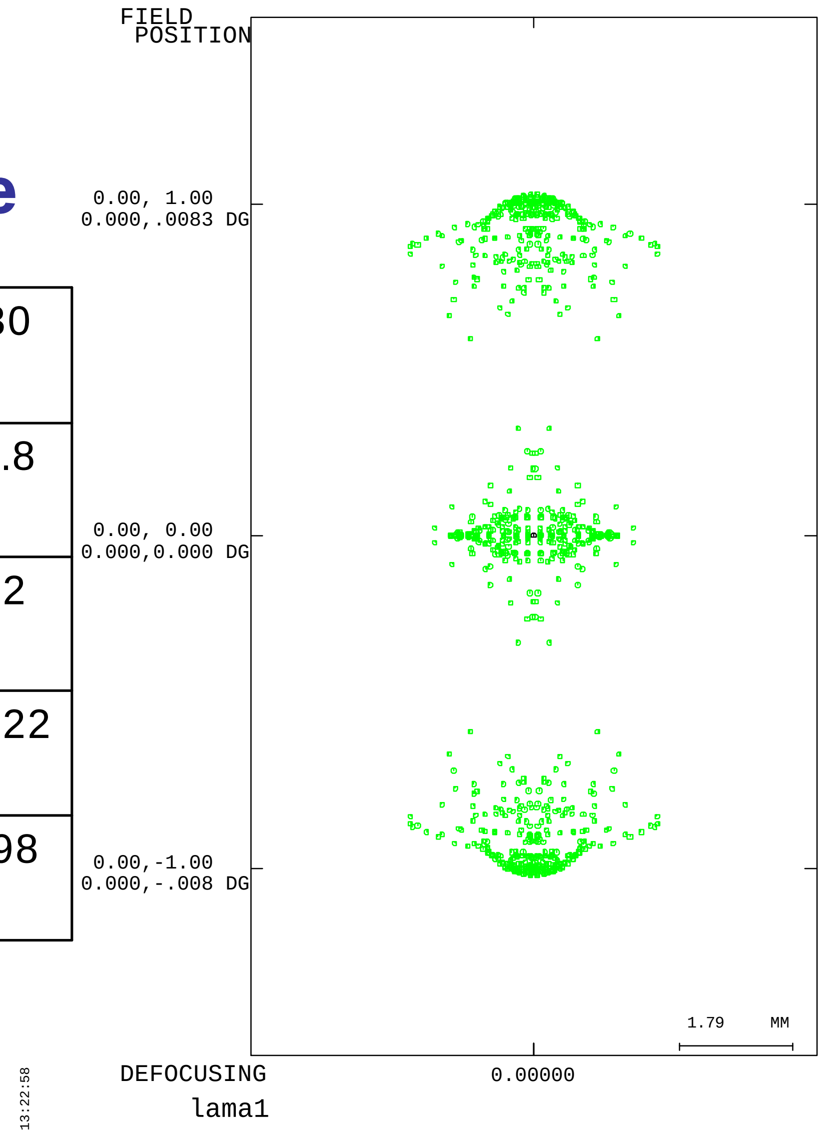
MNRAS 330, 540, 2002

Performance for 0 degrees zenith angle

Field angle (arcsec)	-30	0	+30
RMS Dia. (mas)	12.8	13.1	12.8
50% EED (mas)	8.2	10.9	8.2
RMS wave (λ = 1 um)	0.022	0.043	0.022
Strehl (λ = 1 um)	0.98	0.93	0.98



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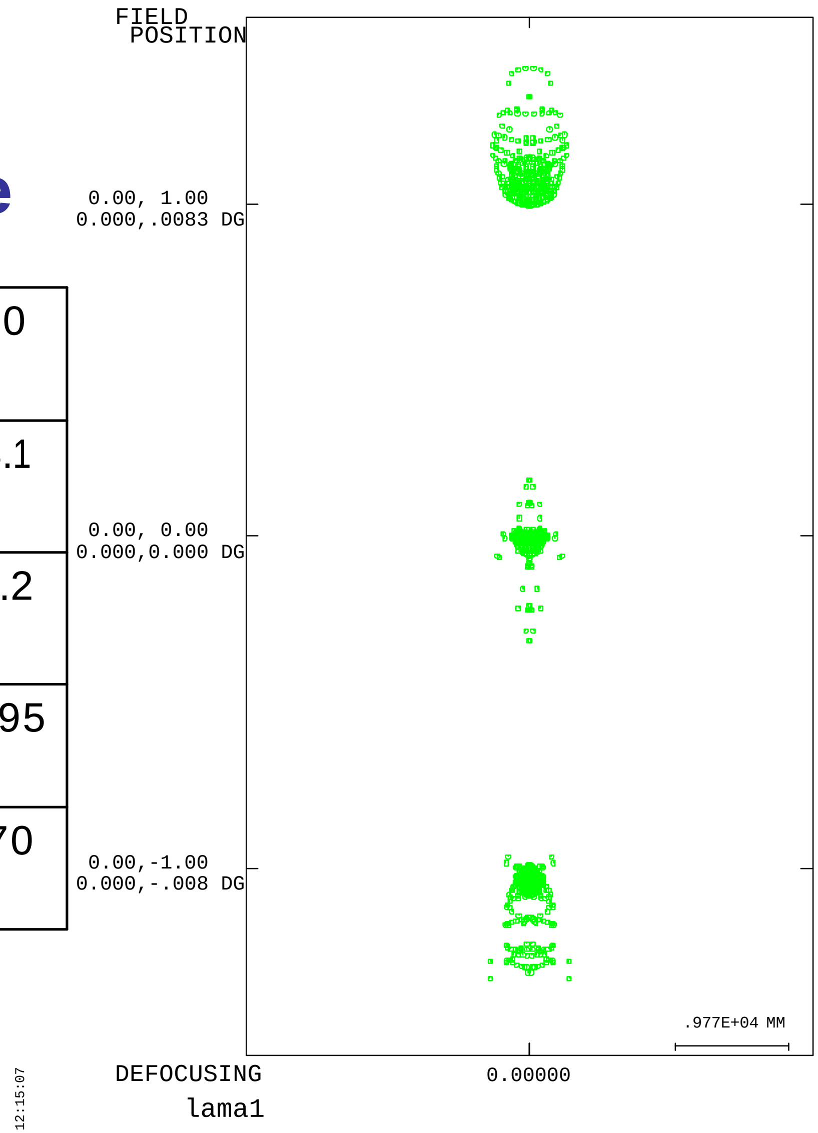
Performance for 4 degrees zenith angle

Field angle (arcsec)	-30	0	+30
RMS Dia. (mas)	44.0	30.3	44.1
50% EED (mas)	17.3	15.0	27.2
RMS wave (λ = 1 um)	0.080	0.062	0.095
Strehl (λ = 1 um)	0.77	0.86	0.70



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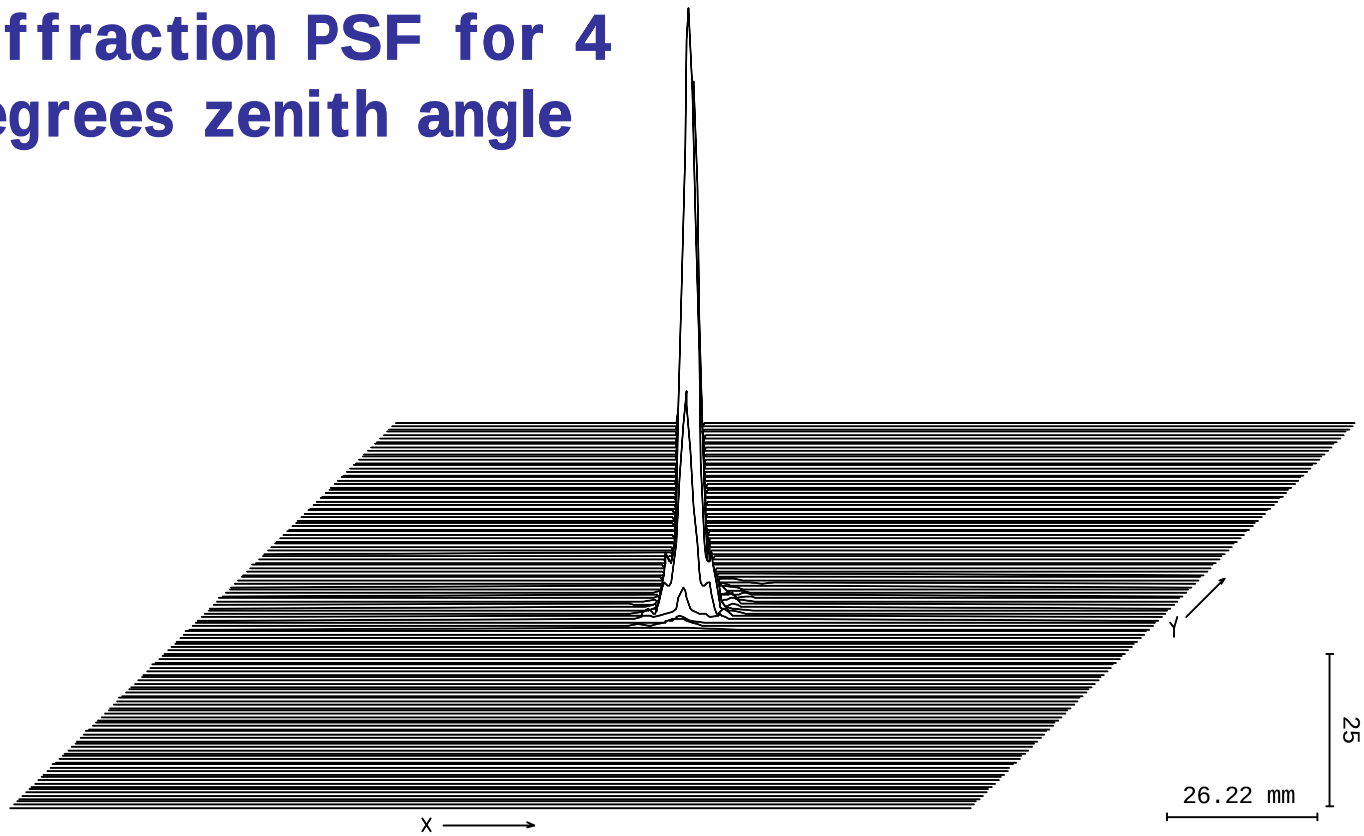
Diffraction PSF for 4 degrees zenith angle



lama1 POSITION 1	DIFFRACTION INTENSITY SPREAD FUNCTION FLD(0.00, 1.00)MAX;(0.0, 0.0)DEG DEFOCUSING: 0.000000 MM	WAVELENGTH WEIGHT 1000.0 NM 1
13-Apr-02		

Performance of LAMA tracking system

- Points and tracks over an 8-degree diameter area of sky
- Tracking for up to 30 min per field
- All-reflecting design – wide wavelength range
- Feeds light to a fixed focus
- Sub-arcsec natural images
- High Strehl ratio (with AO)

Zenith angle (deg)	0	1	2	3	4
Field angle (arcmin)	Strehl Ratio (λ = 1 um)				
+0.5	0.98	0.99	0.98	0.93	0.77
0	0.93	0.93	0.92	0.90	0.86
-0.5	0.98	0.97	0.94	0.87	0.70

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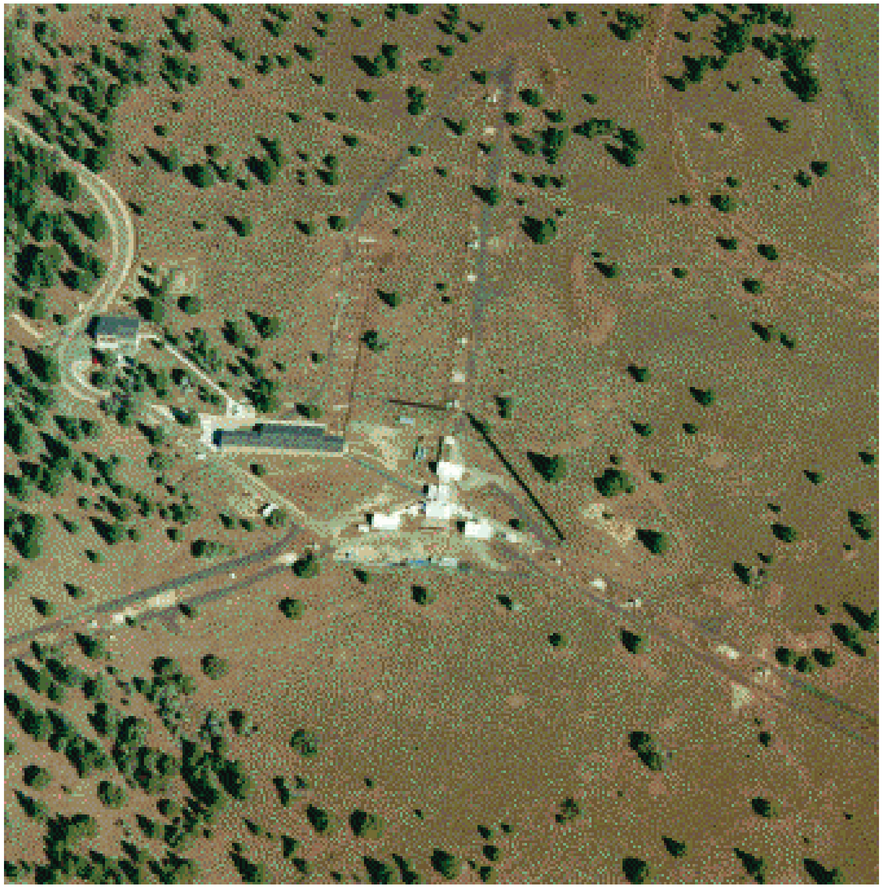
Optical Interferometry

- Demonstrated technology:
  - phase closure
  - pathlength control
  - adaptive optics
- Active development
  - NPOI
  - PTI
  - CHARA
  - KECK
  - VLTI



Naval Prototype Optical Interferometer

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Interferometer sensitivity

- Fraction of power in central image equals the filling factor of the array

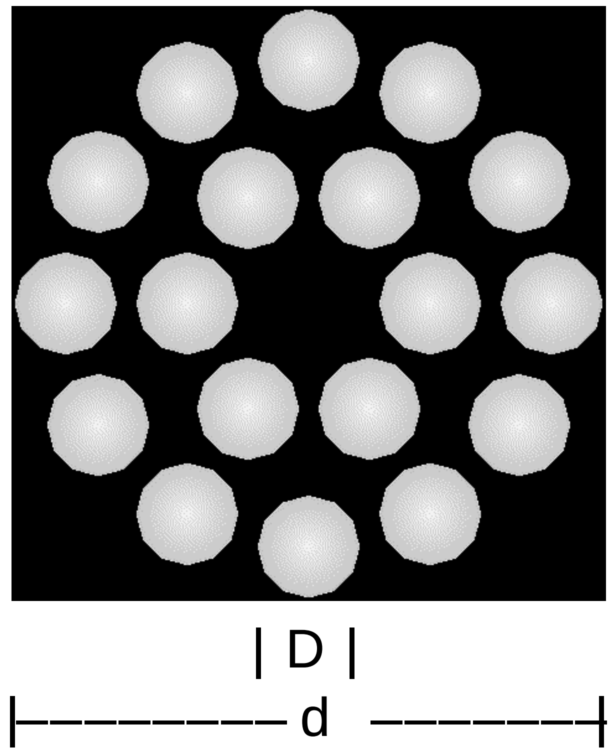
  $f = ND^2/d^2$

- Incoherent beam combination

  $S_I \sim ND^4$

- Coherent beam combination

  $S_c \sim f^2 N D^2 d^2$
  $\sim f N^2 D^4$



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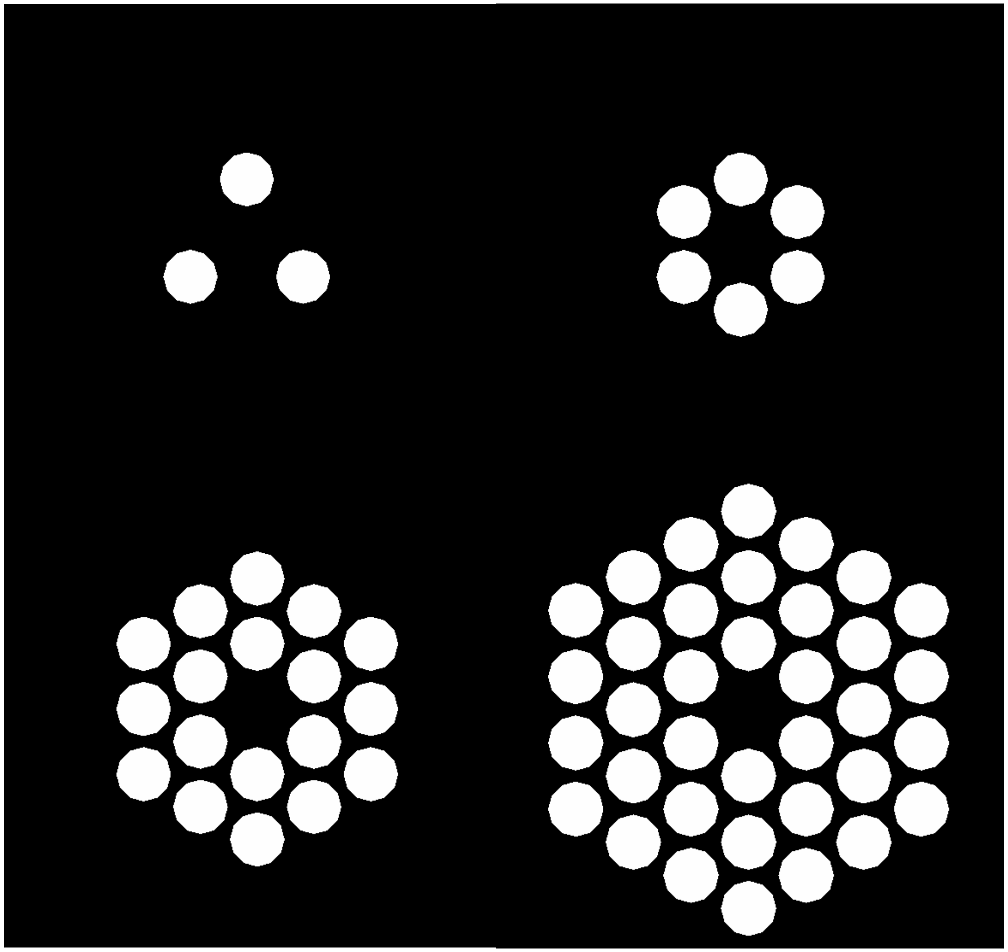
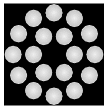
10-metre elements

Equivalent Diameter

D_A	D_θ
17m	31m
24m	35m
42m	60m
60m	85m





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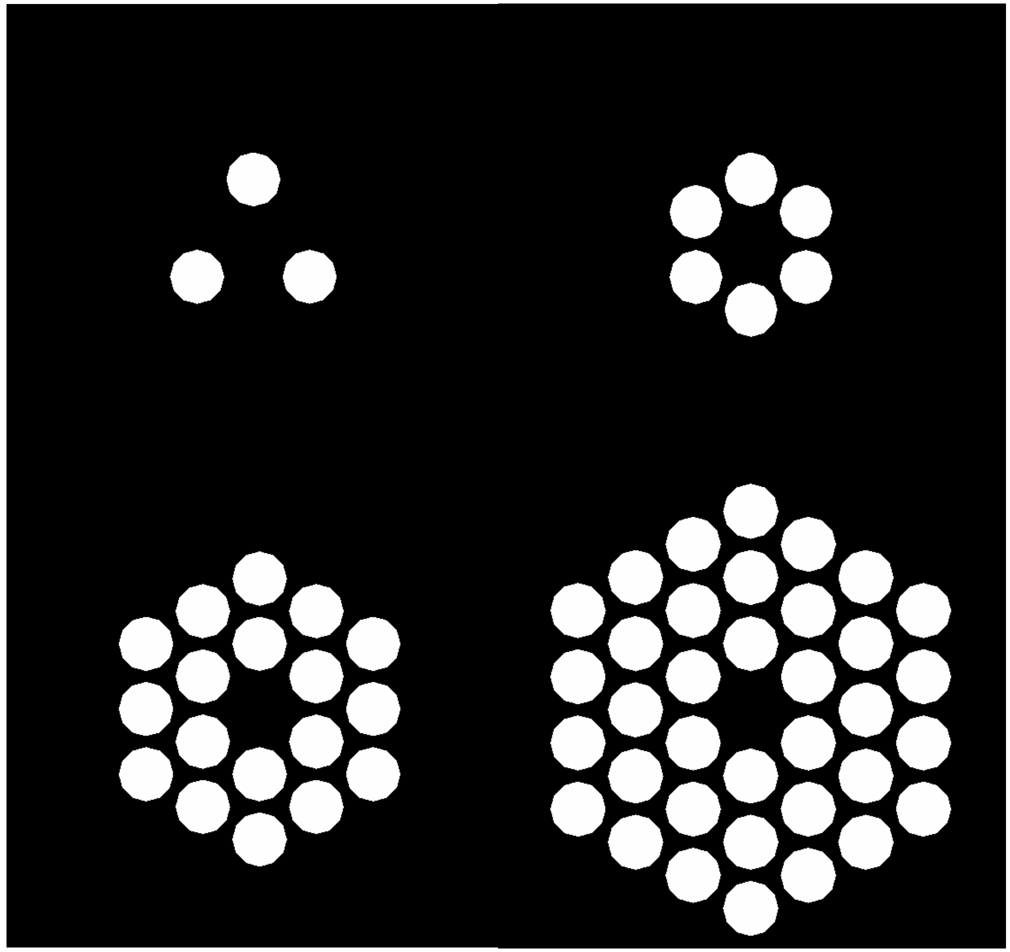
Sensitivity compared to a 10m telescope

S_I	S_c
3	4.5
6	18
18	162
36	648



Primary mirror costs

Approximate costs of possible technologies

Technology	Unit cost (K$ /m²)	Cost for 1400 m^2
Gemini meniscus mirror	400	560 M$
Segmented mirrors	100	140 M$
Liquid mirrors	5	7 M$

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Liquid-mirrors

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The Economist

Fundamentals

- Equilibrium shape

$$j = gz - \tfrac{1}{2} w^2 r^2 = 0$$

$$z = \frac{w^2 r^2}{2g} = \frac{r^2}{4F}$$

- Focal Length

$$F = \frac{g}{2w^2}$$

- Focal ratio

$$f = \frac{F}{D} = \frac{g}{2w^2 D}$$

- Period

$$P = \frac{2p}{w} = 2p\sqrt{\frac{2F}{g}}$$

$$\approx 2.8\sqrt{F} \quad \text{(SI units)}$$

- Rim velocity

$$u = \frac{1}{2} Dw = \sqrt{\frac{gD}{8f}}$$

$$\approx 1.1\sqrt{D/f} \quad \text{(SI units)}$$

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Effect of gravitational divergence

$$j = -\frac{GM}{\left[r^2 + (z + R_\oplus)^2\right]^{1/2}} - \tfrac{1}{2} w^2 r^2 = -\frac{GM}{R_\oplus}$$

$$z = \frac{w^2 r^2}{2g}$$

$$-\frac{r^2}{2R_\oplus} \qquad \left(\sim 10^{-7} D\right)$$ Focus shift

$$+\left[\frac{3}{8R_\oplus^3} + \frac{3w^2}{4gR_\oplus^2} + \frac{w^4}{4g^2 R_\oplus}\right] r^4 \qquad \left(\sim 10^{-9} D\right)$$ Spherical aberration

$$+\cdots$$

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Effect of rotation axis tilt (by angle e)

$$j = -\frac{GM}{\left[r^2 + (z + R_\oplus)^2\right]^{1/2}} - \tfrac{1}{2} w^2 \left[(x \cos e - z \sin e)^2 + y^2 \right] = -\frac{GM}{R_\oplus}$$

$$z = \frac{w^2 r^2}{2g} - \frac{r^2}{2R_\oplus} + \frac{r^4}{8R_\oplus^3}$$

$$-e \frac{w^4}{2g^2} r^3 \cos f \qquad \left(\sim e D / f^2 \right)$$ Coma

$$-e^2 \frac{w^2}{2g} r^2 \cos^2 f \qquad \left(\sim e^2 D / f \right)$$ Astigmatism

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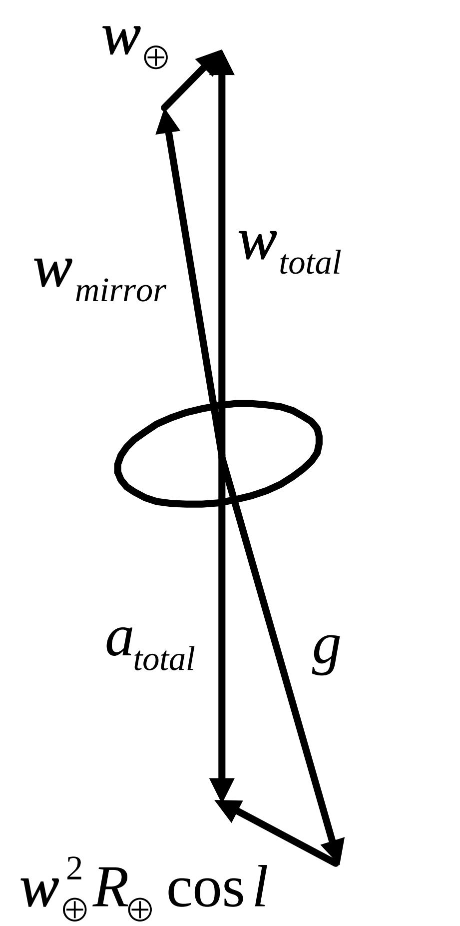
Effect of Earth's rotation (Coriolis force)

- Can be entirely eliminated by a compensating tilt of the rotation axis
- Seen from an inertial frame, the fluid (and container) rotates about an axis given by the sum of the angular momentum vectors of the mirror and the Earth.
- Choose the direction of the rotation axis to make the resultant angular momentum vector parallel to the total acceleration vector.
- An axis tilt of about 12 arcsec is required for the NASA 3m.



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PASP 113, 1511, 2001

Liquid mirror telescopes

A century later…

Robert Wood, 1909

UCLA Lidar, 1995

Liquid-mirror telescopes

UBC	2.7 m	1990
UWO	2.6 m	1992
UCLA	2.7 m	1995
NASA	3.0 m	1996
LZT	6.0 m	2002

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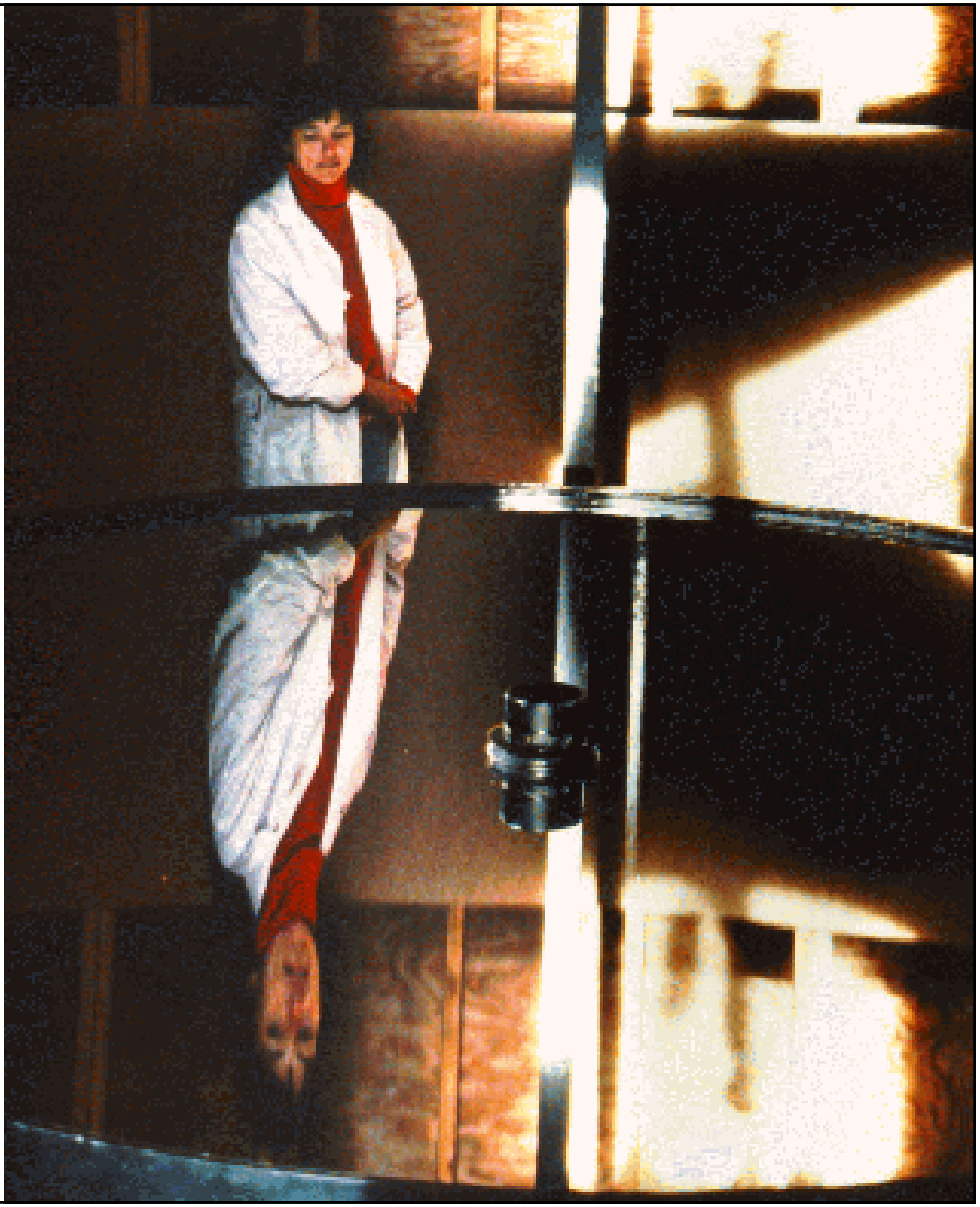
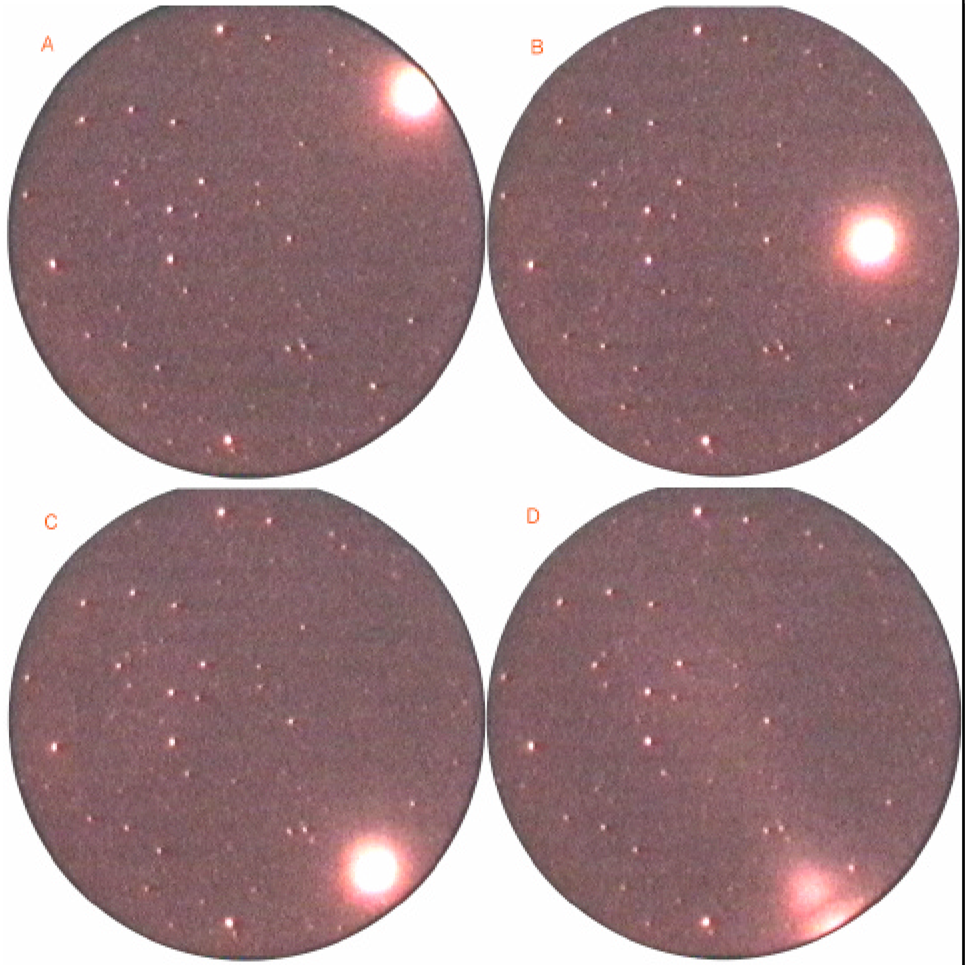


NASA 3-m liquid-mirror telescope (NODO)

Primary NODO mission – space debris

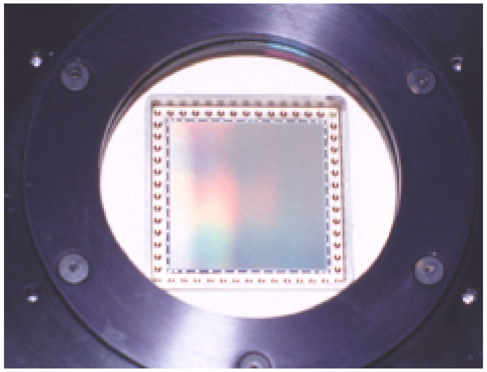
- Detect and characterize the 1-10cm dia debris population in low Earth orbit
- Intensified digital video CCD camera
- Has detected several thousand objects

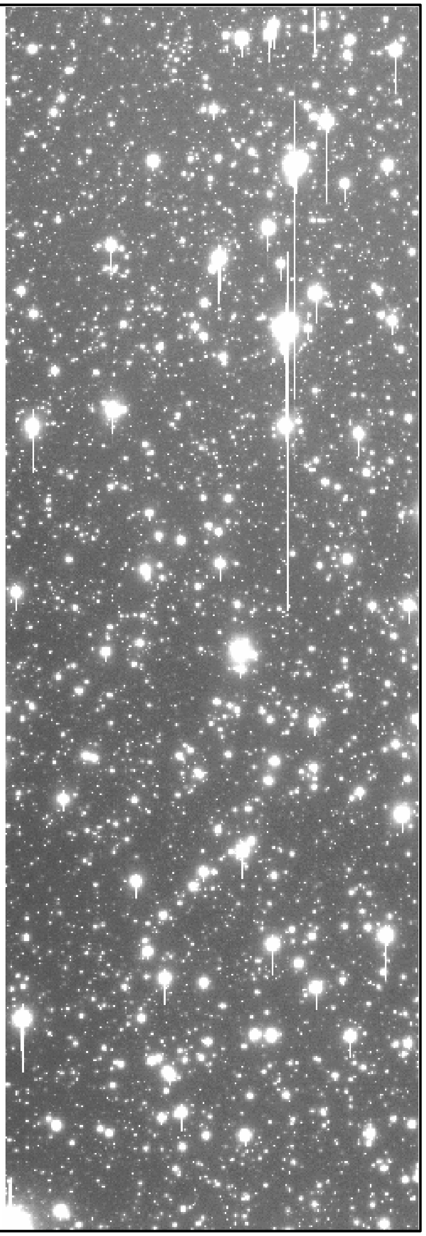


Mark Mulrooney

Time-Delay Integration

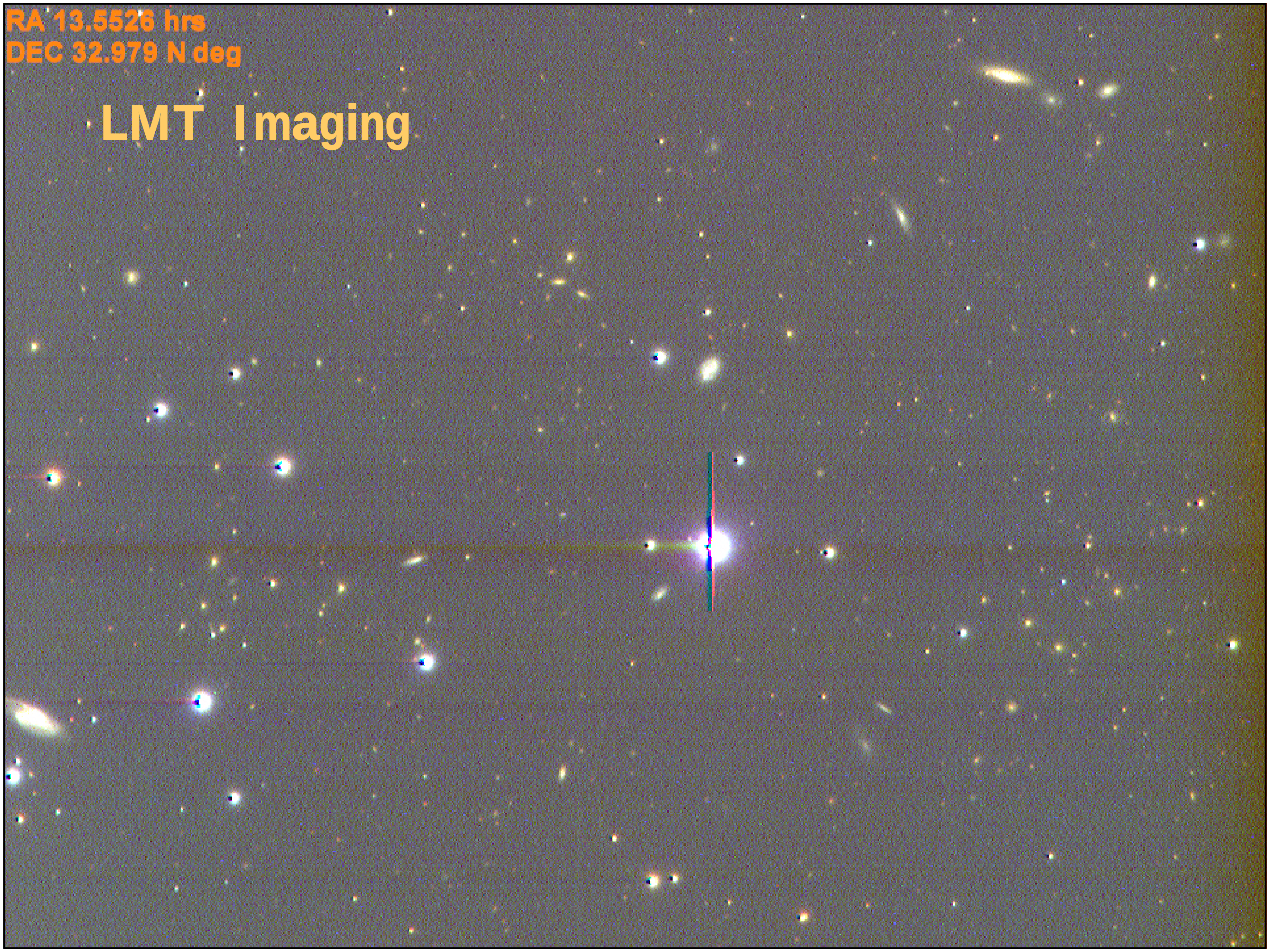
- Image moves continuously across CCD due to Earth's rotation
- Charge being generated by photons is shifted electronically along the CCD columns at the same rate
- Data are read continuously all night long, at approximately 13 lines per second
- Integration time is the time taken for an image to cross the CCD (78 sec for the 1Kx1K)



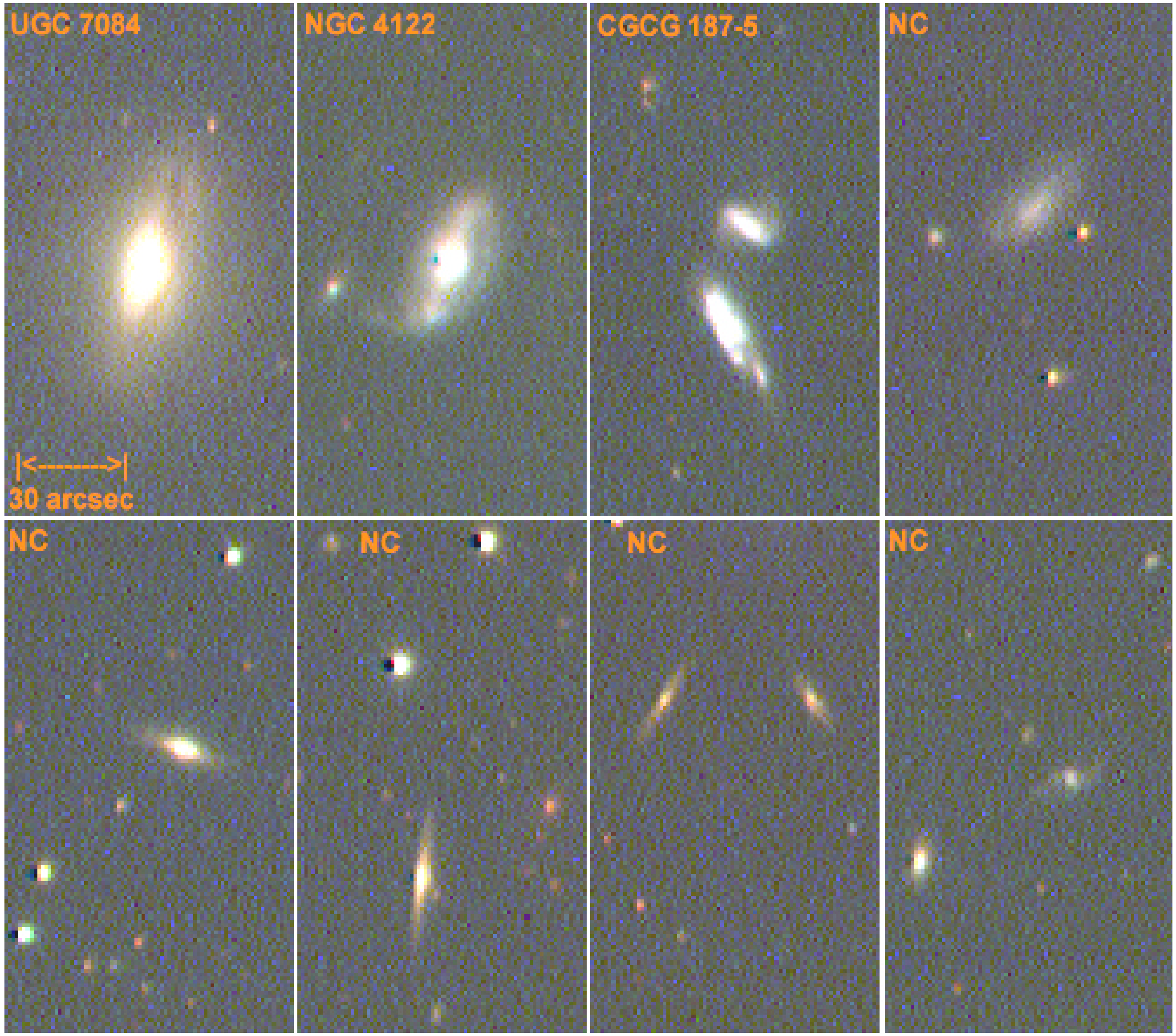


NASA 3m LMT

SUNY 020430


RA 13.5526 hrs
DEC 32.979 N deg
LMT Imaging

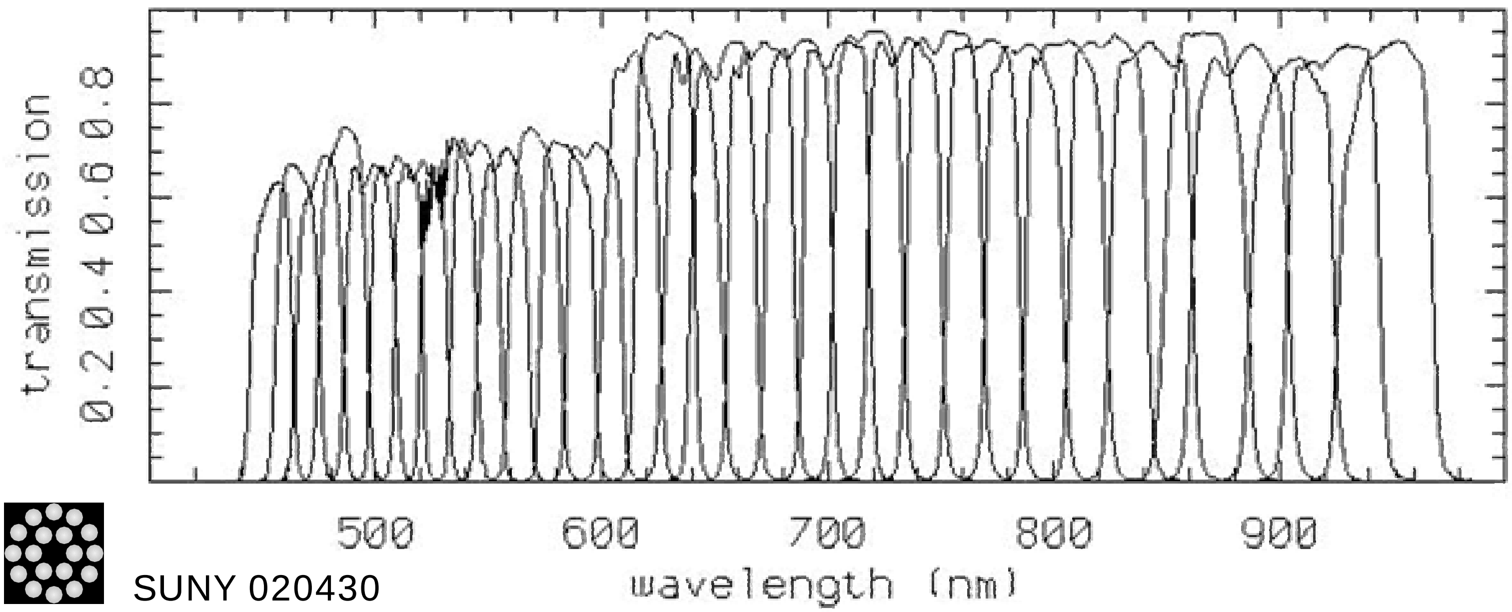
LMT imaging



SUNY

NODO Survey

- Driftscan survey using 1K x 1K CCD
- BVRI + 35 medium band filters
- 12-18 hrs ra at +33 deg dec
- 20-22 magnitude limit
- ~3 million objects



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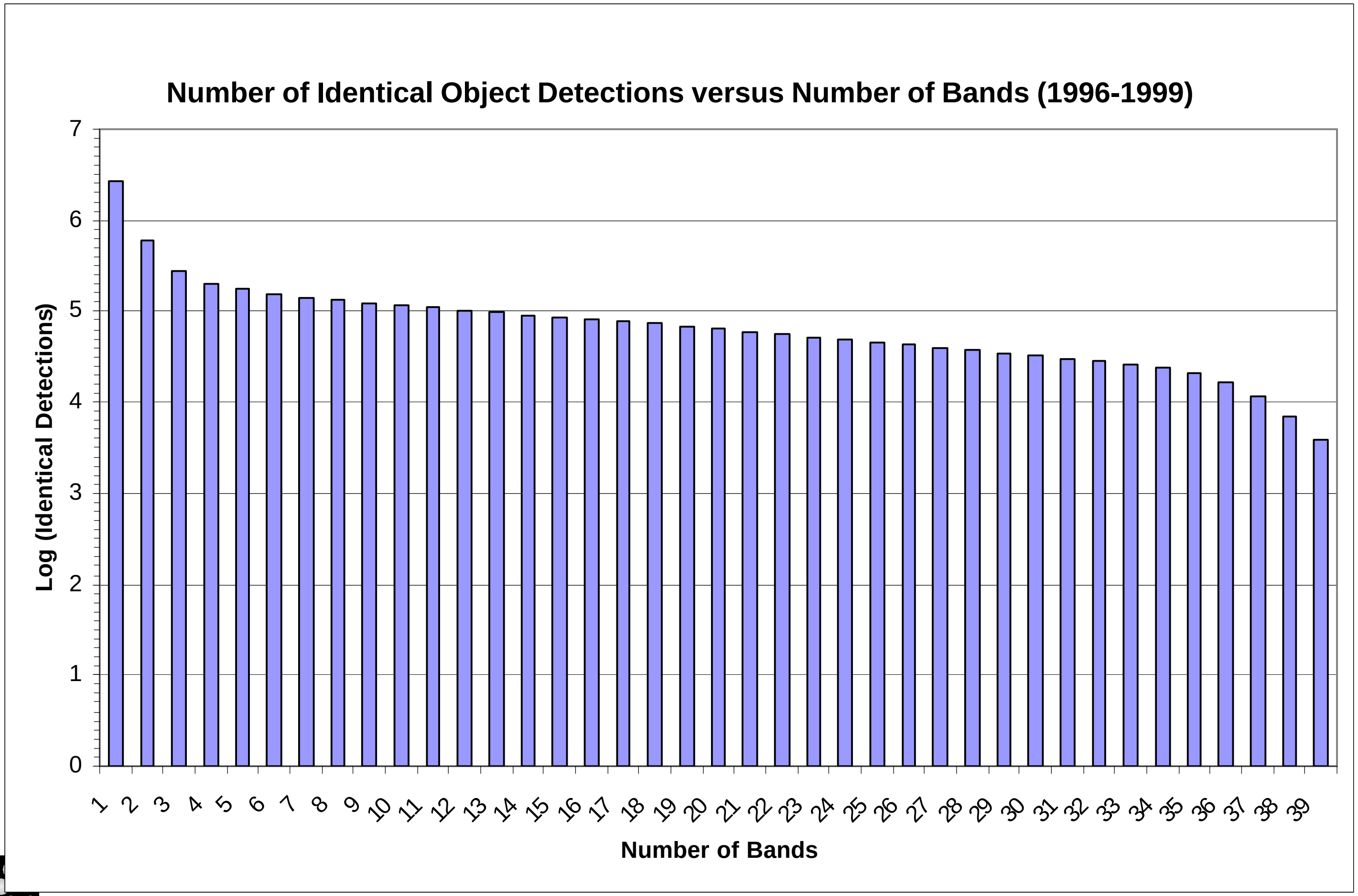
Number of detections vs number of bands



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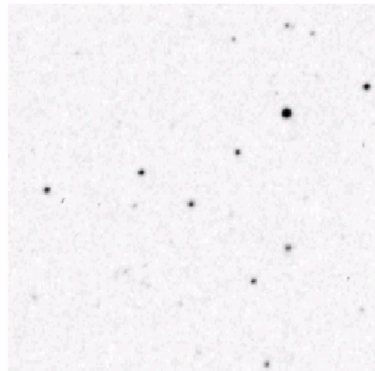
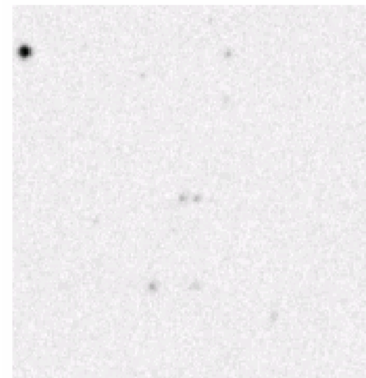
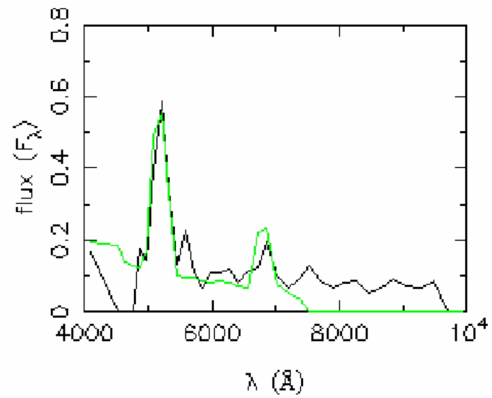
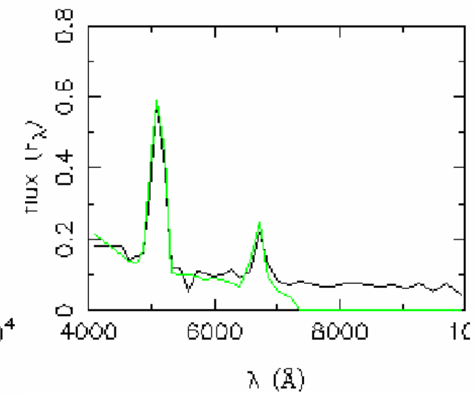
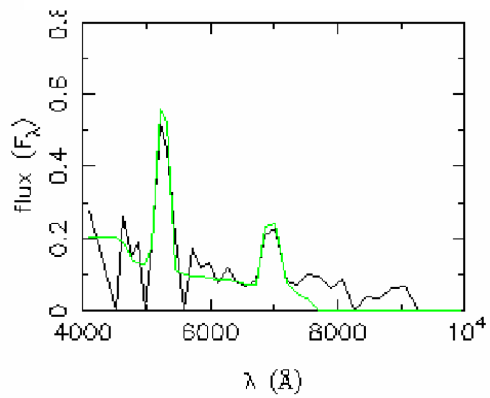
NODO survey: emission-line galaxies











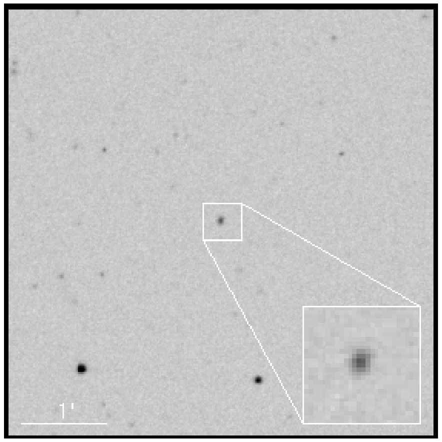
LMT: z = 0.037
NED: z = 0.038

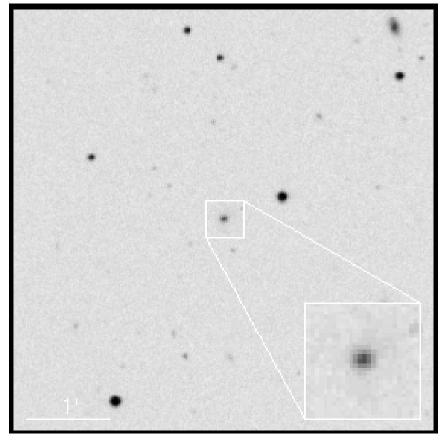
LMT: z = 0.017
NED: z = 0.015

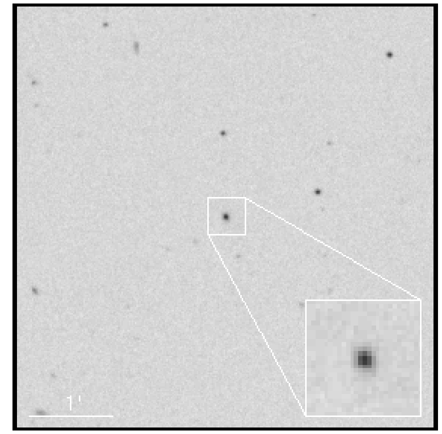
LMT: z = 0.057
NED: z = 0.052

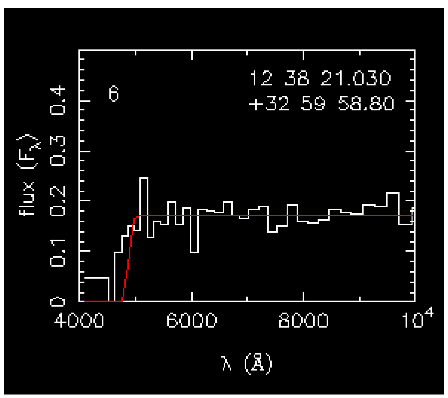
Remi Cabanac

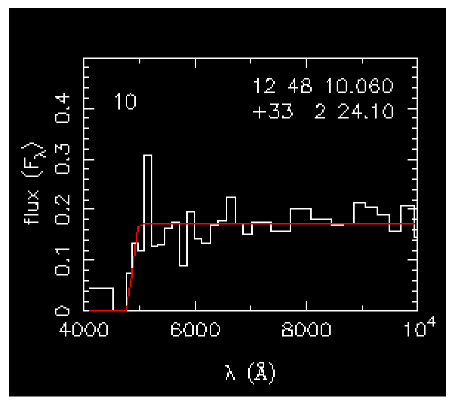
NODO survey: early-type galaxies, z~0.2

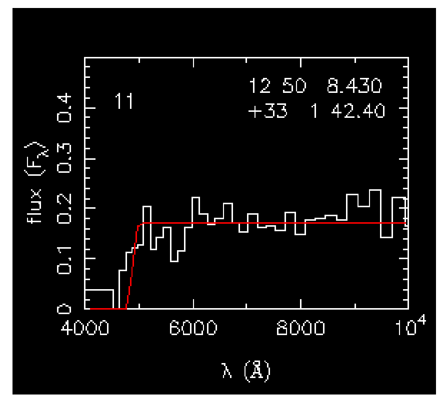












Remi Cabanac

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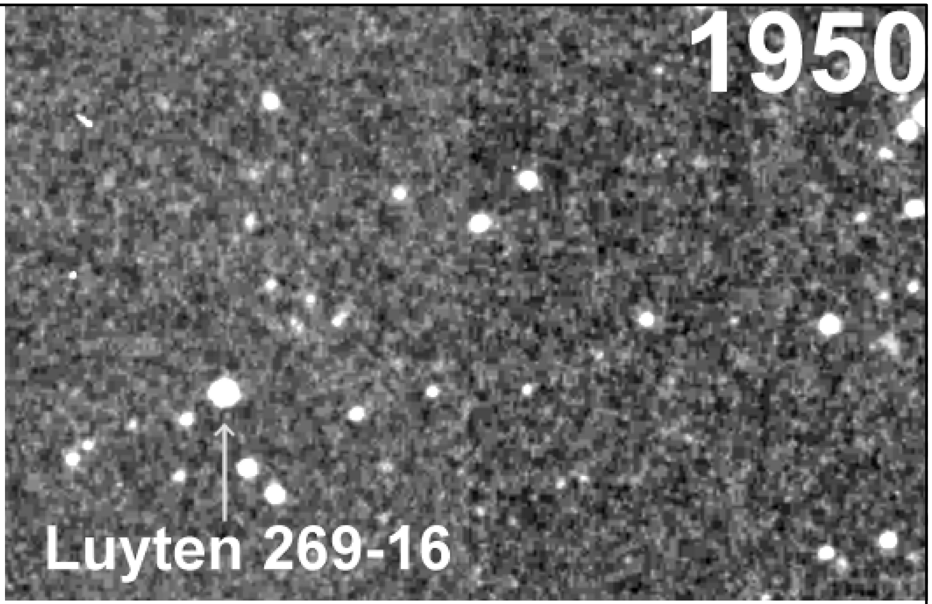
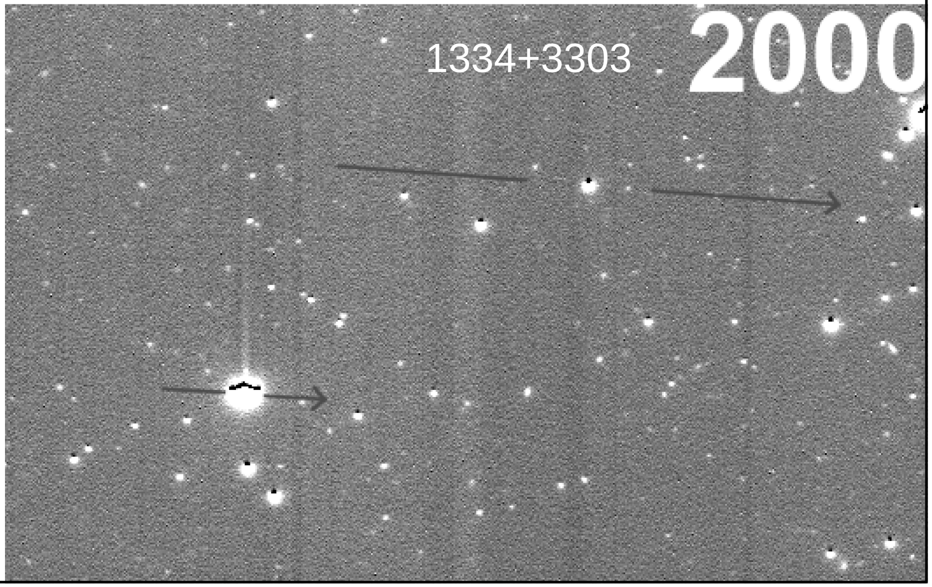
LMT proper motion survey

- Study local halo-disk populations and search for old halo white dwarfs (dark matter candidate)
- NODO R band blinked against Gen 1 POSS
- 50-year baseline
- 20 sq degrees to ~19 mag
- Pm limit ~ 40 mas/yr
- 1104 high-proper-motion stars found (from 1 night of LMT data)
- BVRI and Multiband data
- 2MASS identifications for 804 stars





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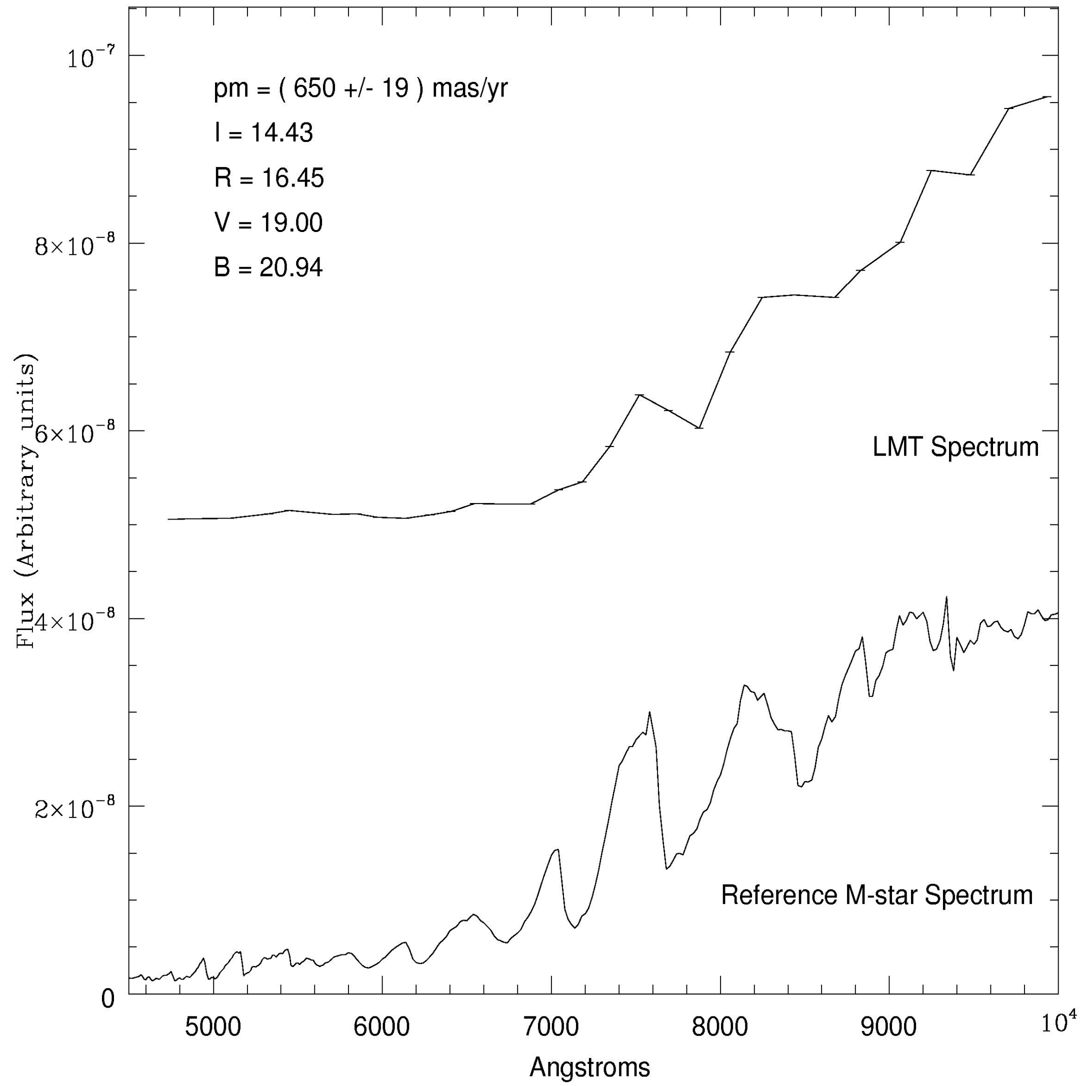
1334+3303 photometry and spectral energy distribution



Spectral type ~ M8

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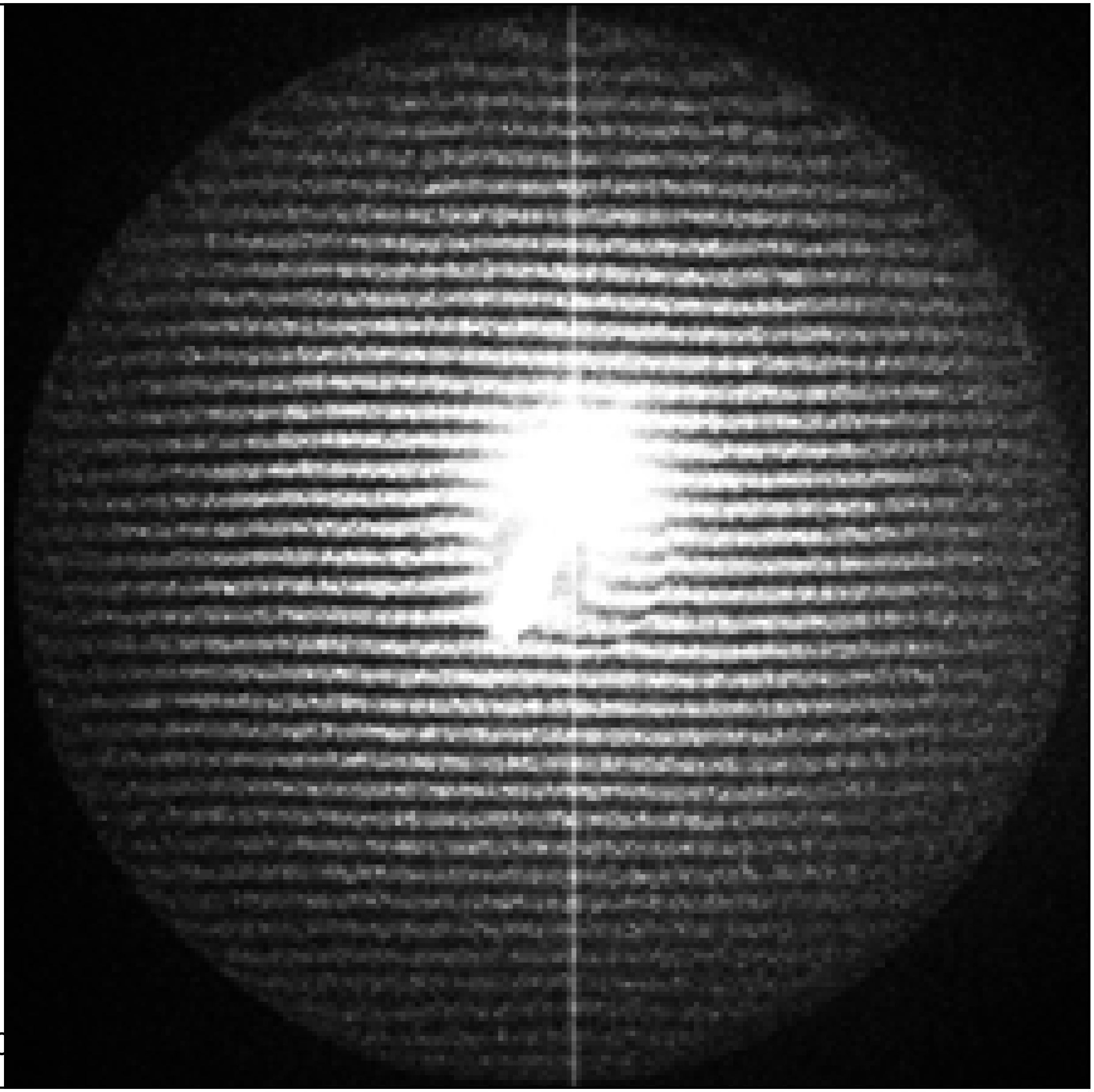
Liquid-Mirror Optical Testing



Ermanno Borra

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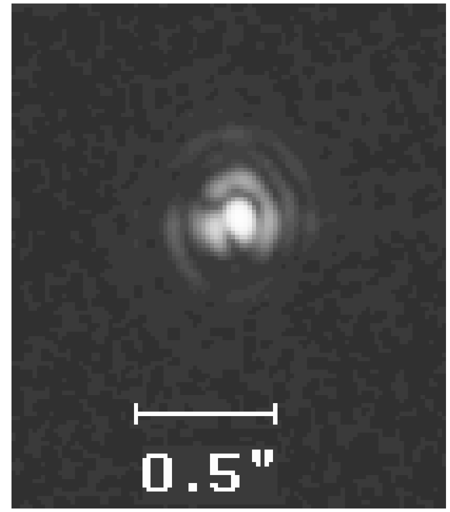
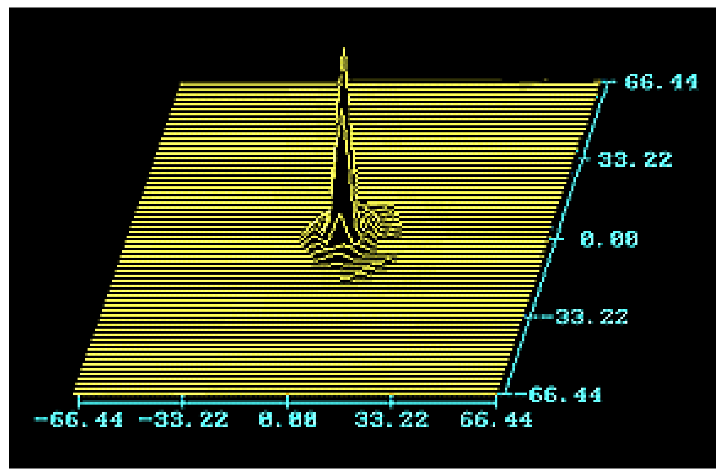
Laboratory Performance

- Strehl Ratio
  S = central intensity/ideal central intensity

- S = 0.81 measured in lab tests of 2.5m LM (at 0.6 um)

- S ~ exp($-k^2\sigma^2/2$)
  $k = 2\pi/\lambda$
  σ = RMS OPL error





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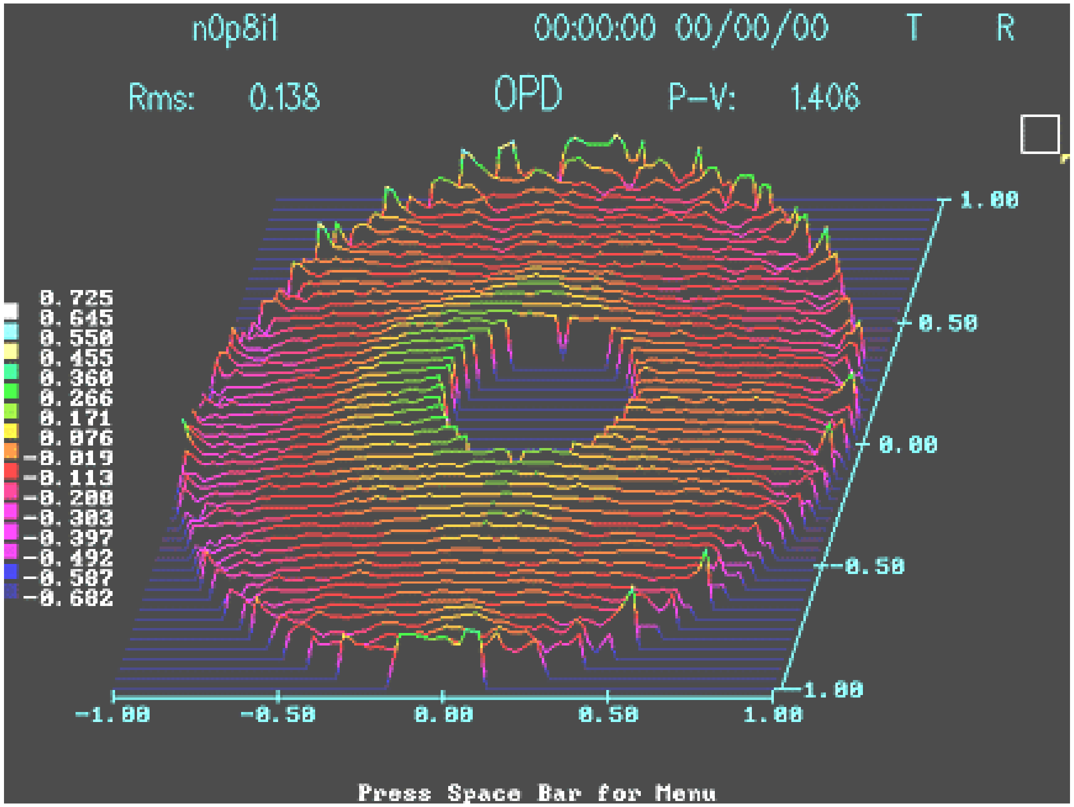
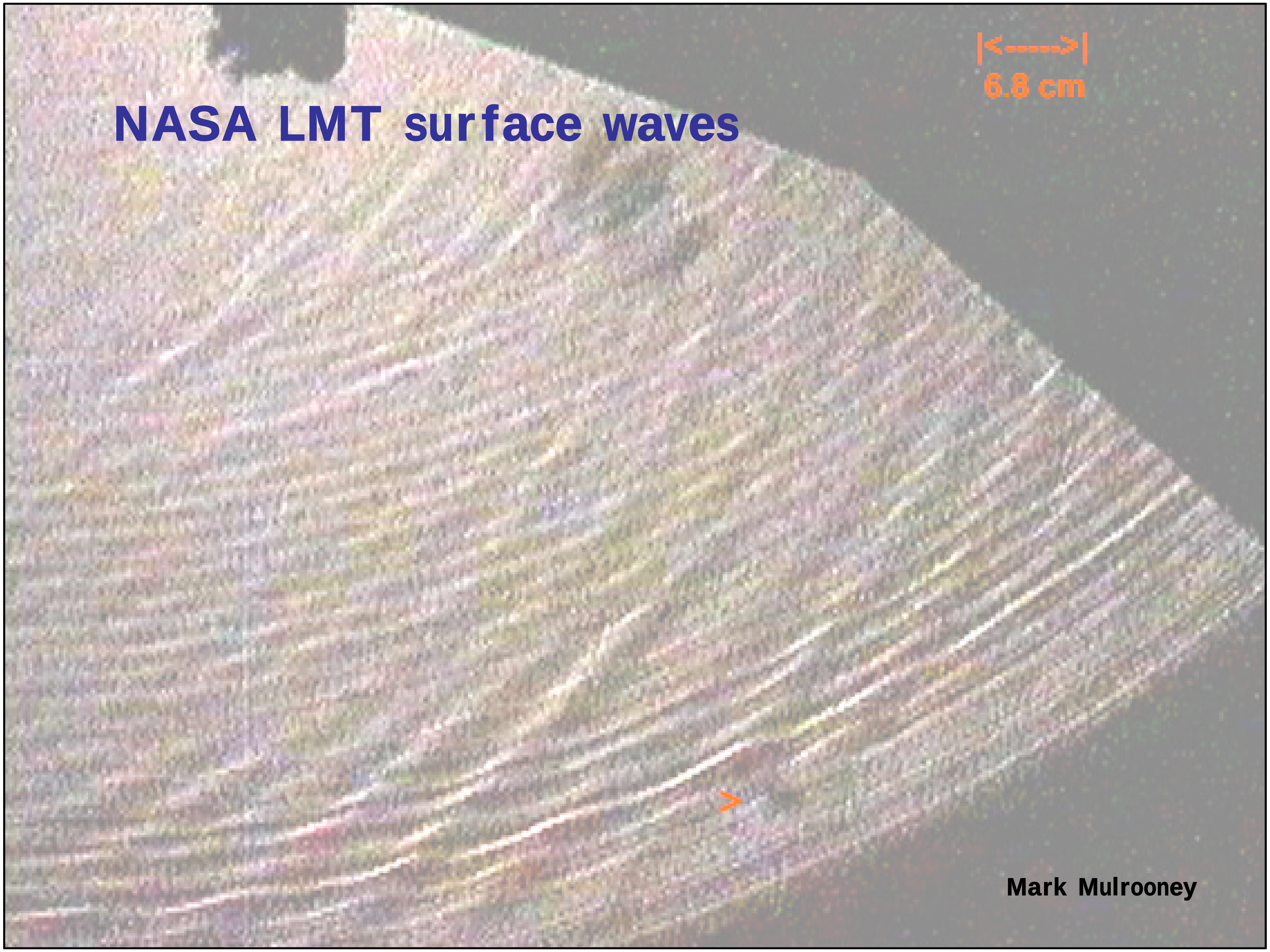
Ermanno Borra

Liquid-Mirror Surface Quality

- 85 nm RMS error
- S = 0.93 at λ = 2 um




NASA LMT surface waves
|<----->|
6.8 cm
>
Mark Mulrooney

NODO mirror surface analysis

- RMS wave amplitude:
  46 nm (5 kt wind)
  73 nm (15 kt wind)

NASA 3m LMT

Strehl ratio (no atmosphere)

Wavelength (um)	Strehl ratio 5 kts	Strehl ratio 15 kts
0.50	0.313	0.185
0.65	0.670	0.368
0.85	0.791	0.559
1.00	0.845	0.657
1.25	0.897	0.764
1.60	0.936	0.848
2.00	0.959	0.900

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Large Zenith Telescope

- SW British Columbia (Canada)
- 400 m altitude
- 6-m LMT

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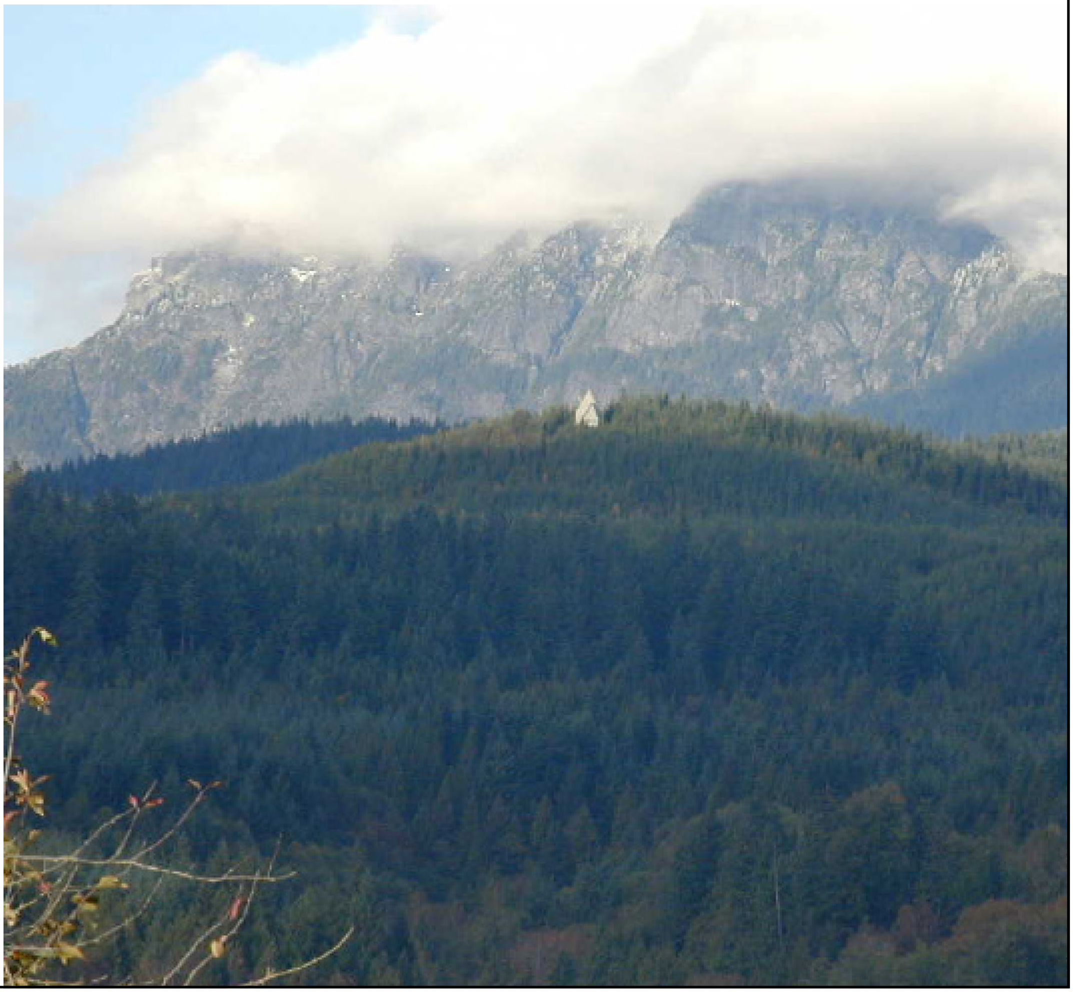
Technical challenges

- Mirror stability
- Air bearing capacity
- Telescope structure and control system
- Cost (< $0.4 M)



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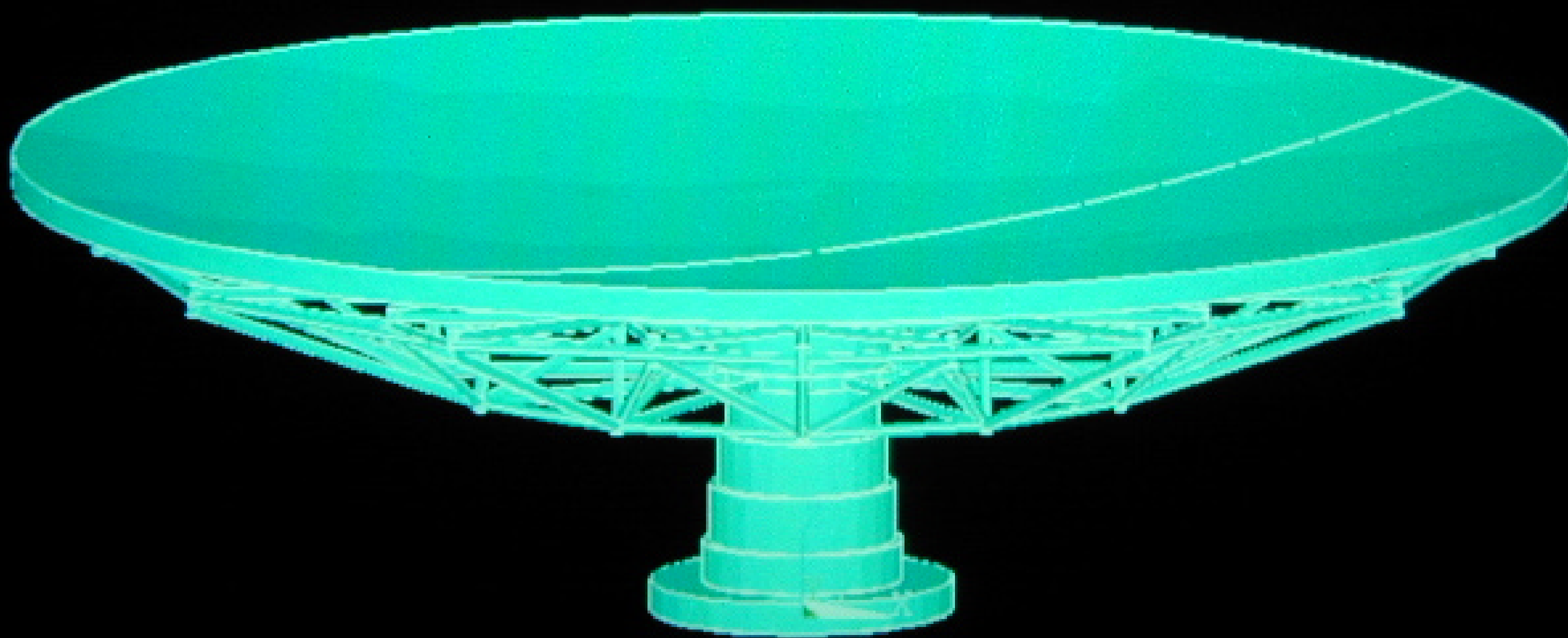
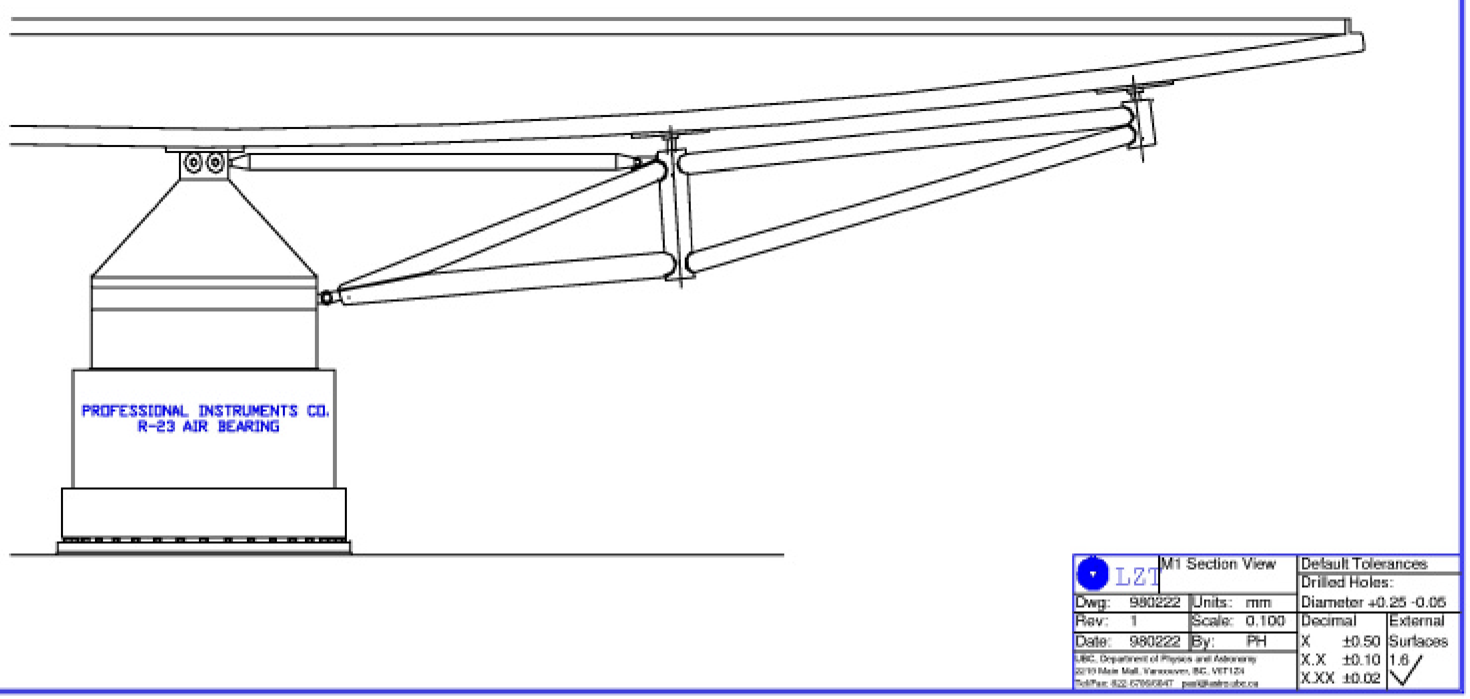
LZT primary mirror concept



LZT mirror design



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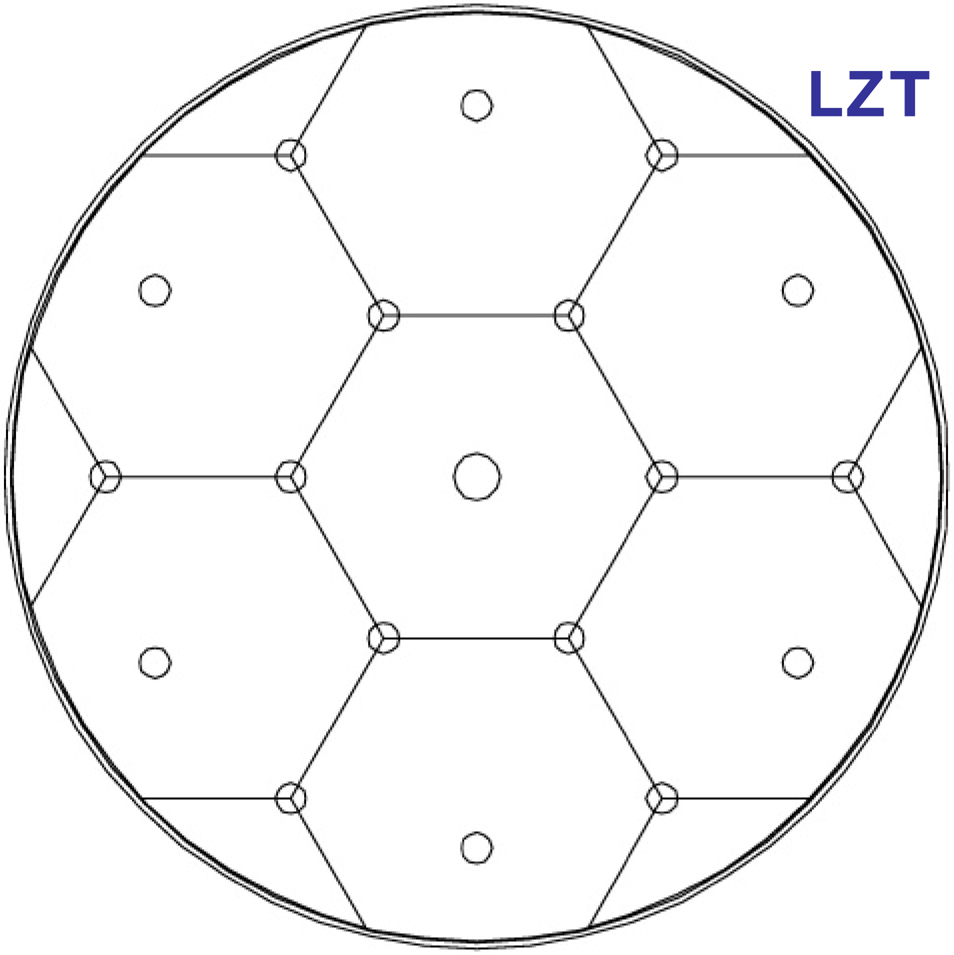
LZT mirror design



LZT	M1 Hexagon Plan	Default Tolerances	
		Drilled Holes: Diameter +0.25 -0.05	
Dwg: 970128	Units: mm	Decimal	External
Rev: 1	Scale: 0.040	X ±0.50	Surfaces
Date: 970128	By: PH	X.X ±0.10	1.6
		X.XX ±0.02	

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LZT air bearing

- Designed specifically for large LMT
- 2-year development
- Up to 10 m capacity

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6m Primary Mirror Truss

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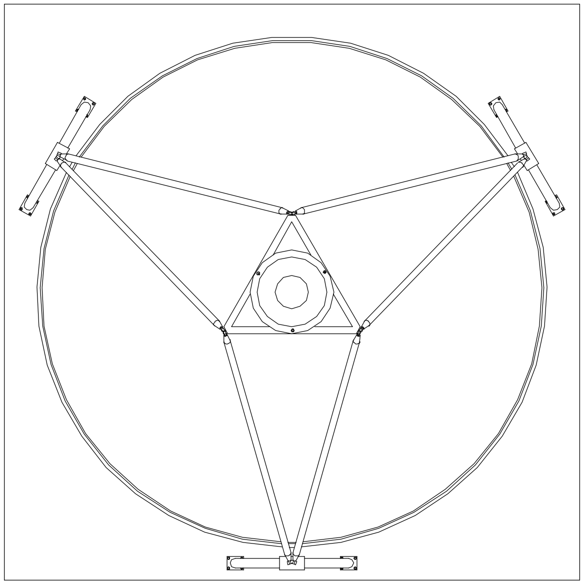
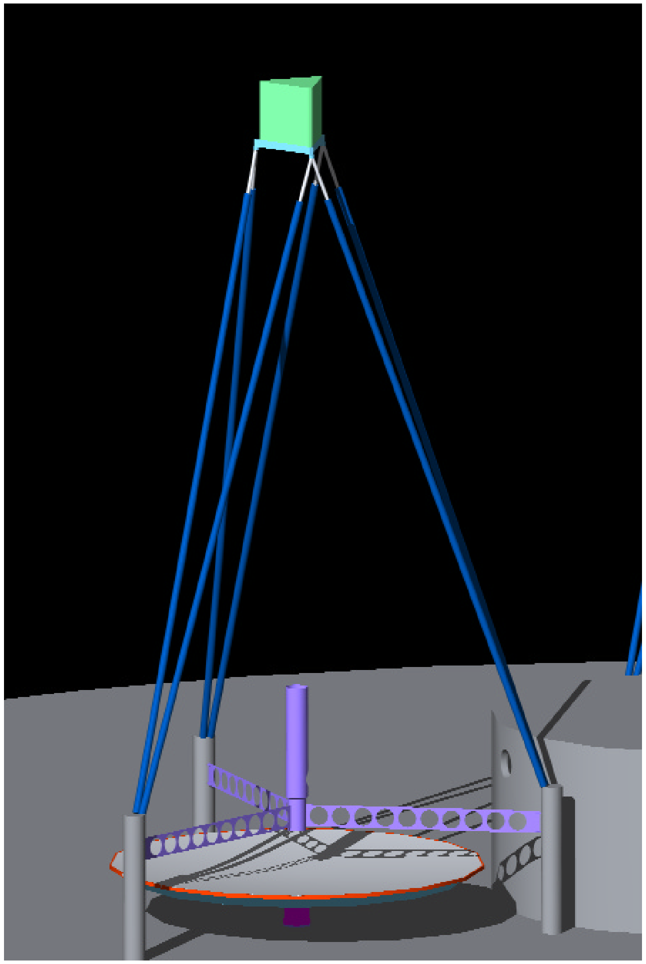
LZT telescope structure

- Hexapod design
- Interchangeable top-end units
- Provision for future Nasmyth





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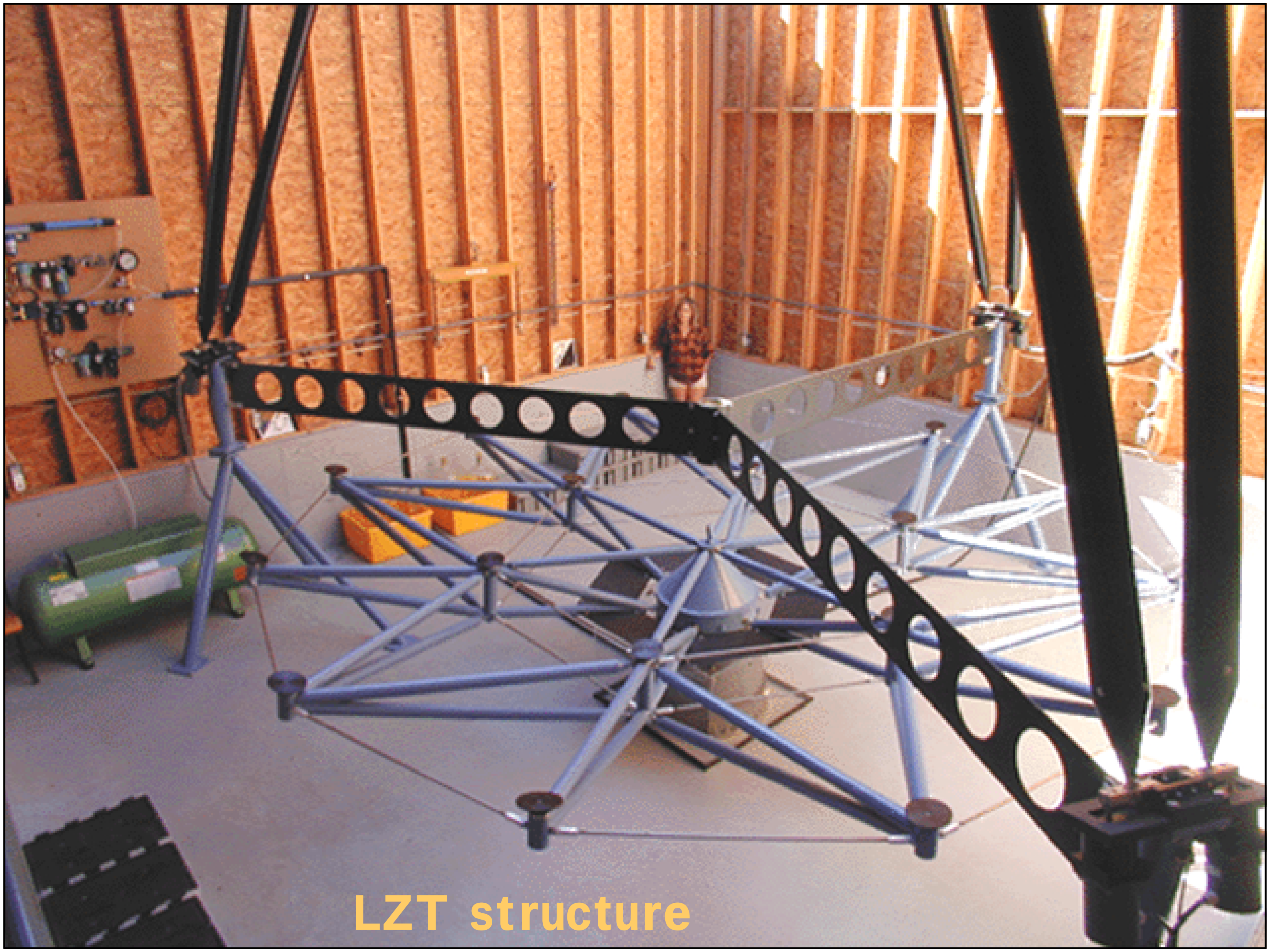
LZT structure

LZT hexapod

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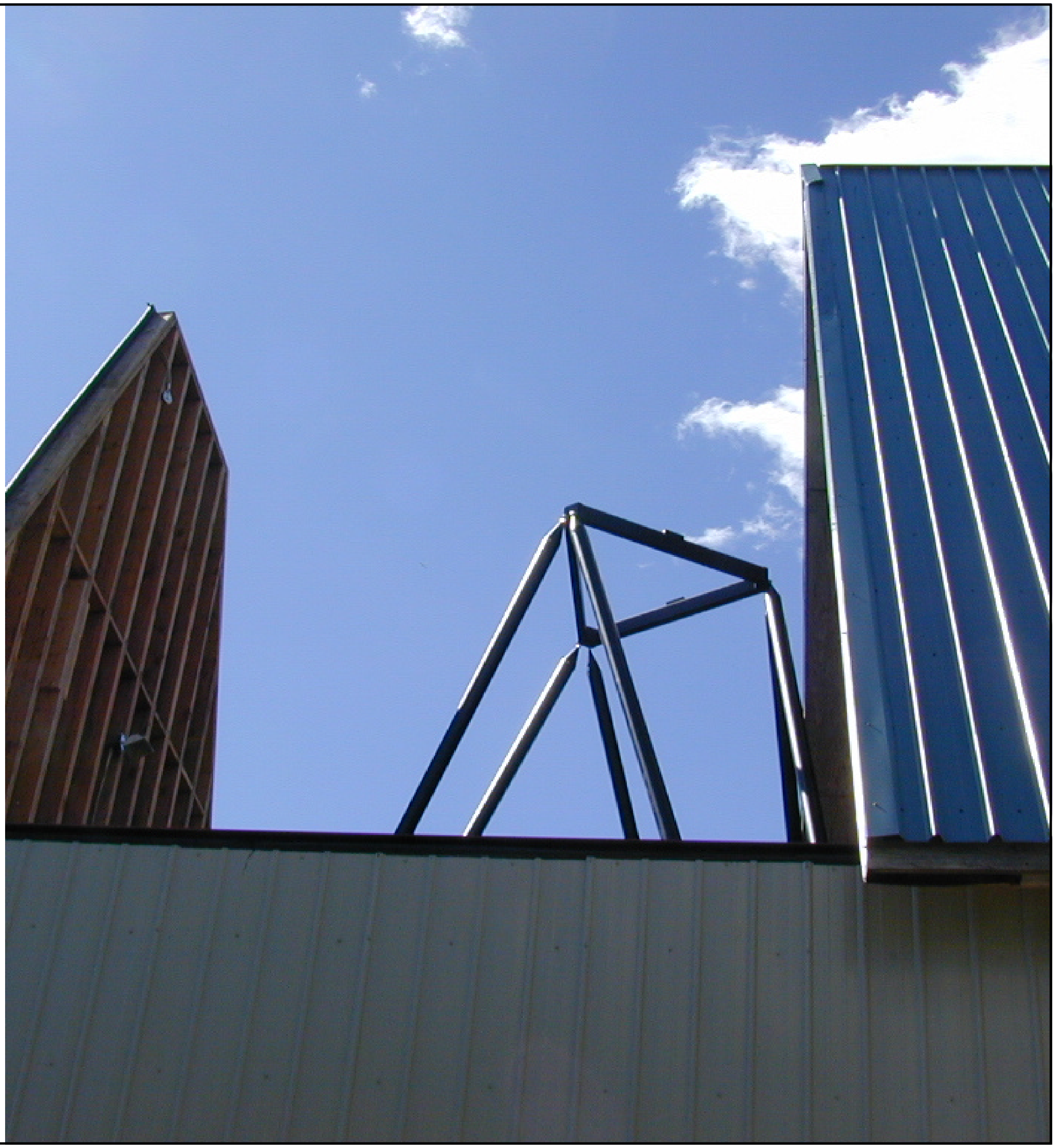
Gene Sprouse

LZT enclosure



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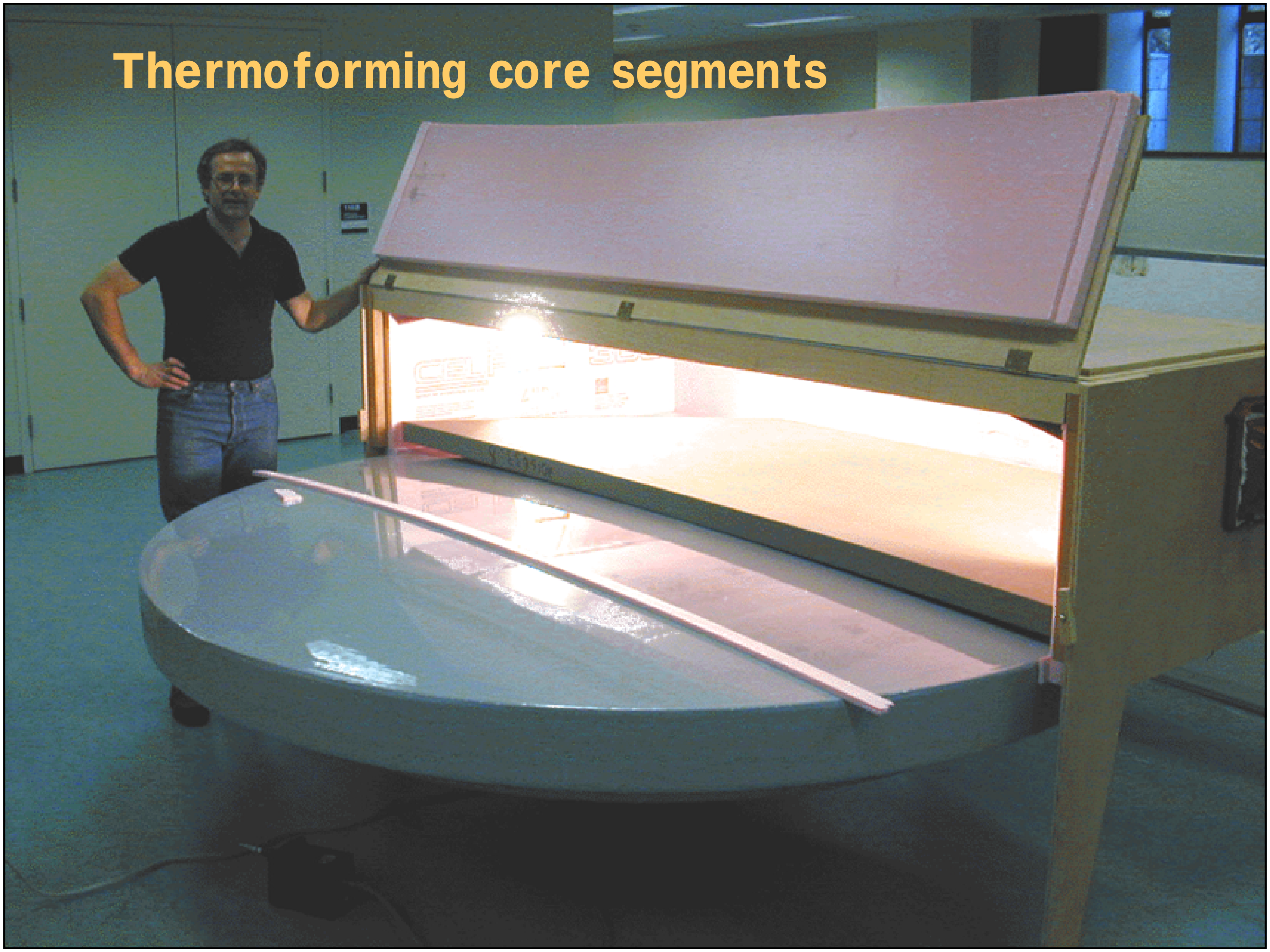
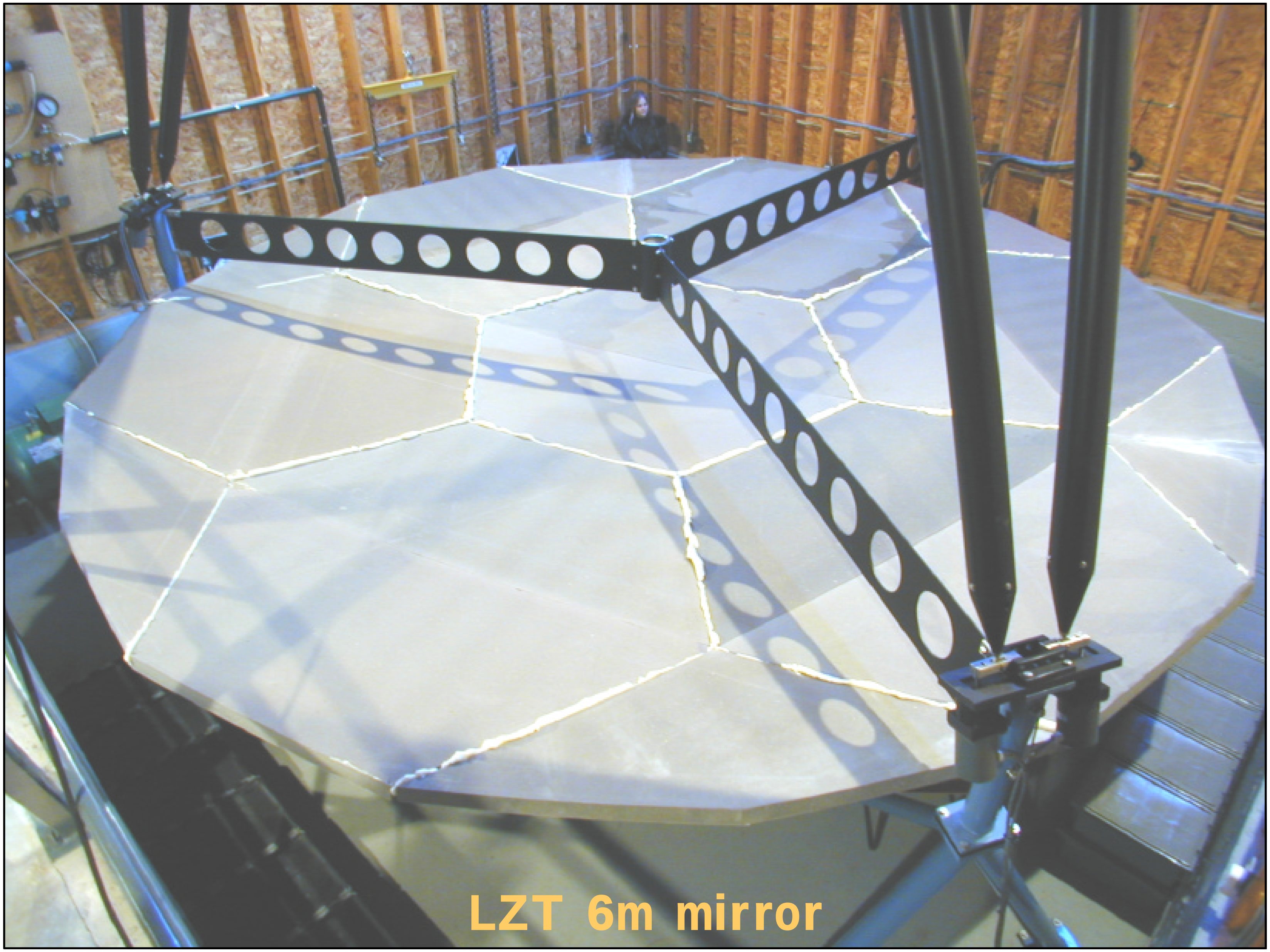
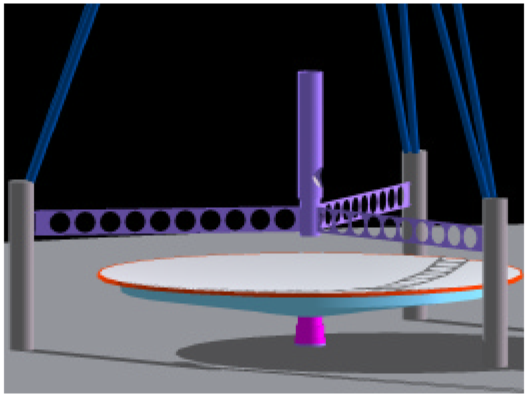
Thermoforming core segments

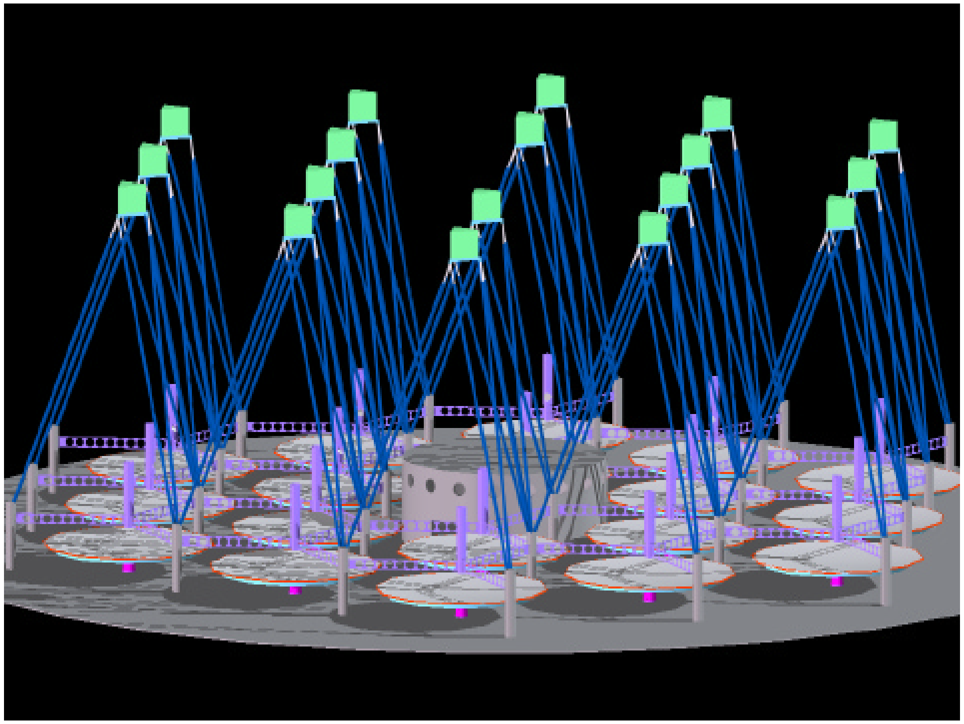



LZT 6m mirror

Large-Aperture Mirror Array



- Array of fixed mirrors
- Near-zenith pointing and tracking
- Incoherent and coherent modes
- Multiband optical/IR imaging camera
- High-resolution spectrograph



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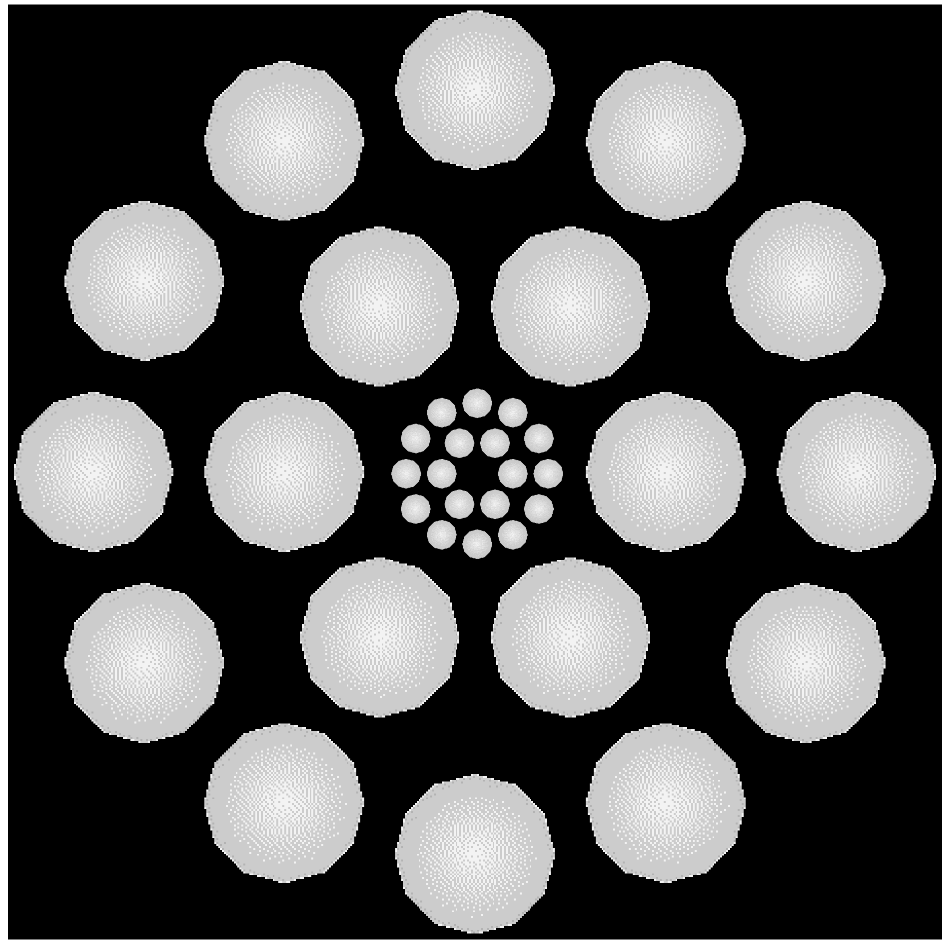
Interferometric mode

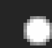
- Interferometric (Fizeau) imaging over an extended field of view
- Optical path lengths must be the same to within a few wavelengths ($\lambda^2/\Delta\lambda = R\lambda$)
- Geometry of beam combiner must match that of mirror array



LAMA PSF

Incoherent

40 mas FWHM at 2 um



Coherent

6 mas FWHM at 2 um

LAMA Performance

Mode:	Coherent	Incoherent
Resolution (λ = 1 um)	4 mas	20 mas
Pixel size	2.0 mas (IR) 1.0 mas (visible)	12.5 mas (IR) 6.5 mas (visible)
Instantaneous field of view	30 arcsec	60 arcsec
Maximum detector size	12k x 12k (IR) 24k x 24k (visible)	4k x 4k (IR) 8k x 8k (visible)
Max. exposure time (typical)	30 min	30 min
5s flux limit (30 min, K band)	400 pJy AB = 32.4	2.5 nJy AB = 30.4
5s flux limit (50 day, K band)	57 pJy AB = 34.5	354 pJy AB = 32.8
5s flux limit (30 min, I band)	40 pJy AB = 34.9	250 pJy AB = 32.9
5s flux limit (50 day, I band)	6 pJy AB = 37.0	36 pJy AB = 35.0

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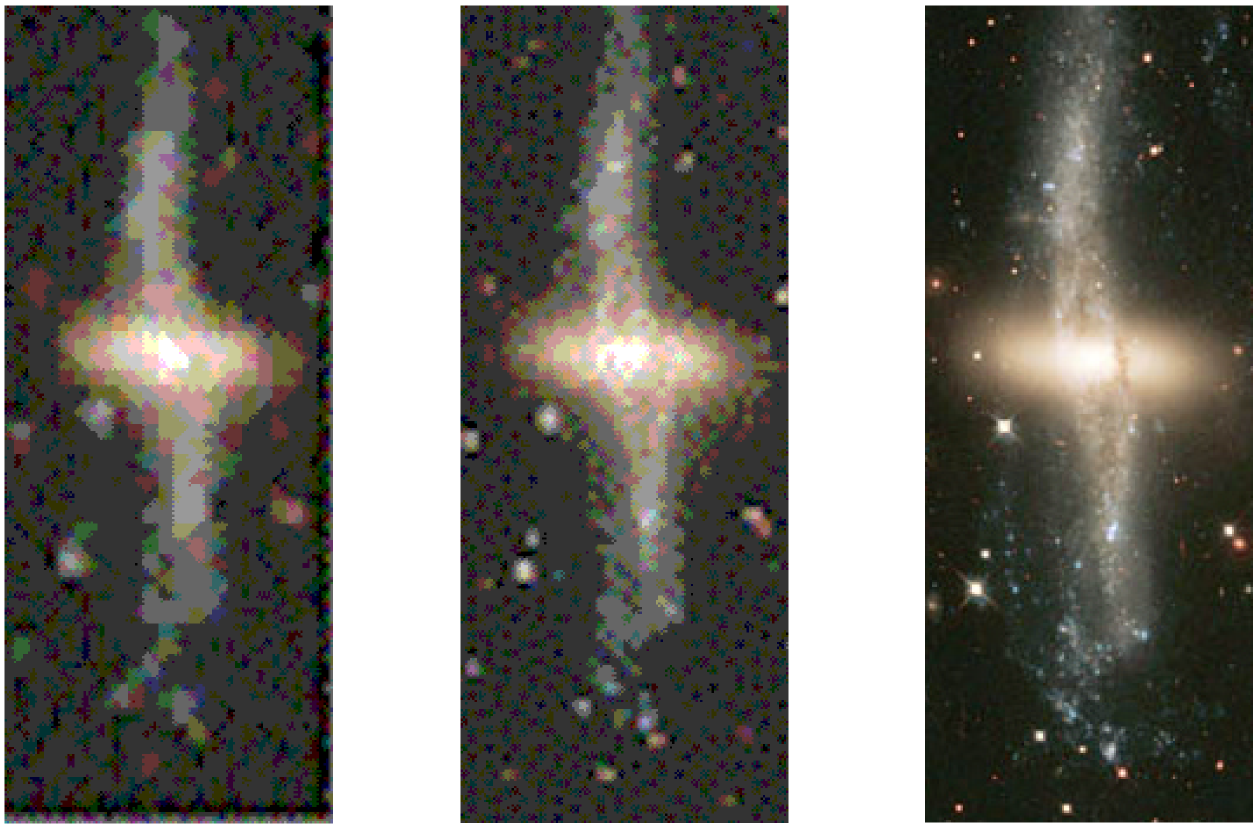
LAMA Imaging

HST 2.4m NGST 8m LAMA 60m



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NASA

Summary

- A multi-aperture very-large optical telescope is feasible now
- Such a telescope would open new frontiers in astronomy
- Liquid-mirror technology makes this project possible for a fraction of the cost of other very-large optical telescope proposals

www.astro.ubc.ca/lmt/lama