hWAET

Ben Monreal
CWRU Physics

with:
Rob Halliday (thermal engineering, optics)
and:
Ama Carney (mechanical)
Christian Rodriguez (UCSB) (planet populations)
Mingyuan Wang (Zemax/optical)

Great Paris Exhibition Telescope
(lens at the same scale)
Paris, France (1900)

Yerkes Observatory
(40" refractor
lens at the same scale)
Williams Bay,
Wisconsin (1893)

Hooker (100")
Mt Wilson,
California
(1917)

Hale (200")
Mt Palomar,
California
(1948)

(1979-1998) (1999-)
Multi Mirror Telescope
Mount Hopkins, Arizona

BTA-6 (Large Altazimuth Telescope)
Zelenchuksky, Russia
(1975)

Large Zenith Telescope
British Columbia, Canada
(2003)

Gaia
Earth-Sun L2 point
(2014)

Kepler
Earth-trailing
solar orbit
(2009)

James Webb Space Telescope
Earth-Sun L2 point
(planned 2018)

Hubble Space Telescope
Low Earth
Orbit
(1990)

Large Sky Area Multi-Object Fiber Spectroscopic Telescope
Hebei, China
(2009)

Hobby-Eberly Telescope
Davis
Mountains,
Texas (1996)

Large Binocular Telescope
Mount Graham,
Arizona (2005)

Gran Telescopio Canarias
La Palma,
Canary Islands,
Spain (2007)

Southern African Large Telescope
Sutherland,
South Africa
(2005)

Very Large Telescope
Cerro Paranal, Chile
(1998-2000)

Magellan Telescopes
Las Campanas,
Chile (2000/2002)

Keck Telescope
Mauna Kea, Hawaii
(1993/1996)

Gemini North
Mauna Kea,
Hawaii (1999)

Subaru Telescope
Mauna Kea,
Hawaii (1999)

Gemini South
Cerro Pachón,
Chile (2000)

Large Synoptic Survey Telescope
El Peñón, Chile
(planned 2020)

Giant Magellan Telescope
Las Campanas Observatory,
Chile (planned 2020)

Thirty Meter Telescope
Mauna Kea, Hawaii (planned 2022)

European Extremely Large Telescope
Cerro Armazones,
Chile (planned 2022)

Human at the same scale

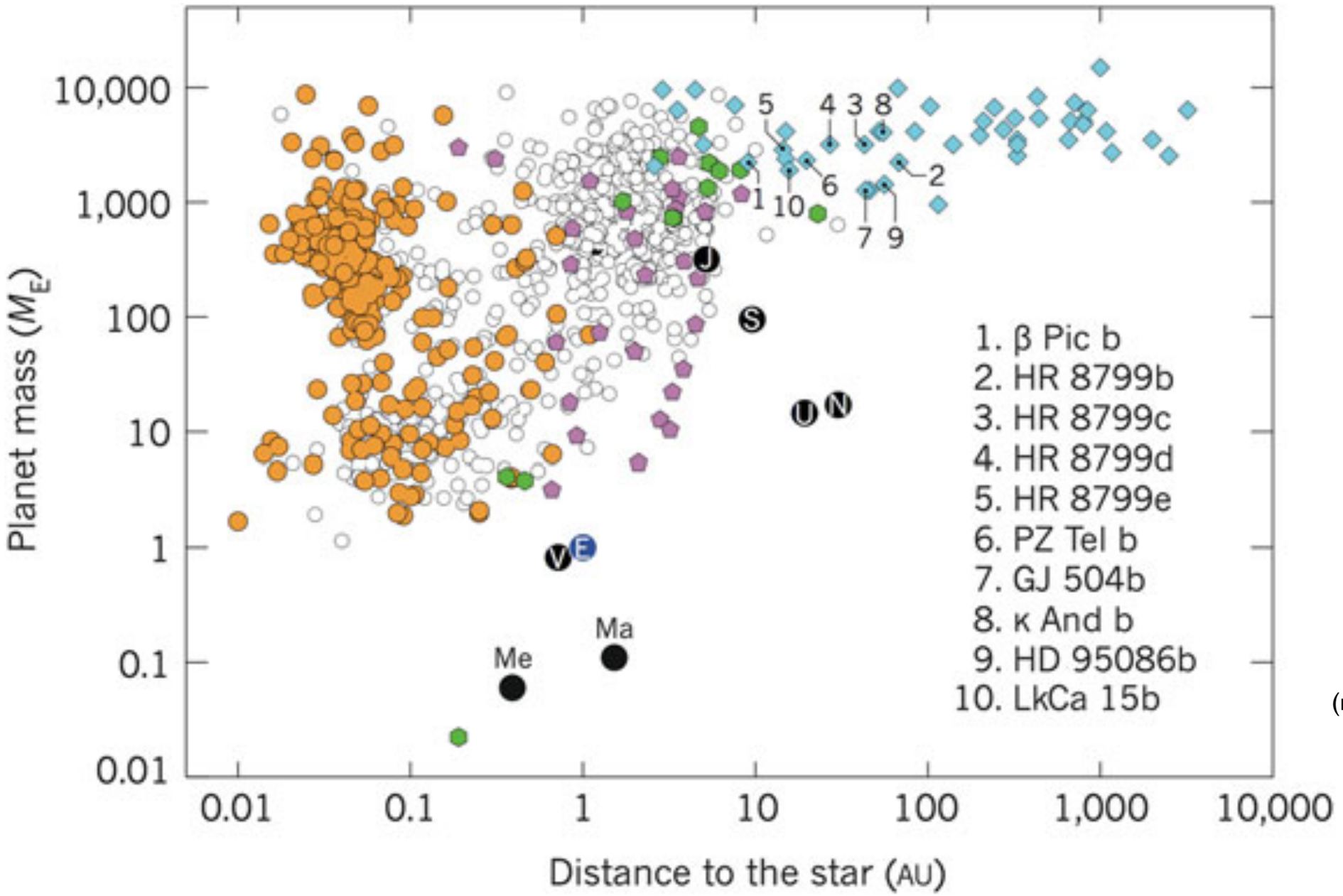
0 5 10 m
0 10 20 30 ft

Overwhelmingly Large Telescope
(cancelled)
Arecibo radio telescope at the same scale

Tennis court at the same scale

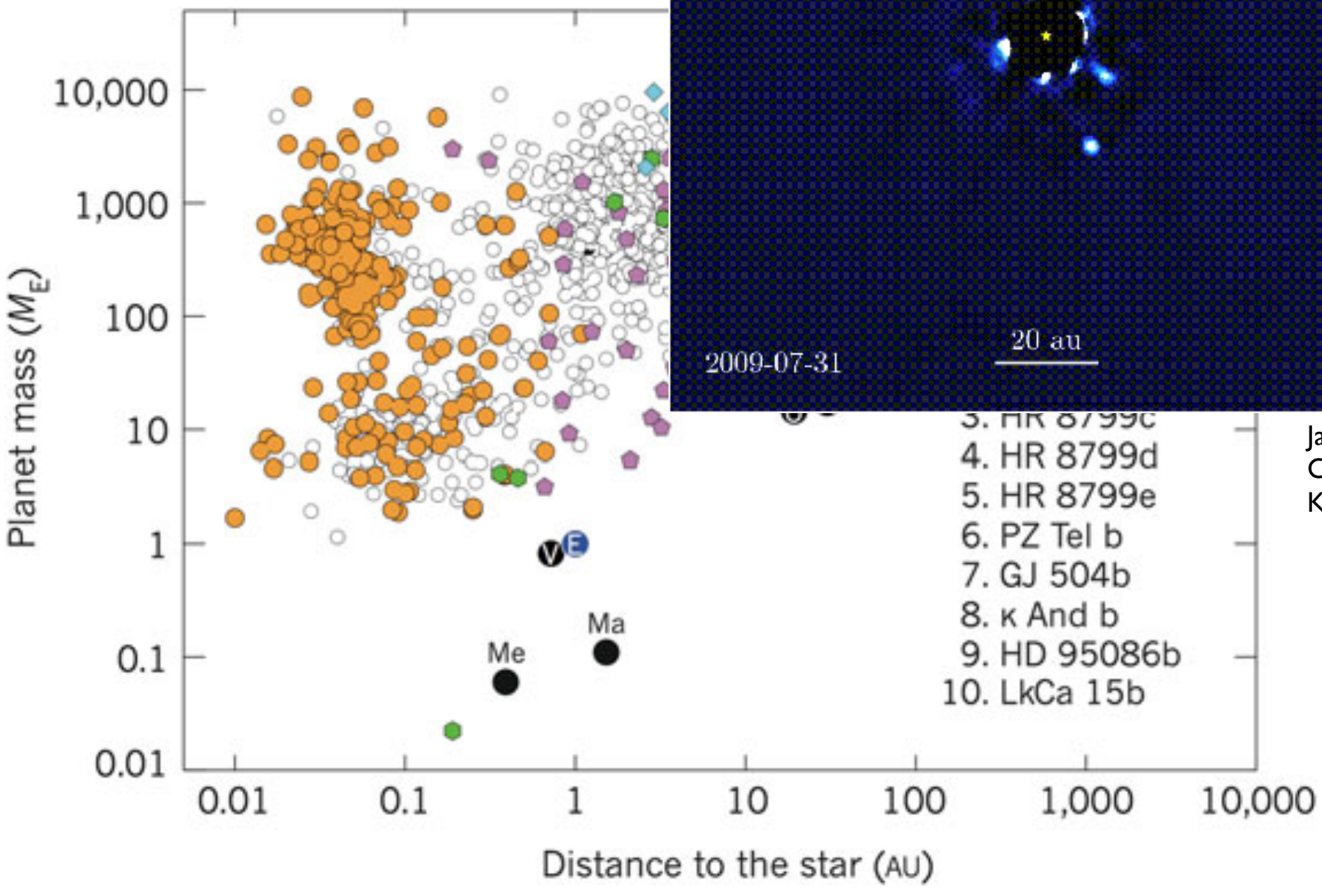
Basketball court at the same scale

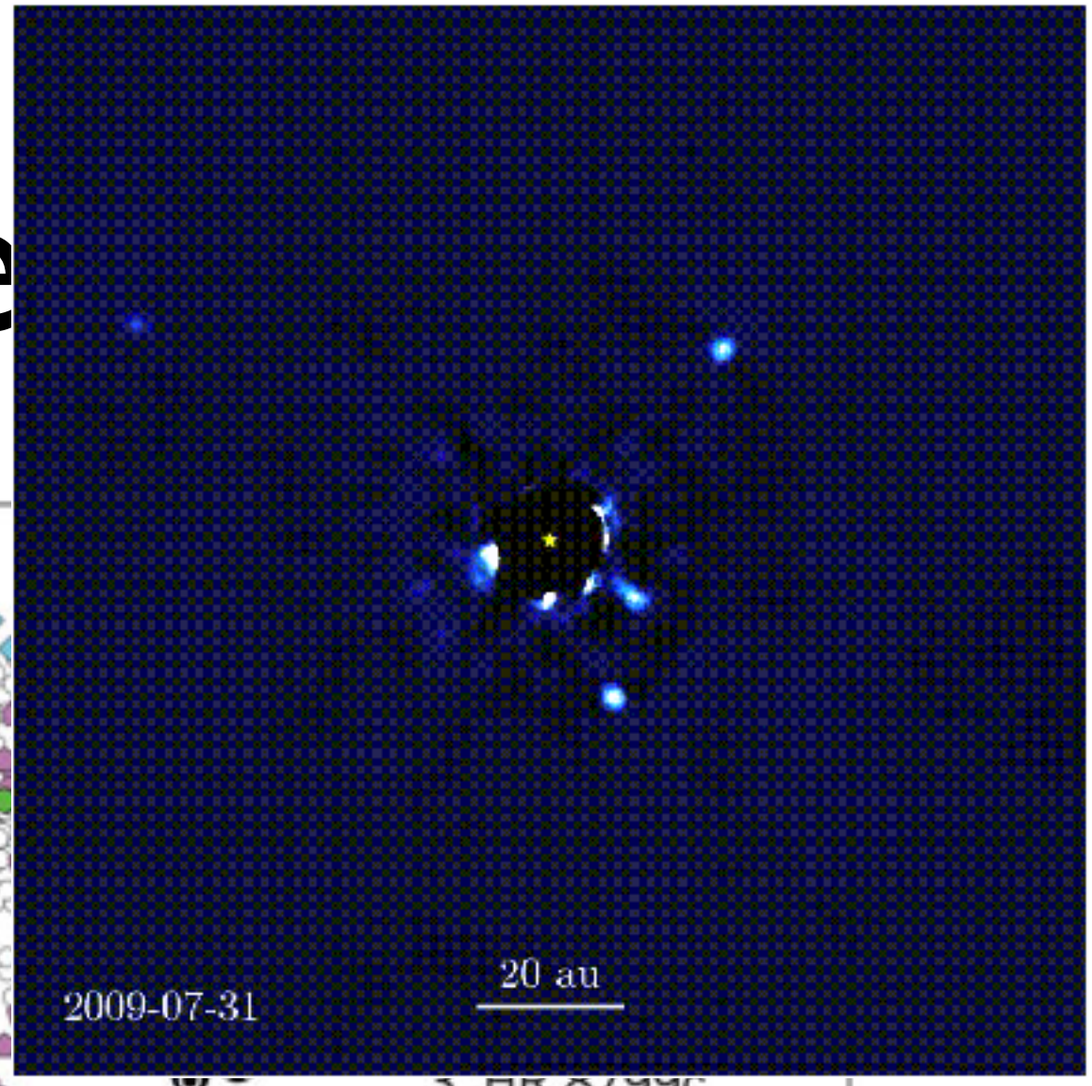
Exoplanet imaging



(reference missing!)

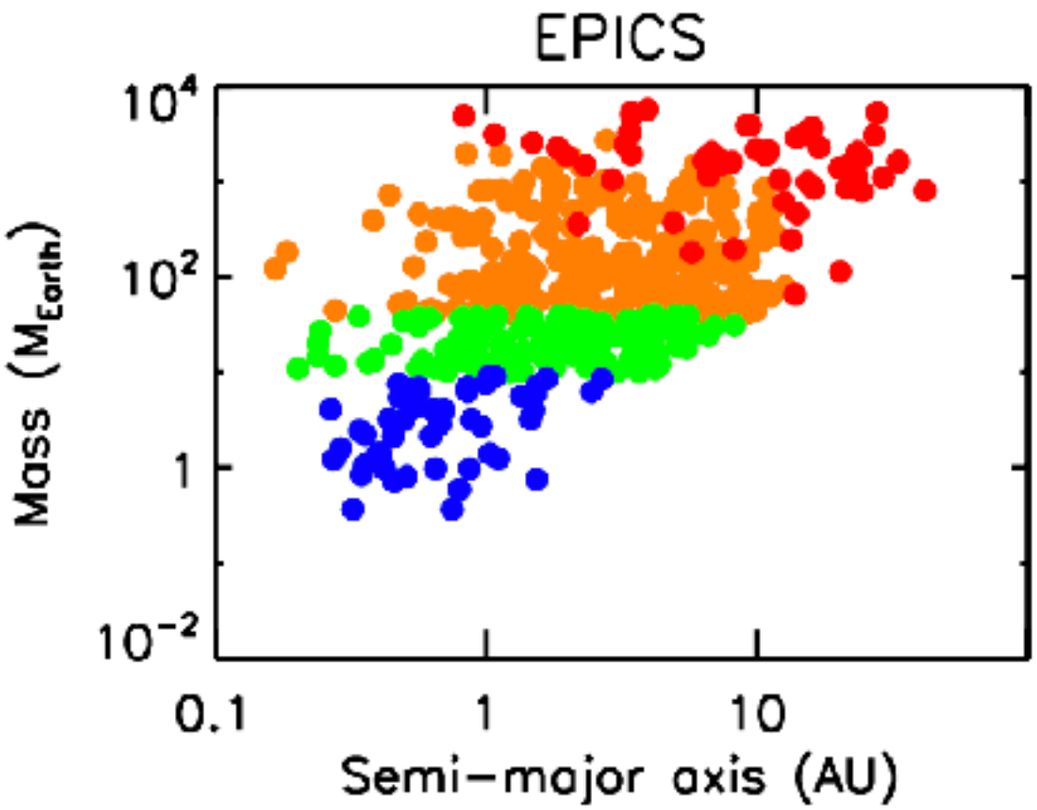
Exoplane





Jason Wang/
Christian Marois
Keck data

Bonavita et al, A&A 537:A67

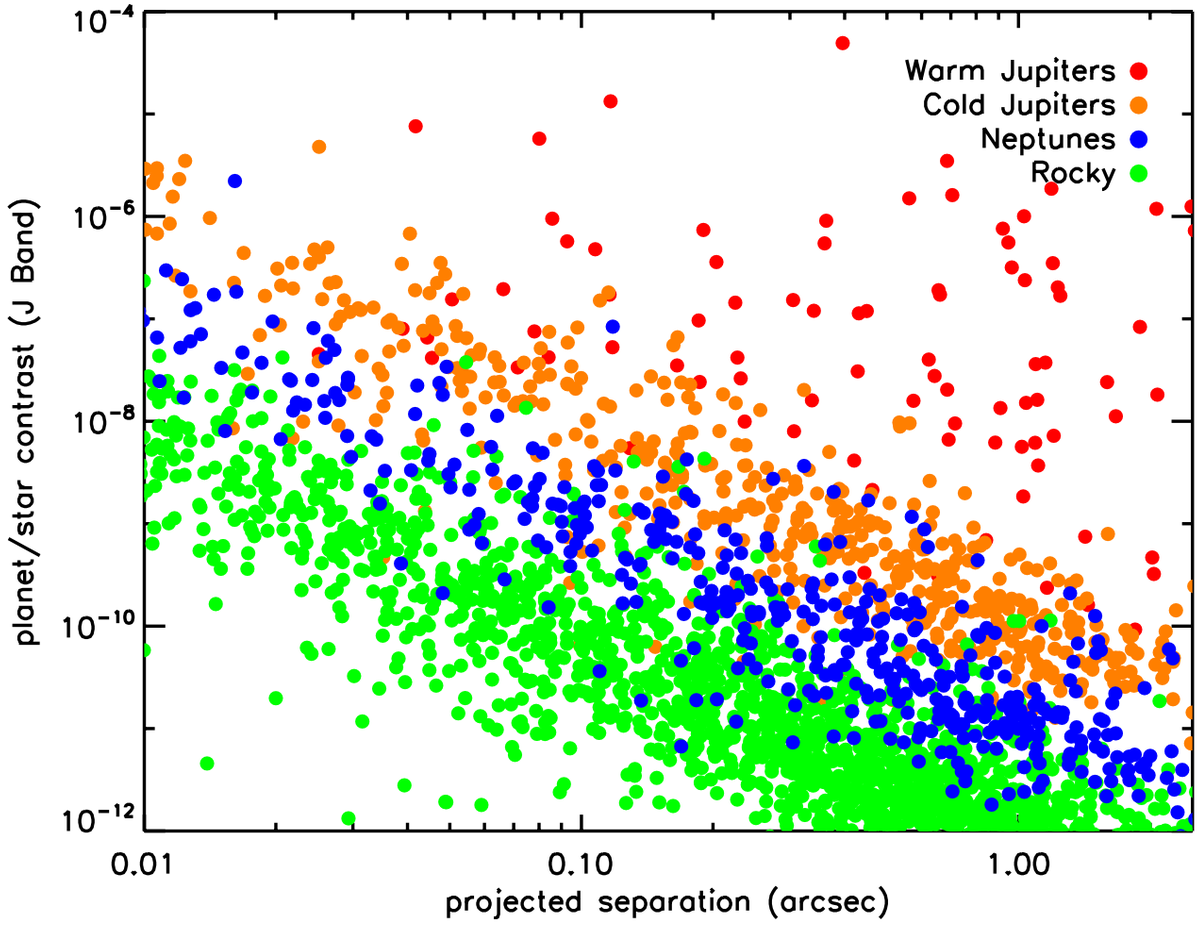


10-year planet discoveries at an EELT with a 30mas IWA:

hundreds of hot Jupiters
hundreds of cold Jupiters
tens of warm Neptunes
"a few" rocky planets

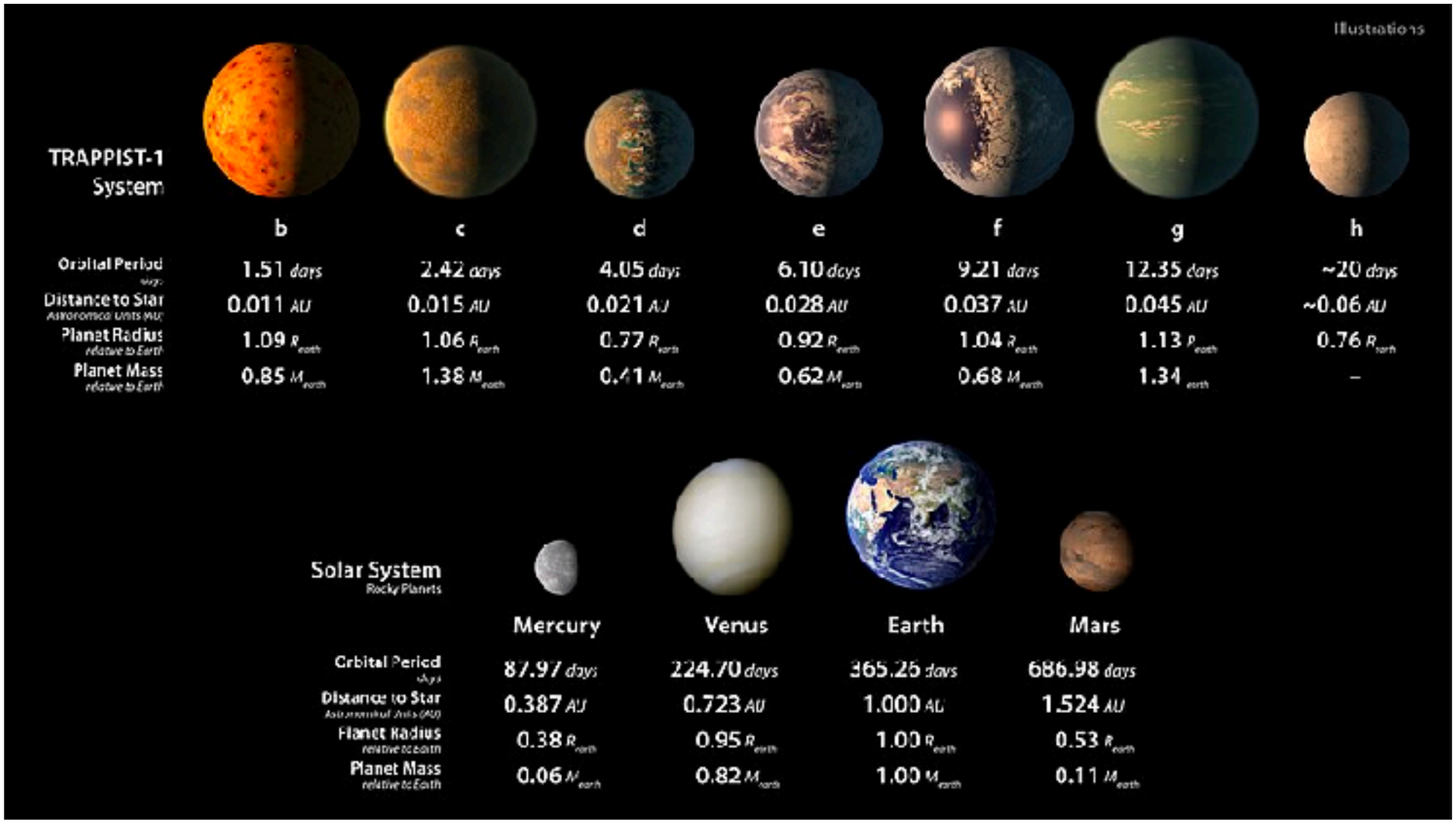
We know there are rocky planets with seeable contrast ratios (10^{-5}—10^{-6}) but they're at few-mas separation

⇐ bigger telescopes



adaptive optics ⇒

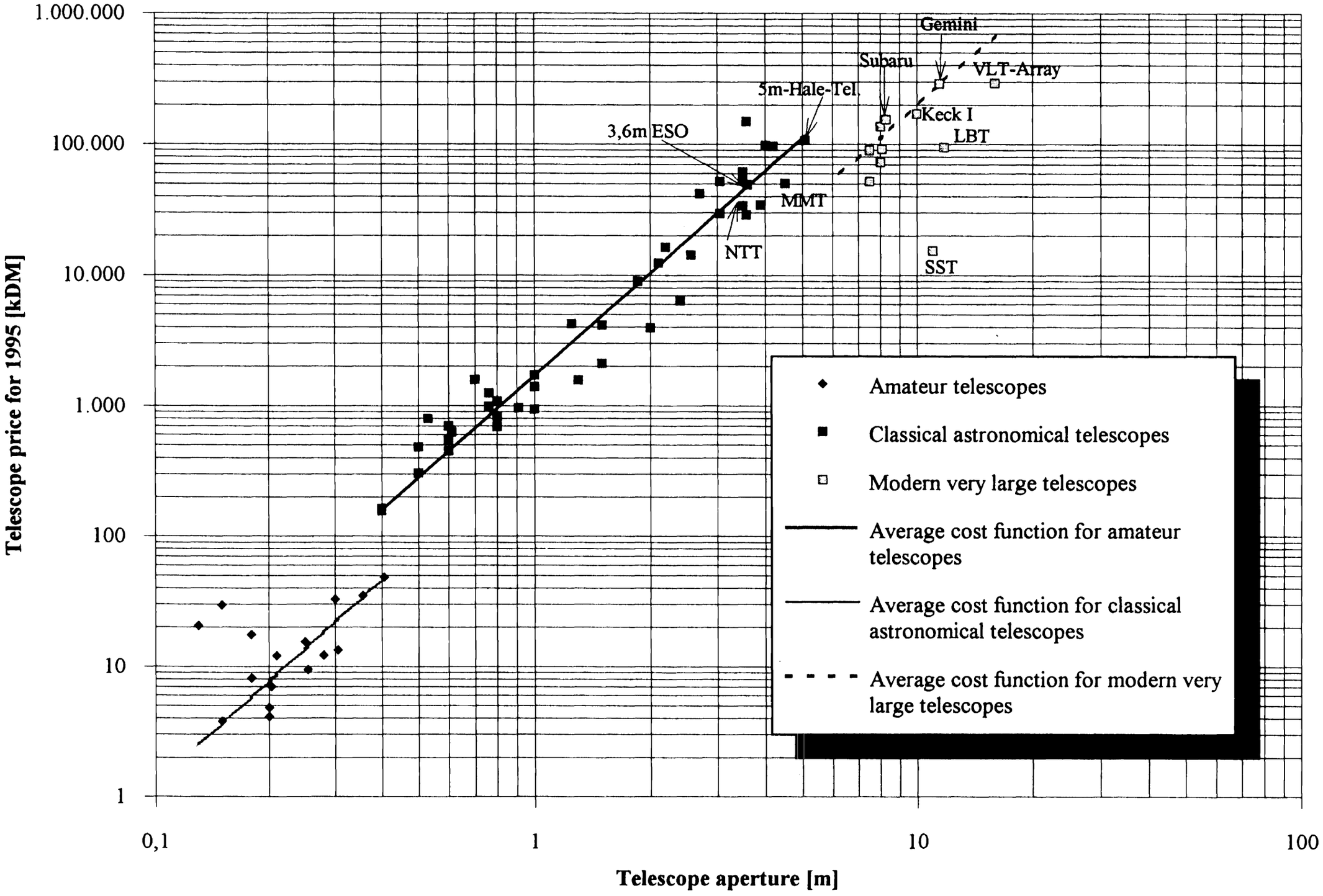
TRAPPIST-1



NASA/JPL-Caltech

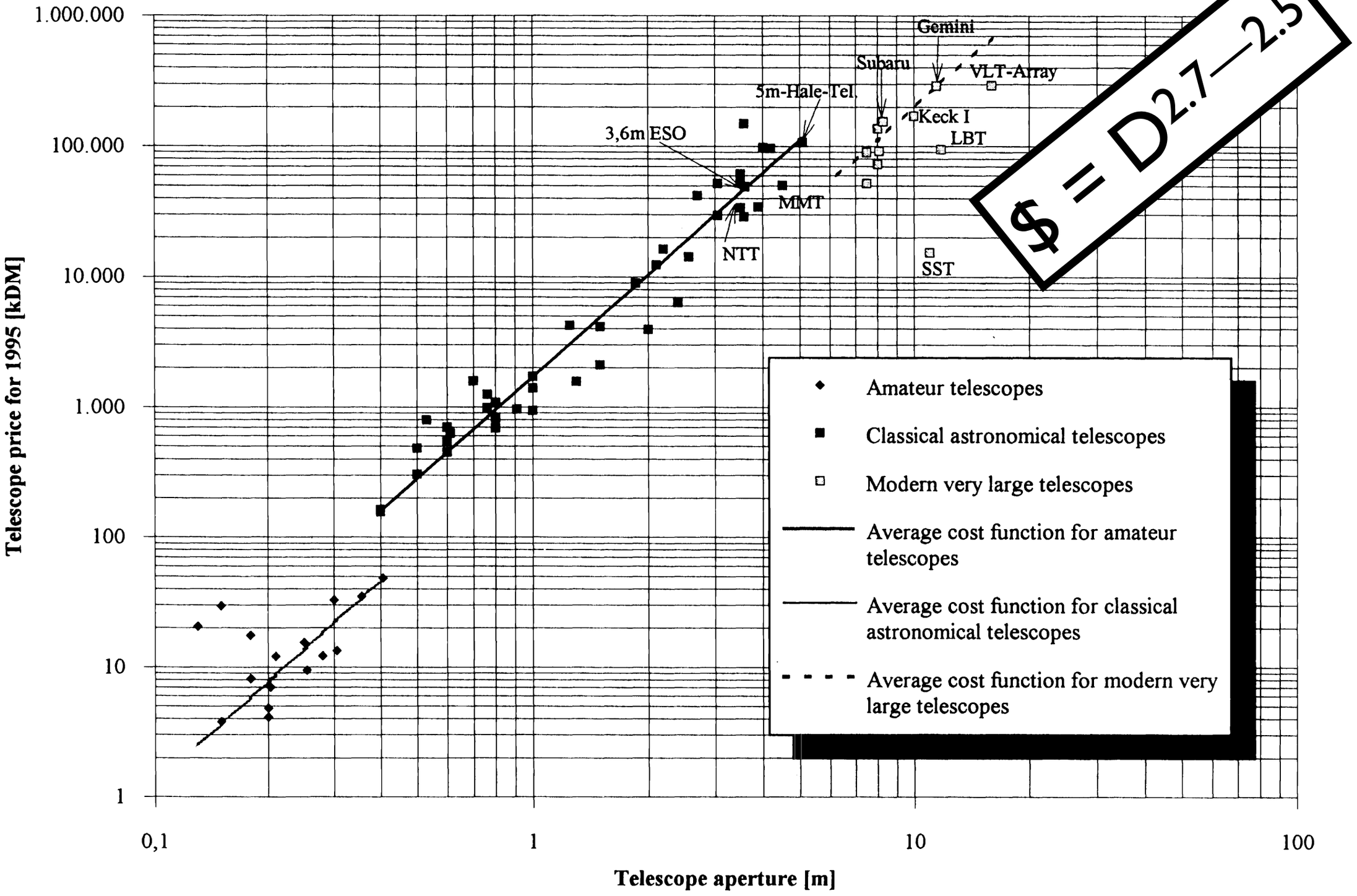
- 0.037 AU at 12pc = 3 mas
- 1.5μm / 3 mas = 100m

Cost estimation



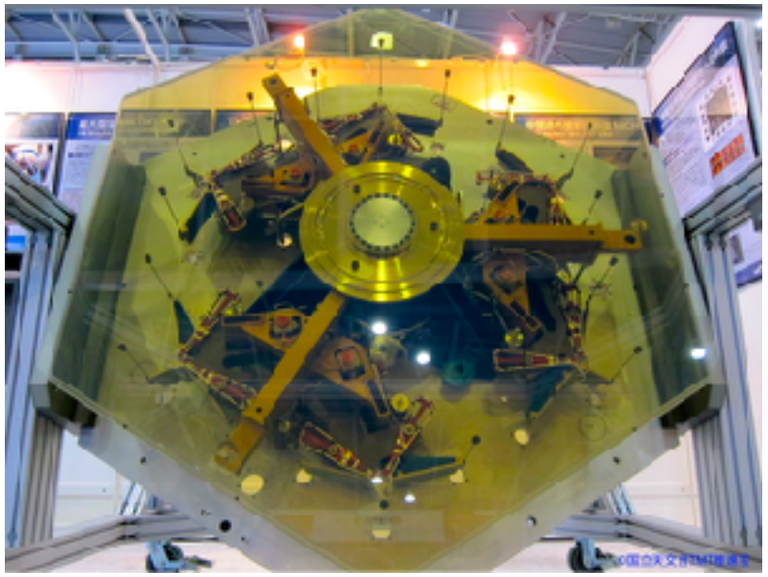
Schmidt-Kaler & Rucks, SPIE 2871 (1997)

Cost estimation

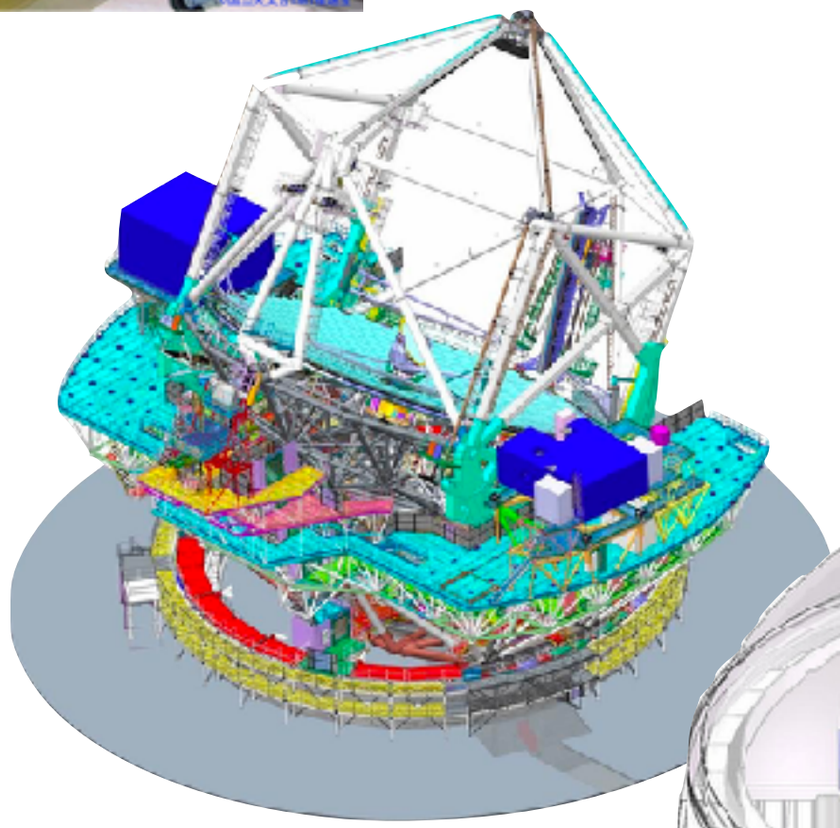


Schmidt-Kaler & Rucks, SPIE 2871 (1997)

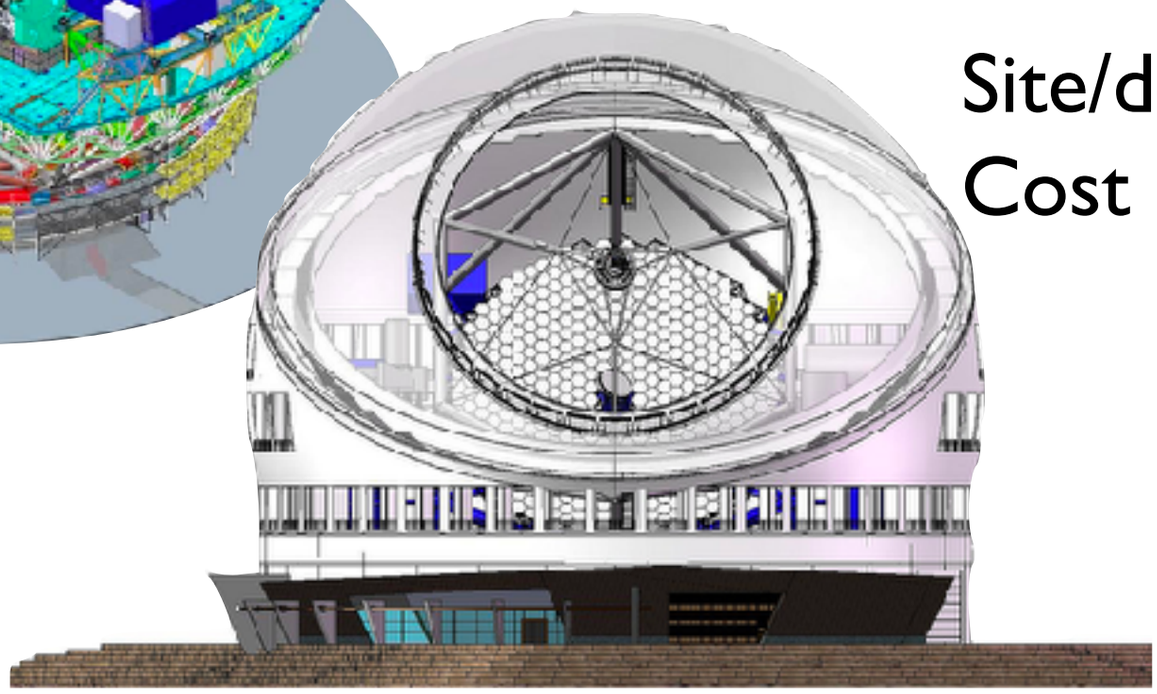
rule of thumb: mount = dome = mirrors



# of mirrors
Cost α A^1 α D^2



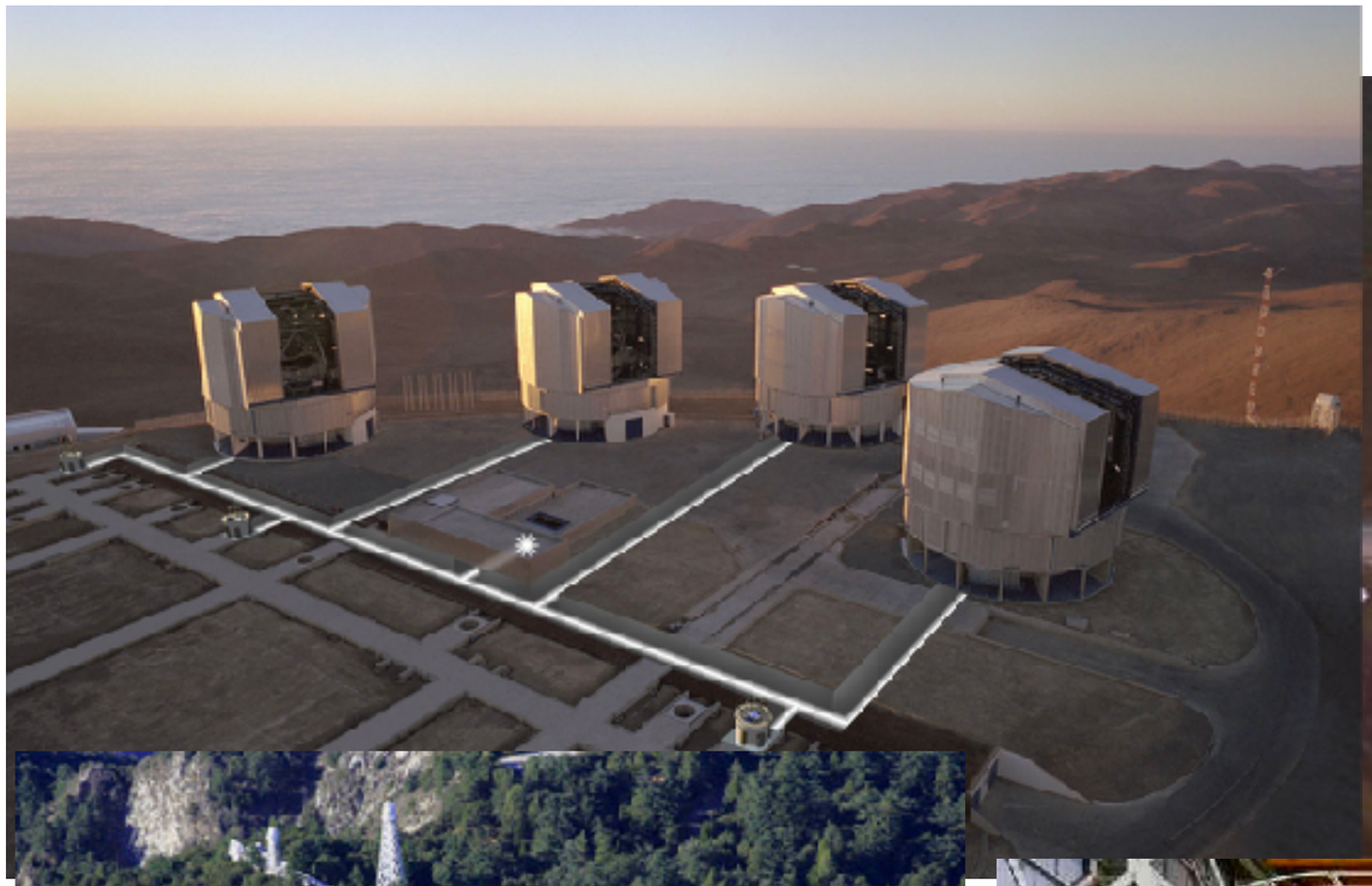
Structure
Cost α $A^{>1.5}$ α $D^{>3}$



Site/dome
Cost α $A^{1.5}$ α D^3

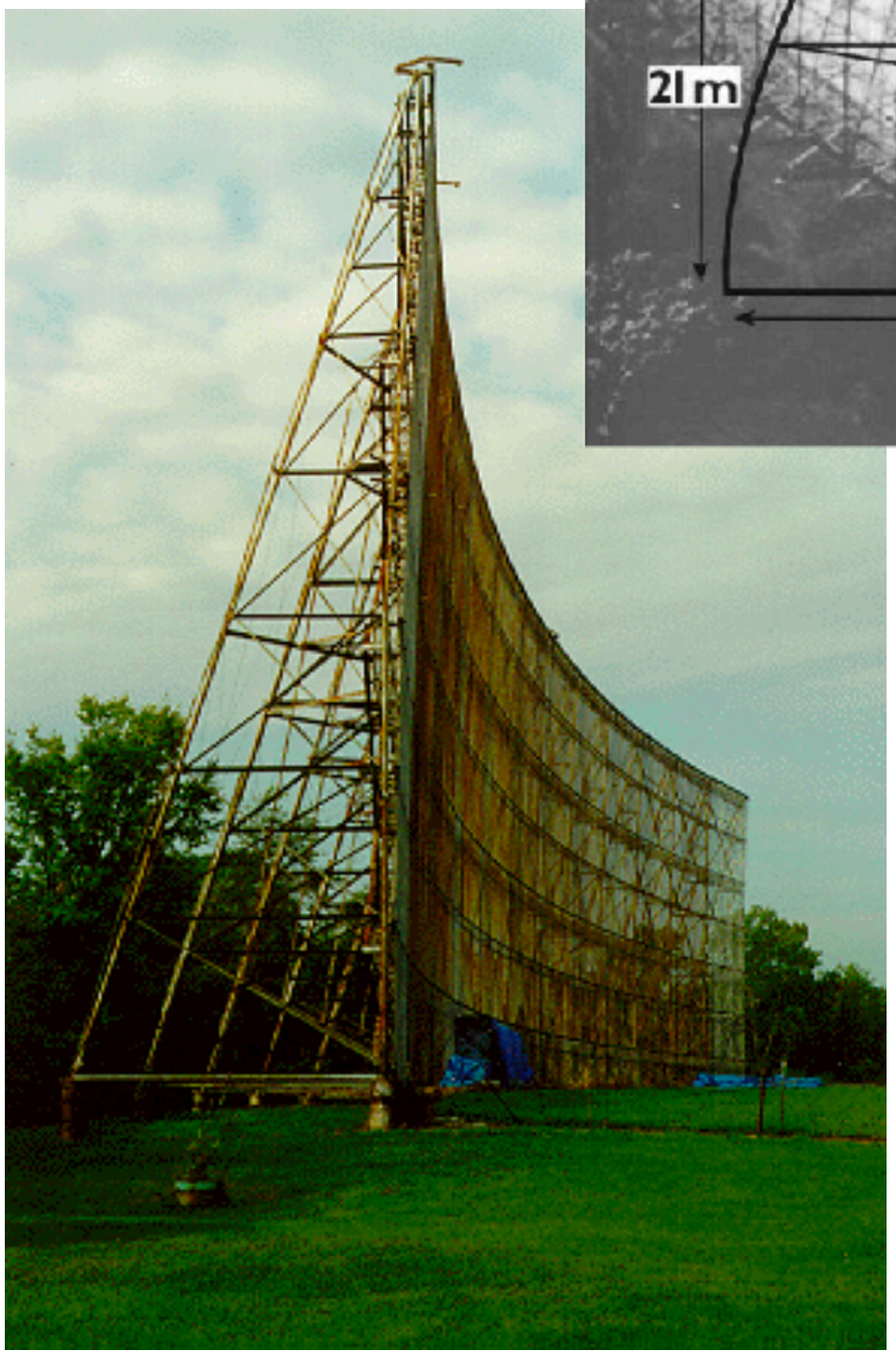
Interferometry is hard

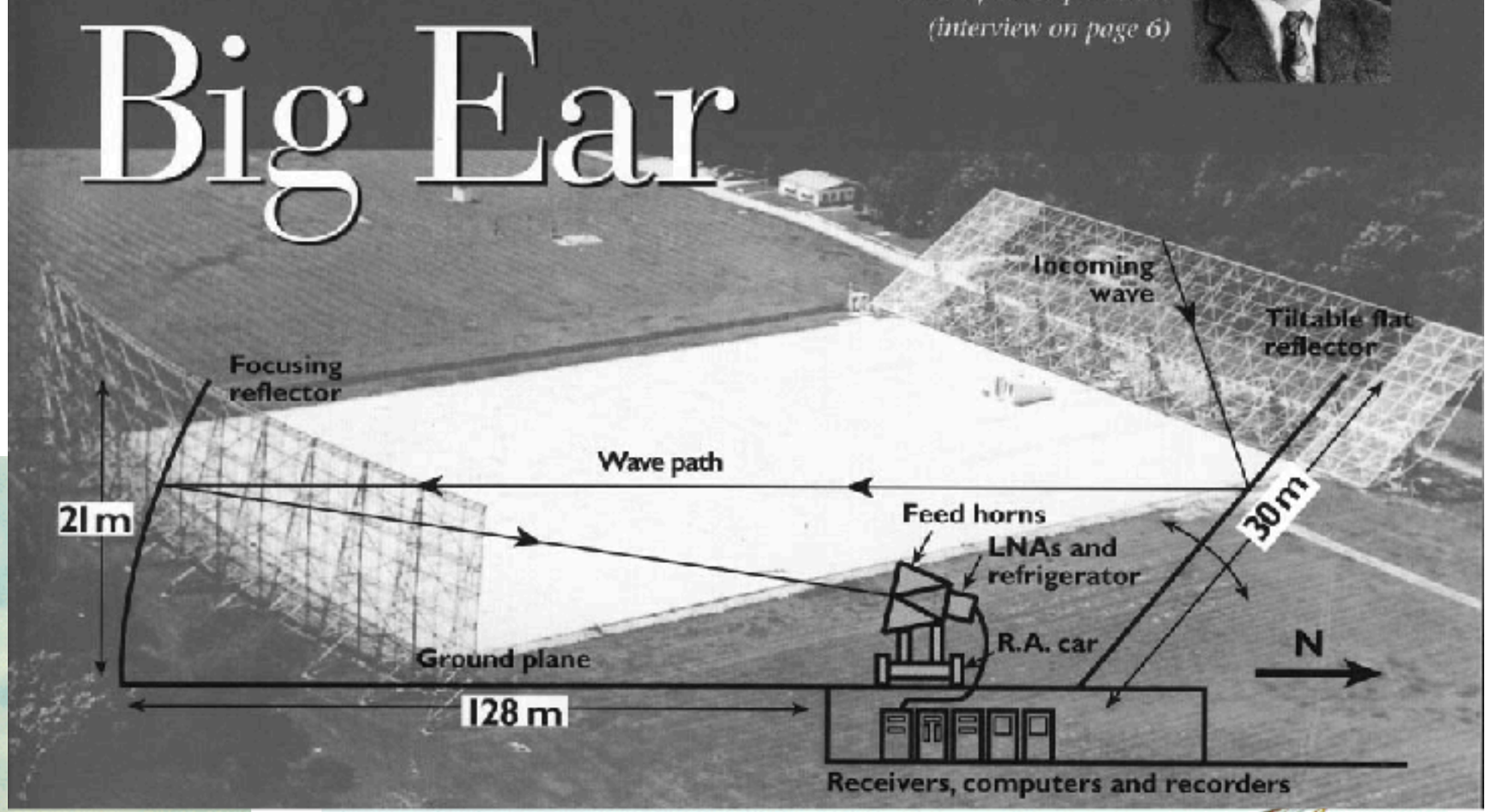
VLTI

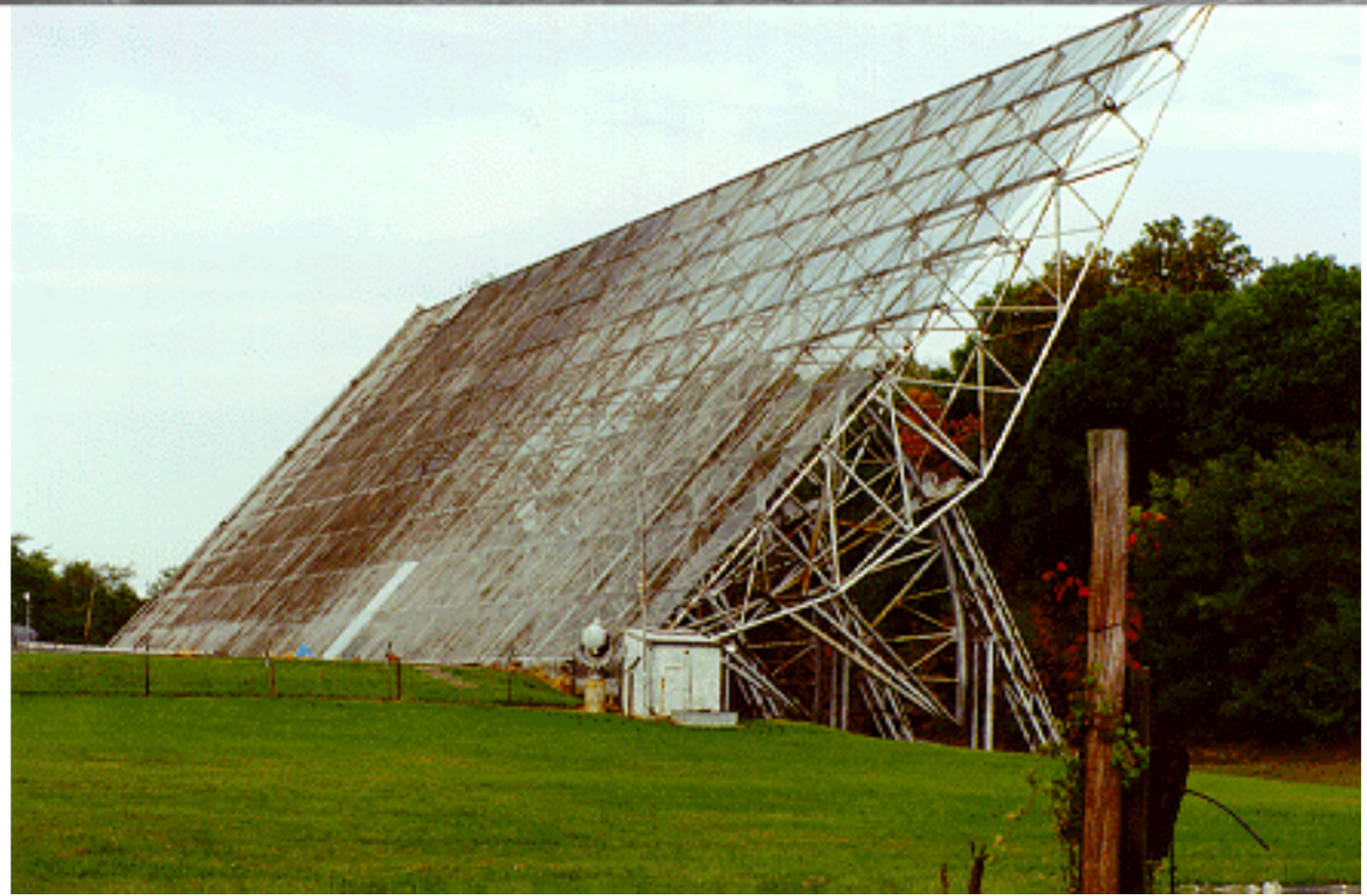


Keck Interferometer (dead)

Kraus -type




Big Ear
(interview on page 6)
Incoming wave
Tiltable flat reflector
Focusing reflector
Wave path
21 m
Feed horns
LNAs and refrigerator
30 m
R.A. car
N
Ground plane
128 m
Receivers, computers and recorders

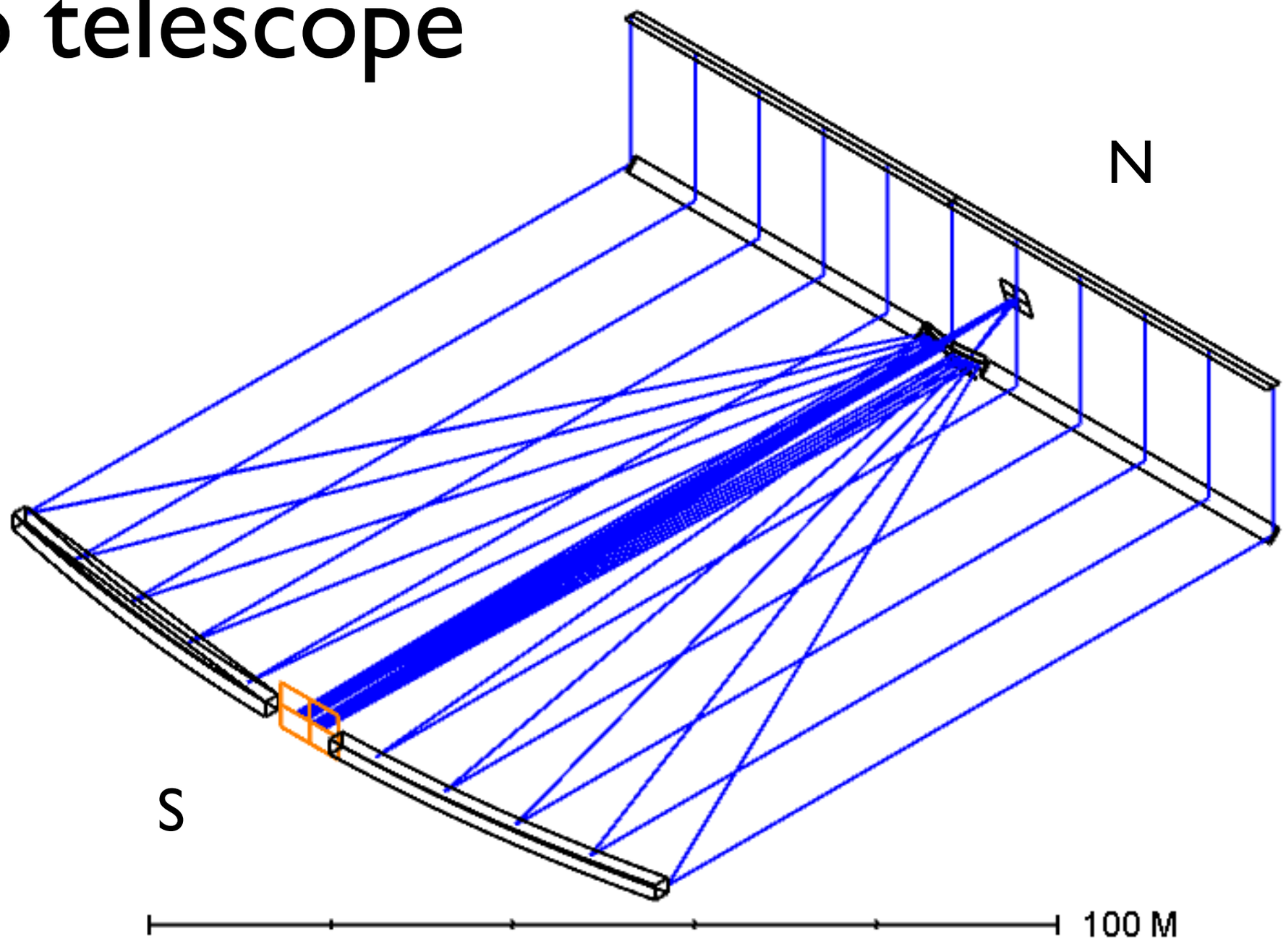


Kraus -type

"Grand Radiotélescope" Nançay

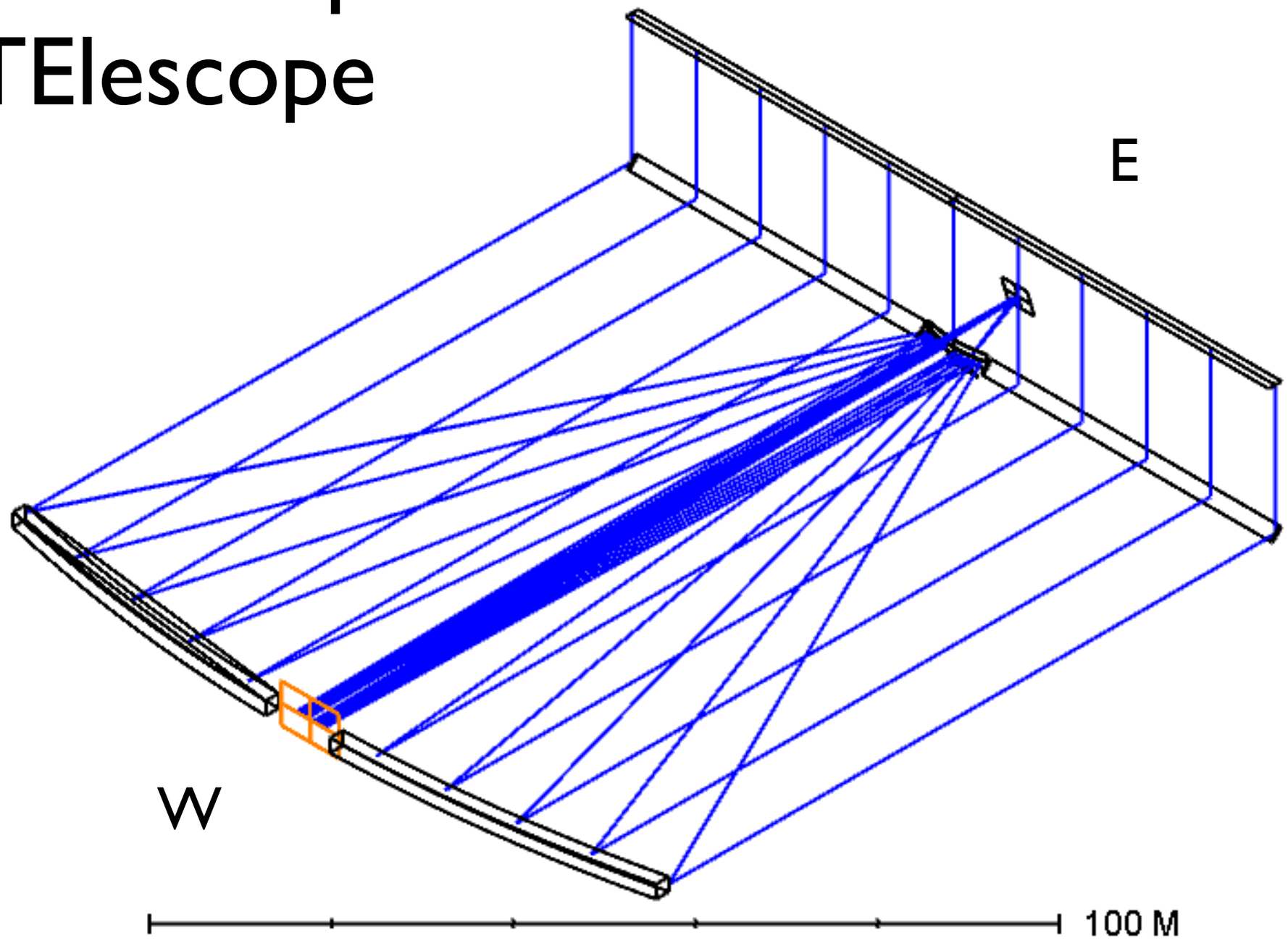
- South-facing transit telescope
  - Flat reflector tilts to desired DEC
  - Spherical primary does not move
  - Focal plane array moves to track RA
    - limited to ~1hr

Kraus-type radio telescope

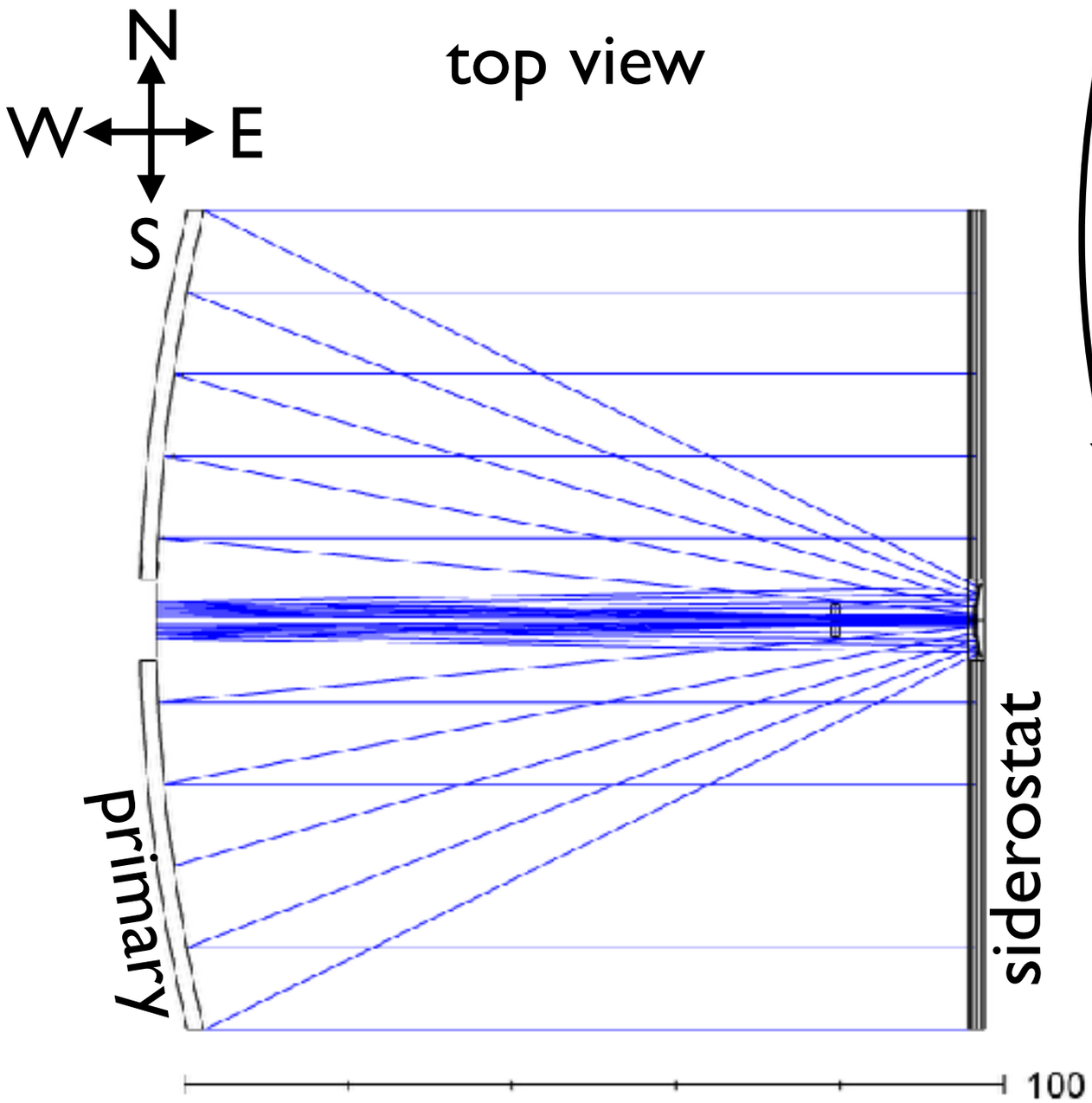


Zemax model by Mingyuan Wang

WAET: Wide Aperture Exoplanet TElescope



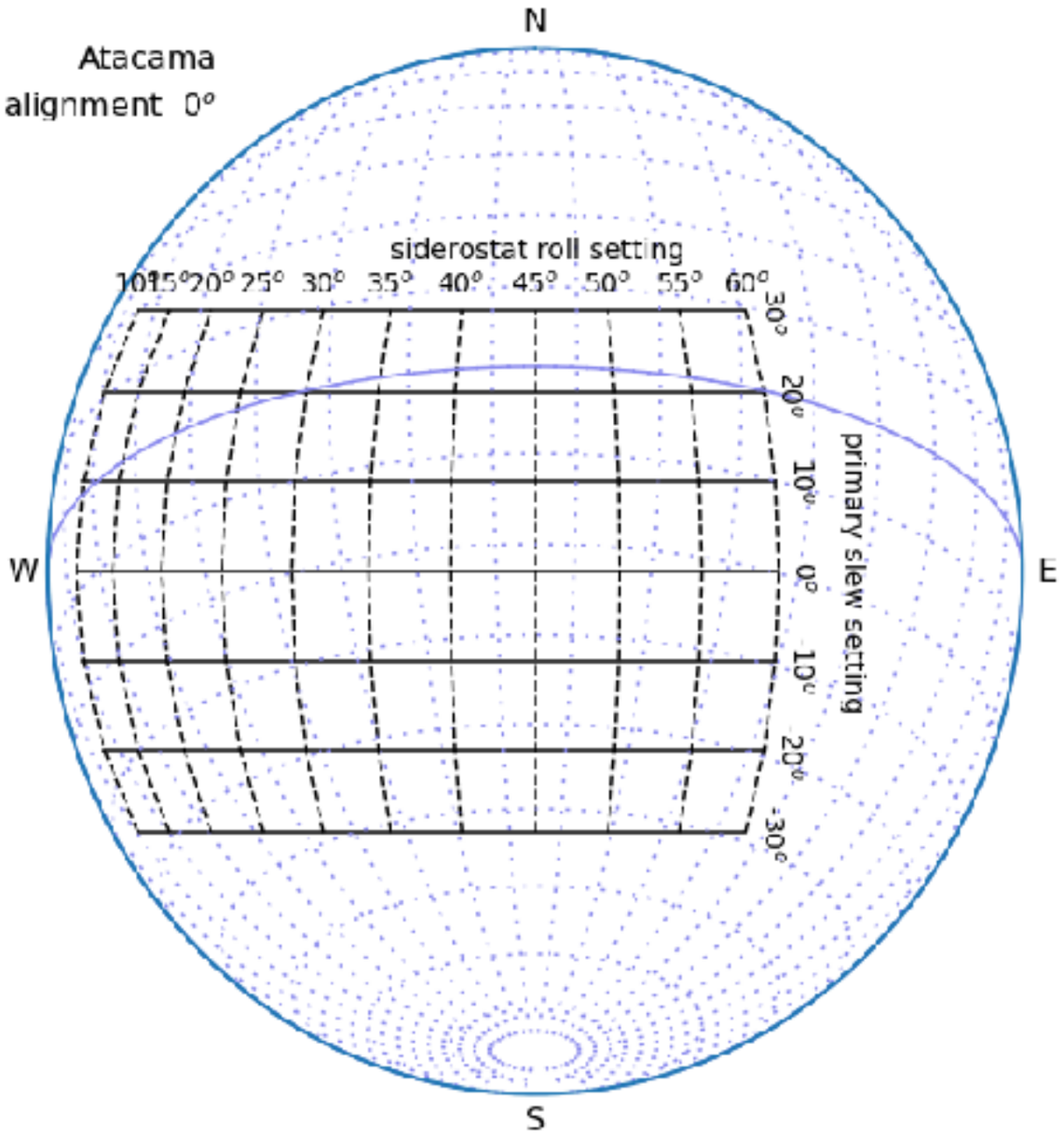
Zemax model by Mingyuan Wang



Primary:

- Only "slew" motion
- Gravity vector never changes
- Structure elevation never changes

Sky coverage



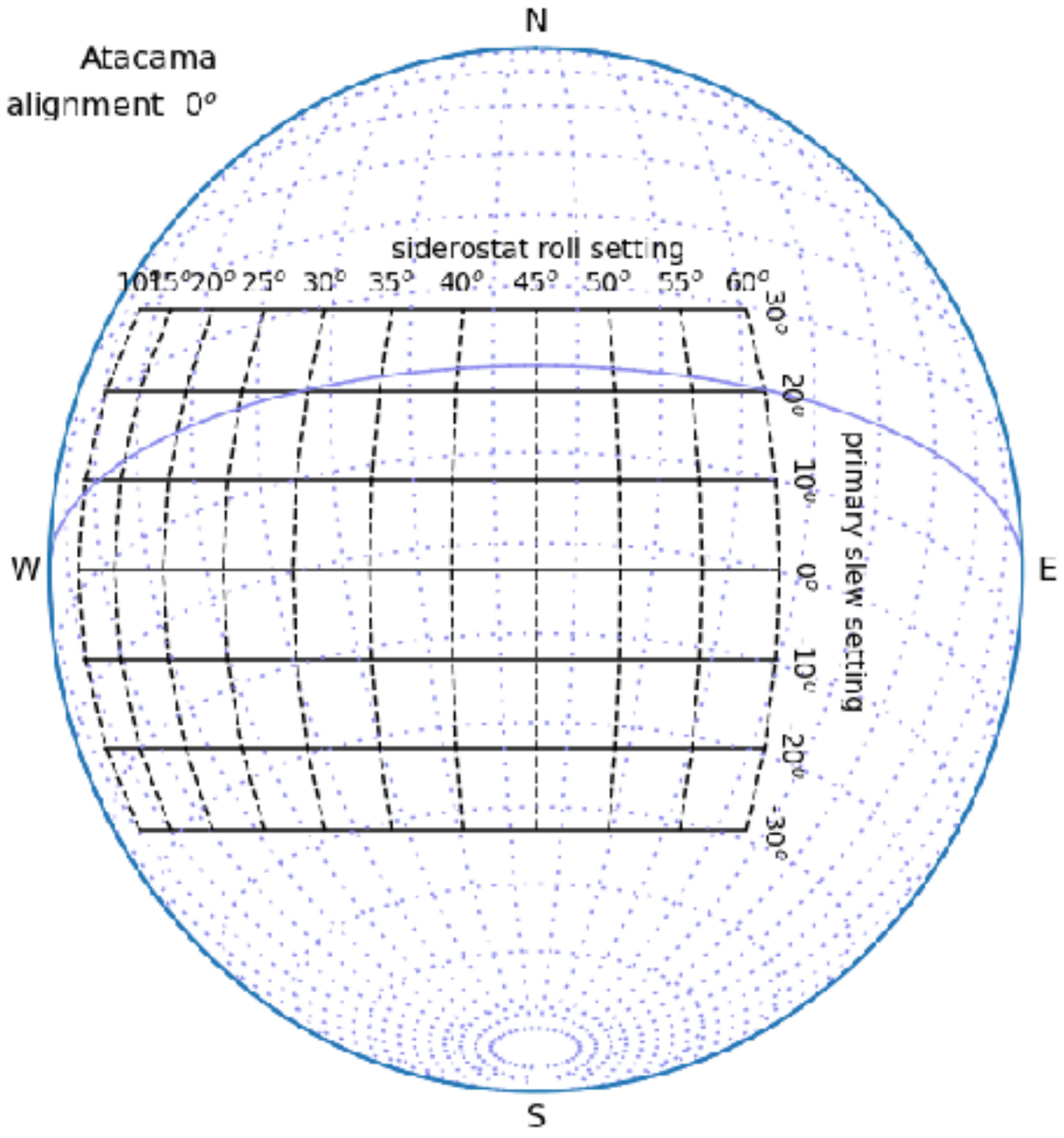
- Siderostat appears narrower at shallow incident angles
- $W_{sidero} = 1.4\,W_{primary}$ is needed to view zenith
- "overhead" angles visible with siderostat vignetting

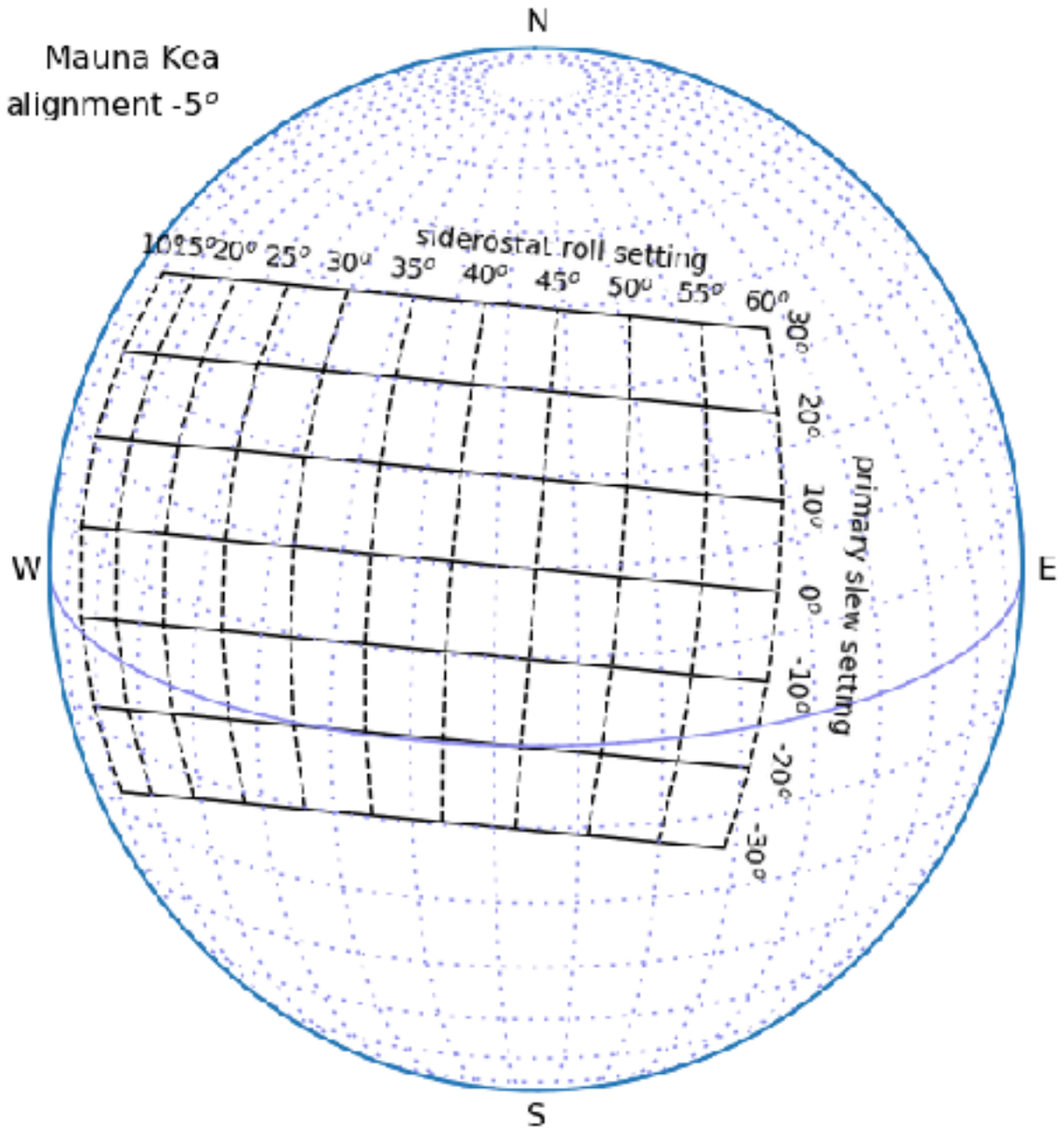
- Primary slew probably has a fixed range, say ±30°
- Requires $L_{sidero} = 1.15\,L_{primary}$

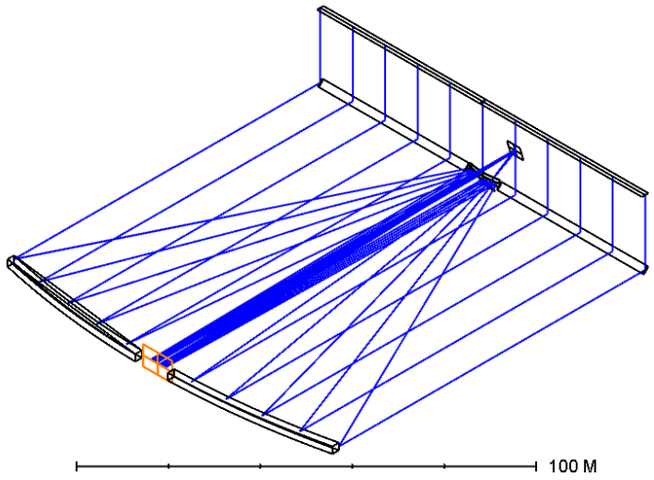
- Roll rate ~7.5°/hr
- Slew rate usually <1°/hr

Sky coverage

- Siderostat axis not necessarily N-S
- Minimize field rotation?



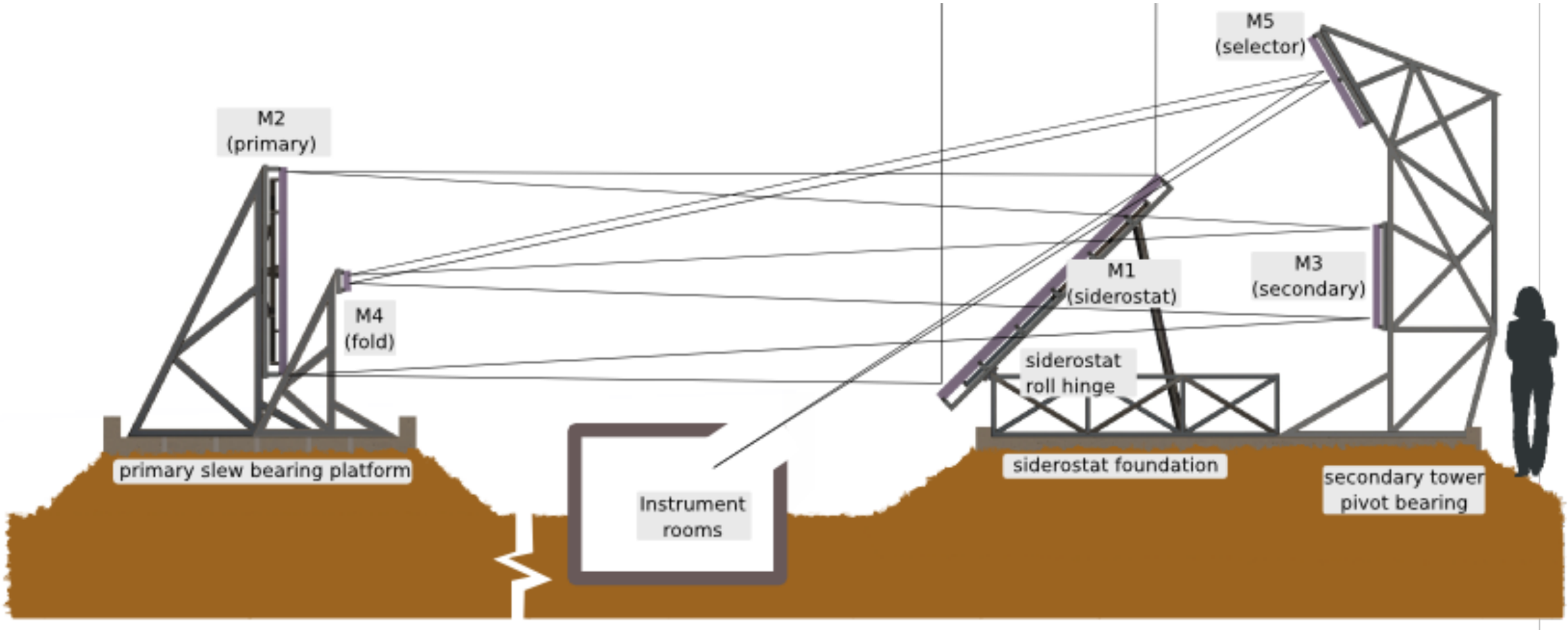




Horizontal plane is a slice of any optical design you like

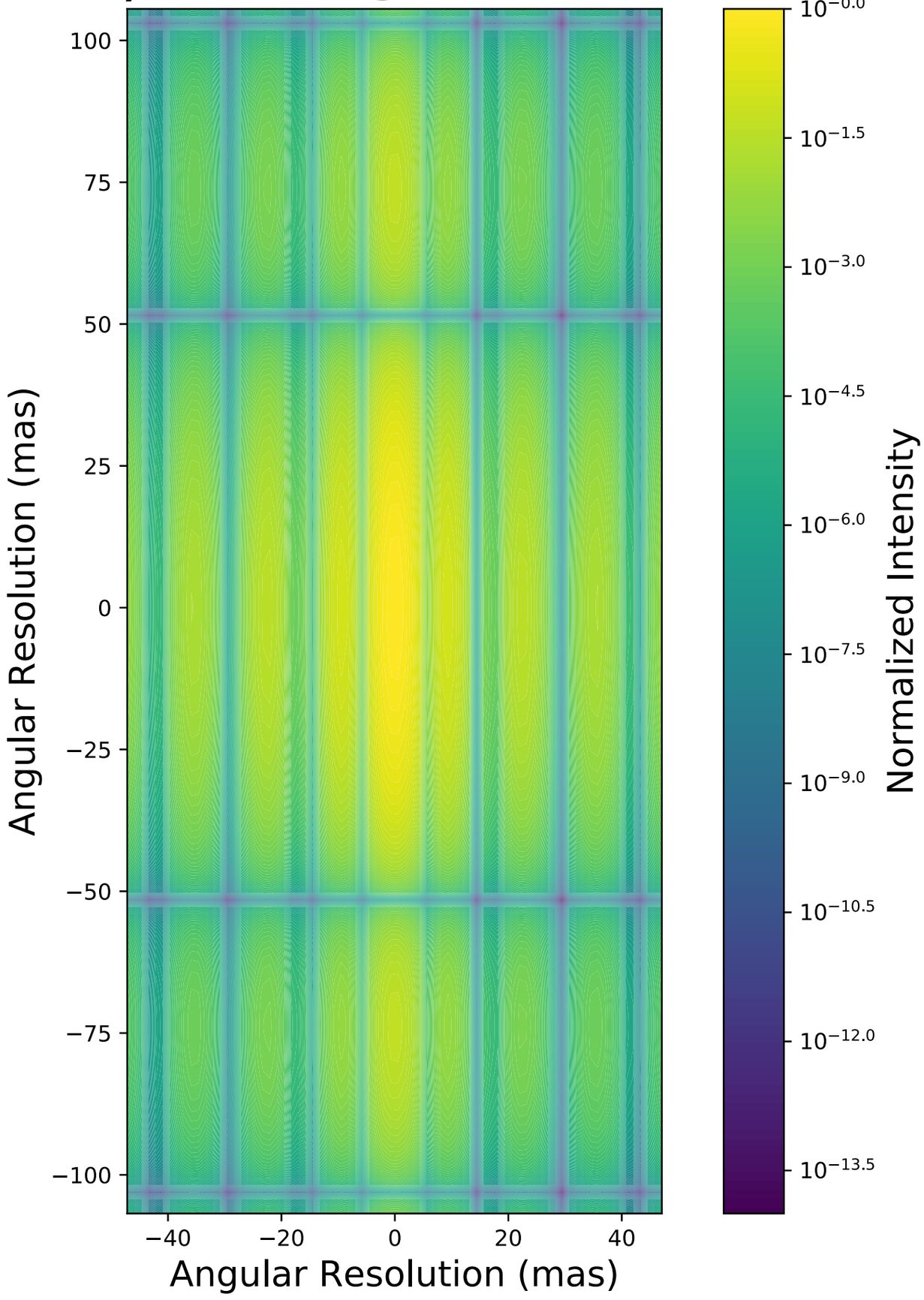
This is a Ritchey-Chretien

OR you can have large instruments at prime focus



engineering by Ama Carney

Rob Halliday 2x100 @ 500nm

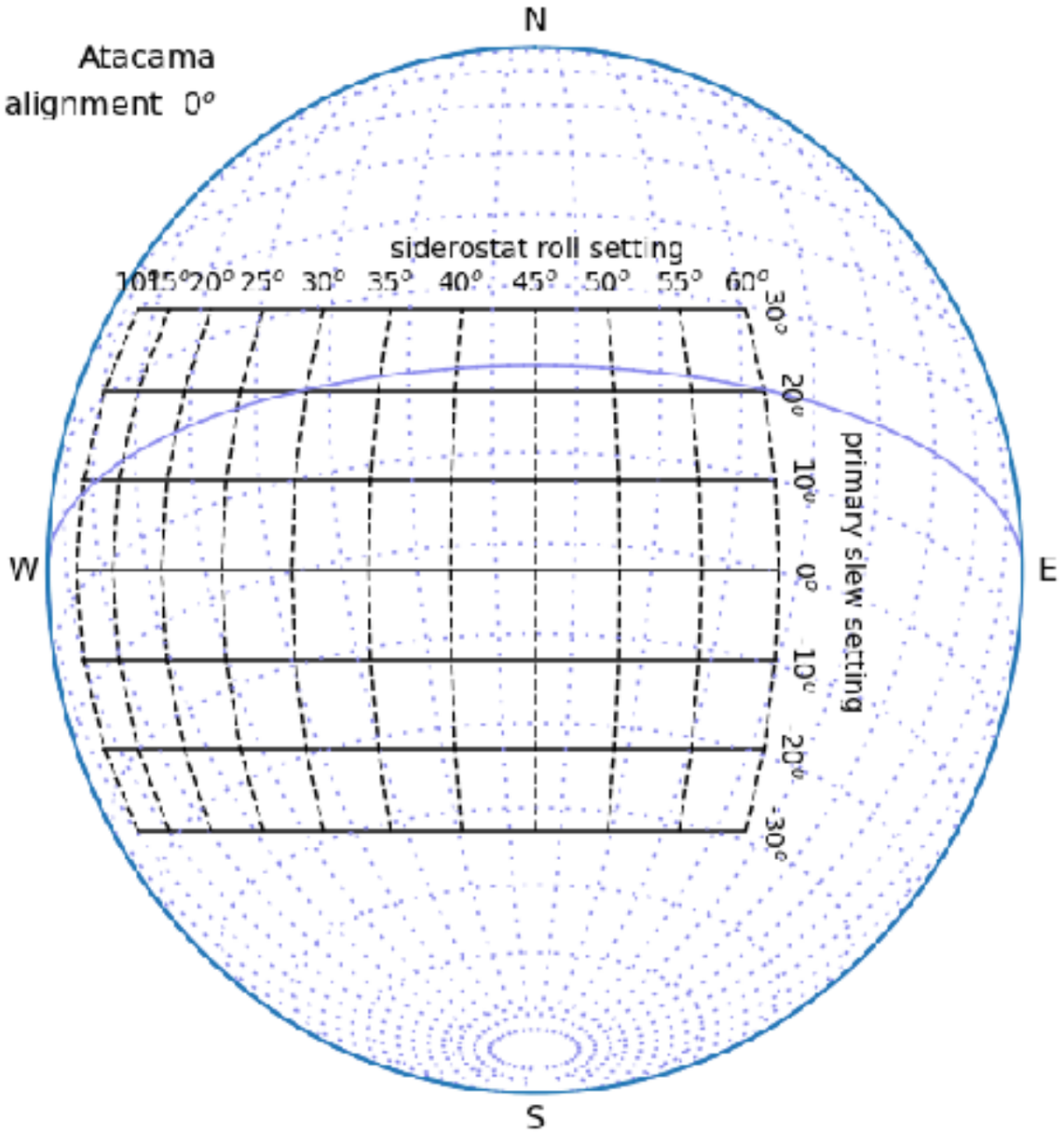


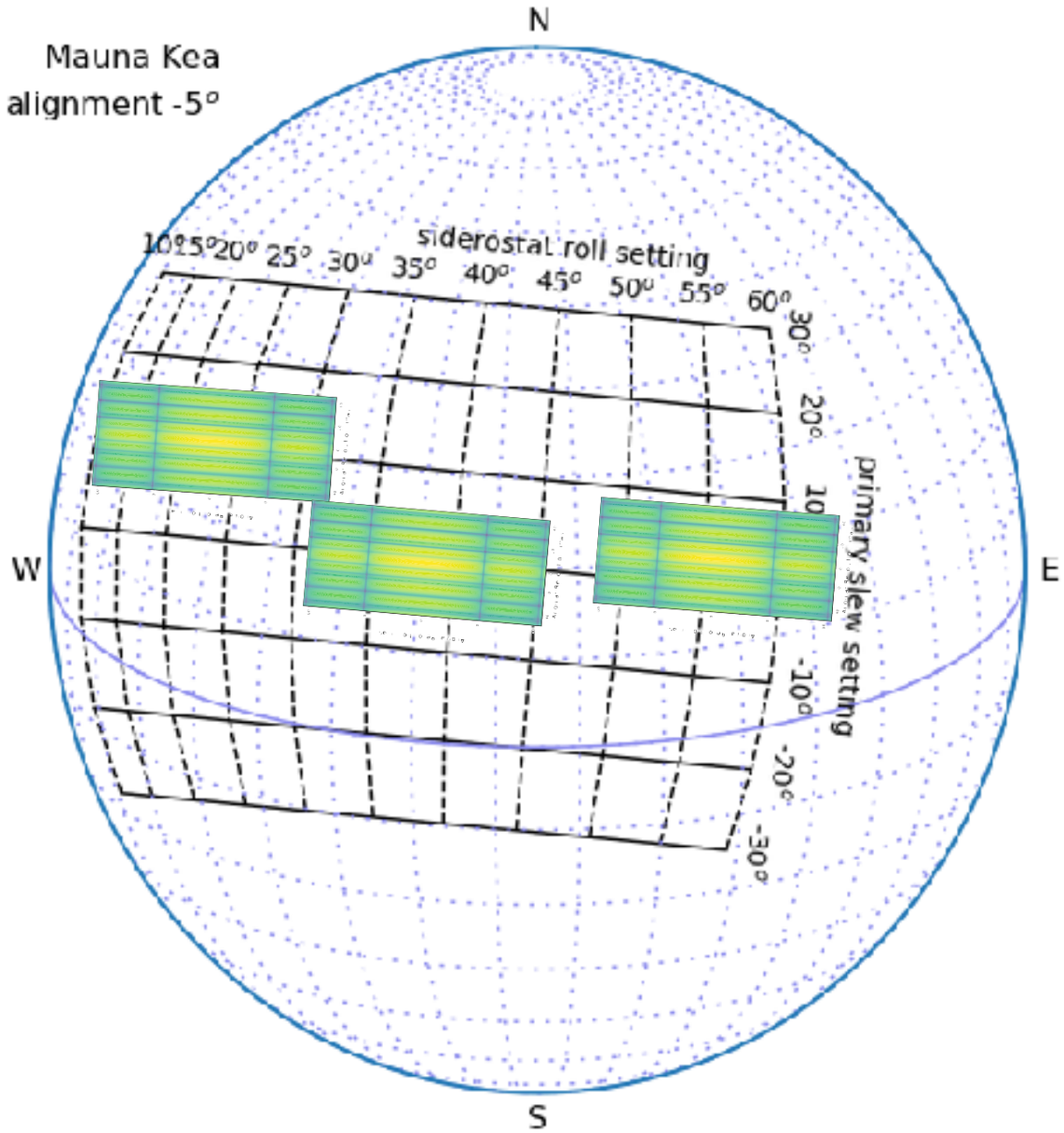
Very asymmetric PSF

- Not necessarily able to do all high-resolution science
  - Crowded fields?
- Fine for exoplanets
  - *most* systems move into in high-res separation *some* of the time
  - Systems randomly oriented
- GAIA does astrometry with a pupil like this

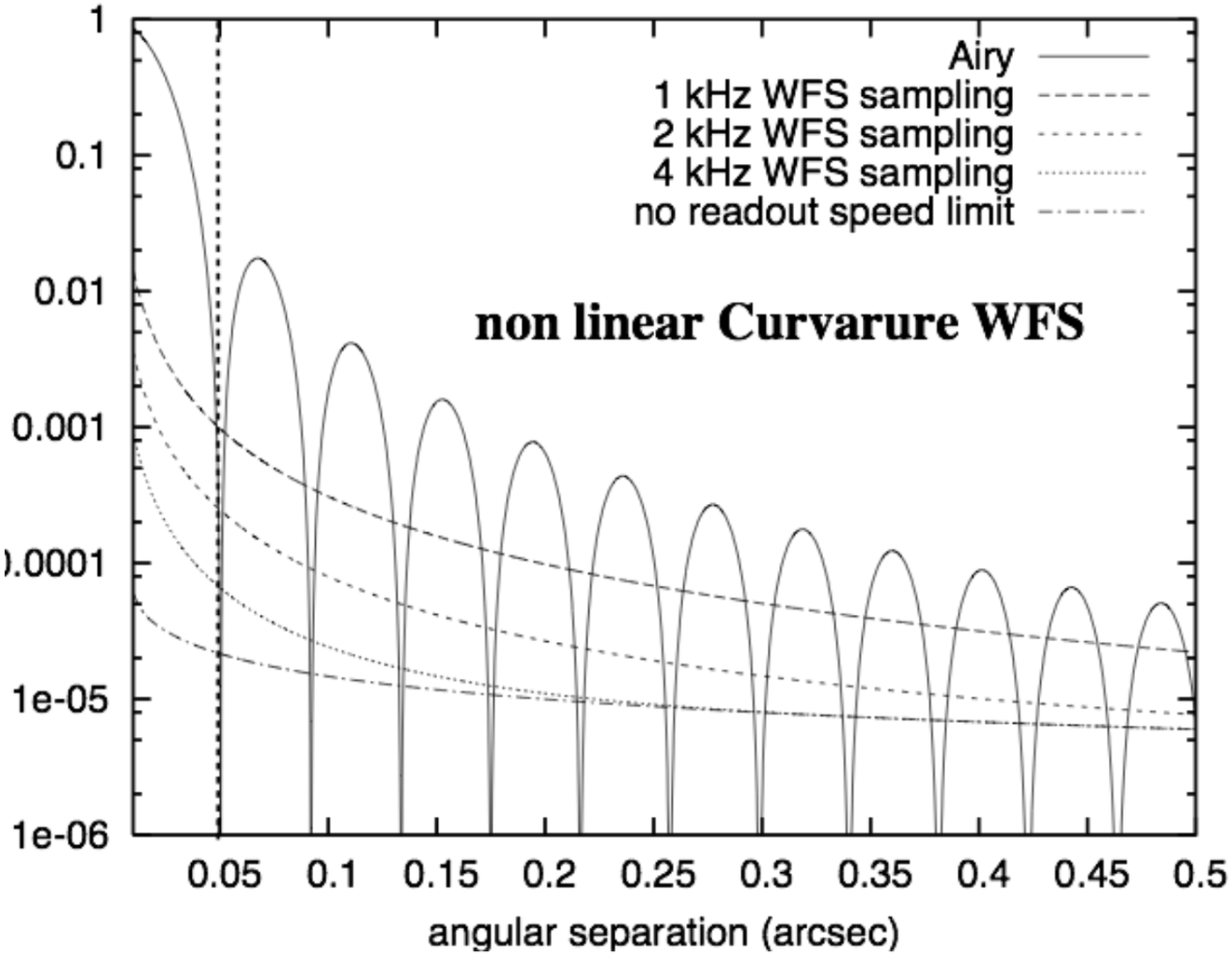
Sky coverage

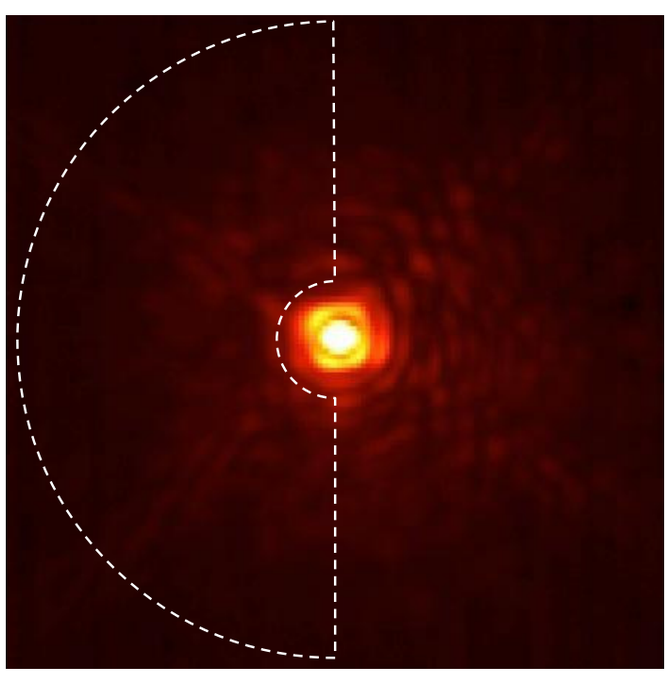
- Siderostat axis not necessarily N-S
- Minimize field rotation?



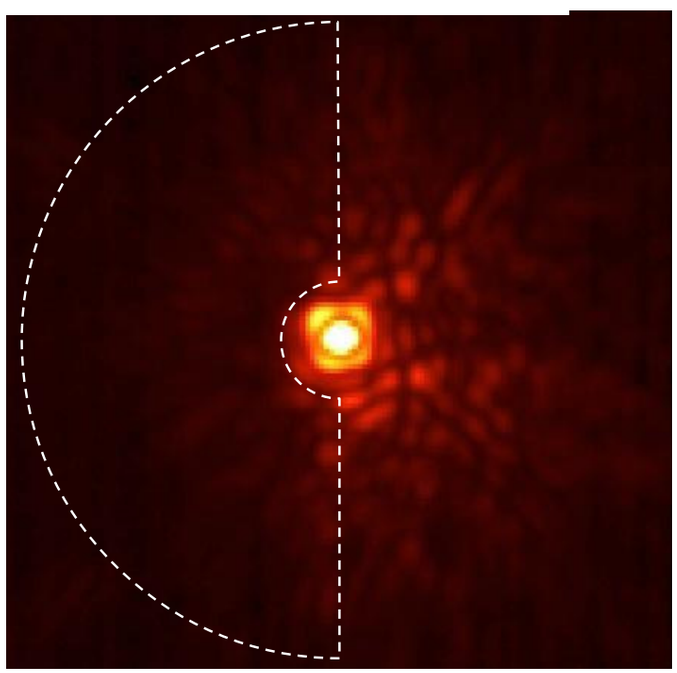


Guyon, O. PASP, 122, pp.49-62 (2010)



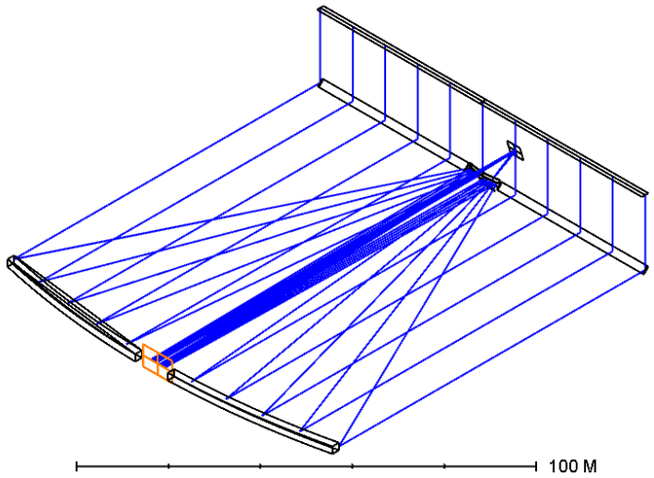


SCExAO speckle nulling

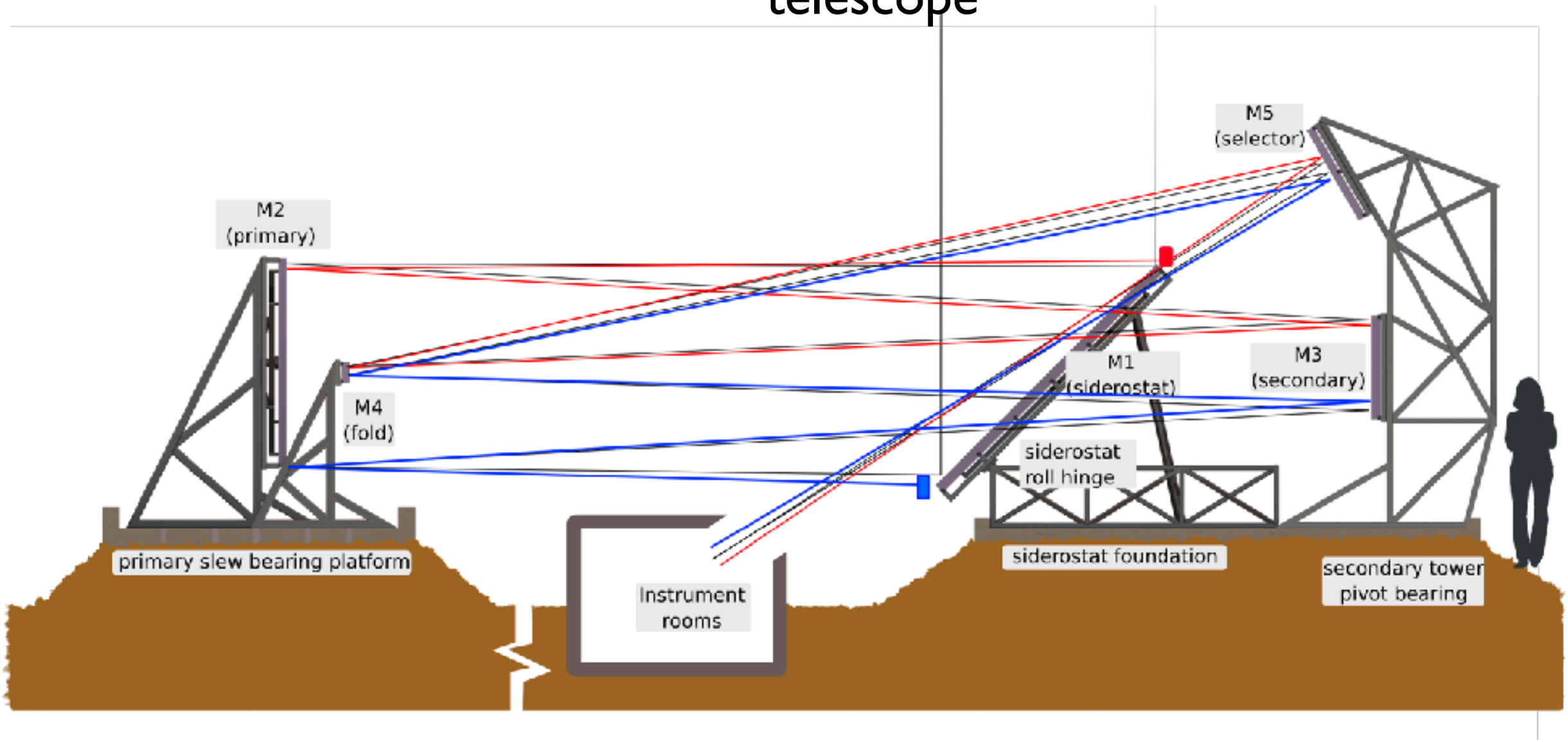


Lozi et. al., PASP 127, 890 (2015)

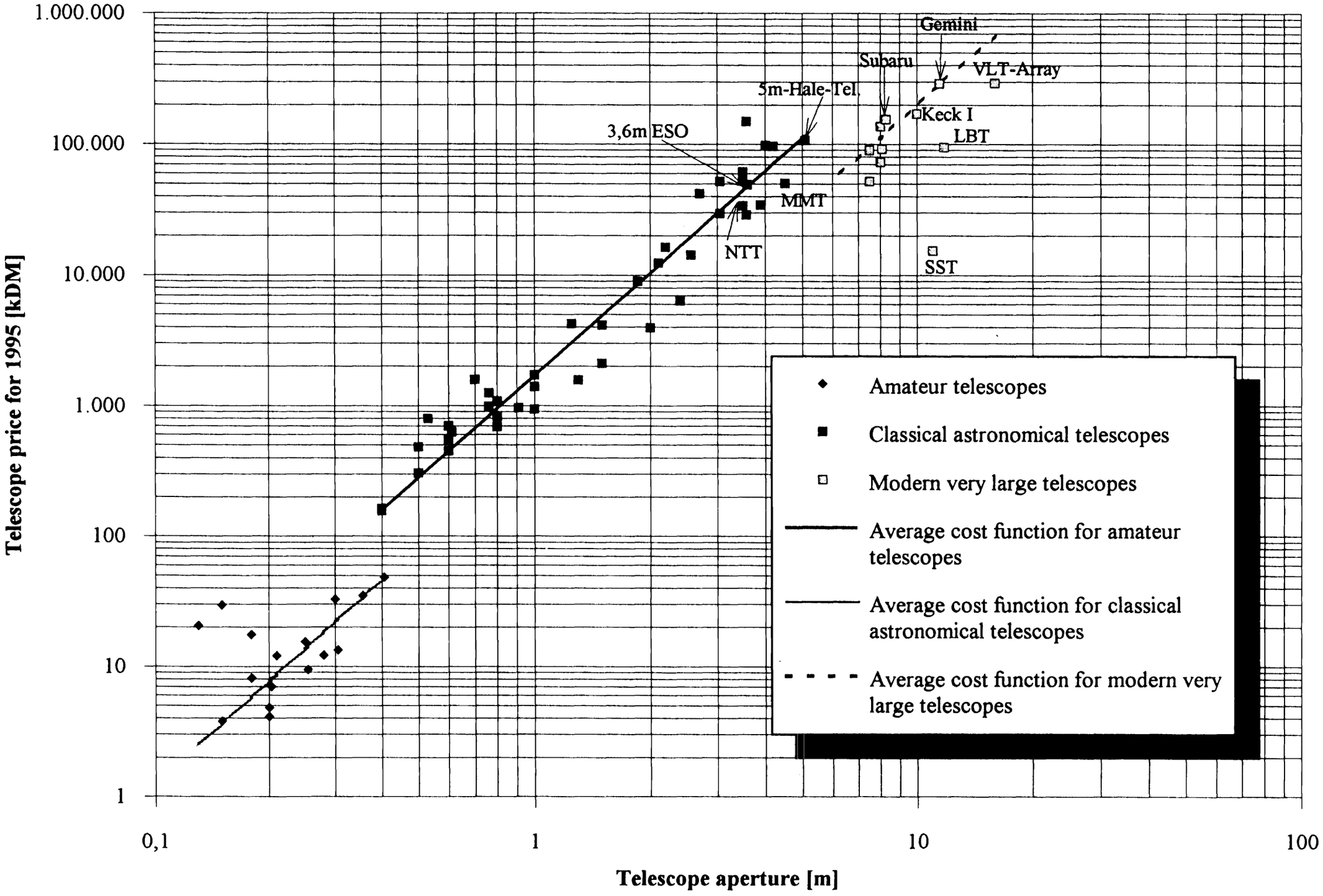
- Diffraction-limited seeing = adaptive optics
- Wavefront displacements increase with separation:
  - $D(r) \alpha r^{5/3}$
  - $10^{5/3} = \sim 50$
  - deformable mirrors need large amplitudes to correct over whole aperture
    - "woofer/tweeter" = ok
- Other than that, no bad scaling problems



- Adaptive optics:
  - conventional (LGS/NGS) for turbulence above the telescope
  - autocollimation wavefront sensing for turbulence within the telescope

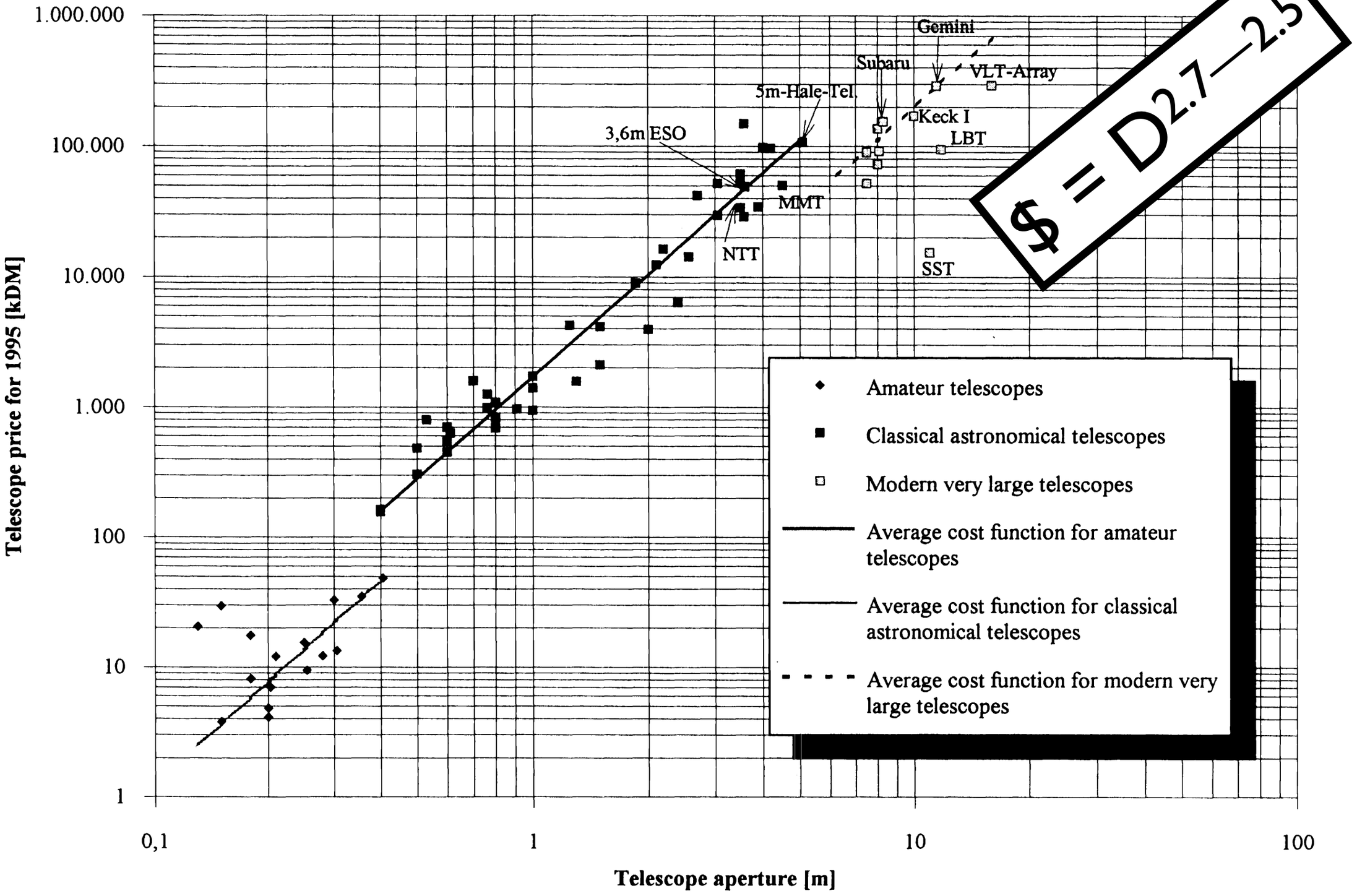


Cost estimation



Schmidt-Kaler & Rucks, SPIE 2871 (1997)

Cost estimation



Schmidt-Kaler & Rucks, SPIE 2871 (1997)

Cost estimation

Cost scaling estimates

Component	Version	Scaling estimate
Steel framework		\$2k L×W
Air bearings		\$2k L×W
Mirror cells		\$10k L×W
Enclosures		\$2k $L \times W^{0.5}$
Siderostat mirror		\$150k L×W
Primary mirror	Aspheric	\$450k L×W
	HET-like	\$200k L×W
	OWL-like	\$80k L×W
Slab and bearing	Primary-slew	\$250 $L^{1.6}$
	Siderostat-pivot	\$150 L^2
Thermal control	Ground cover	\$40 L^2
	Roof (flat)	\$200 L^2
	Roof (tension)	\$1k L^2

Ama Carney 100m engineering model

Christian Rodriguez went to Caltech archives for Keck project records

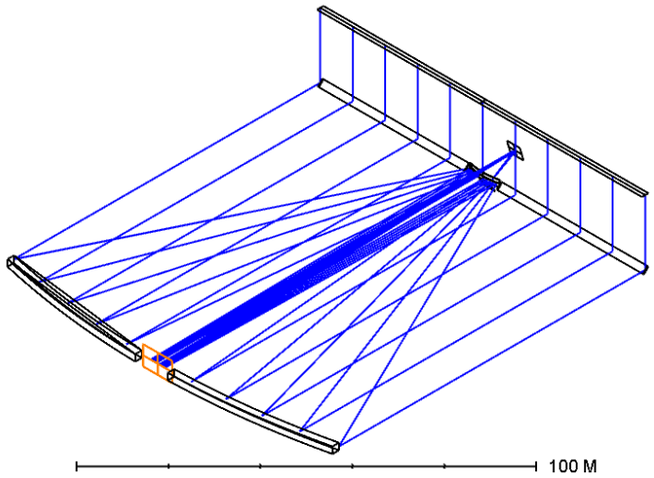
derivable from the literature

Wikipedia, TBH

Gilmozzi et. al.

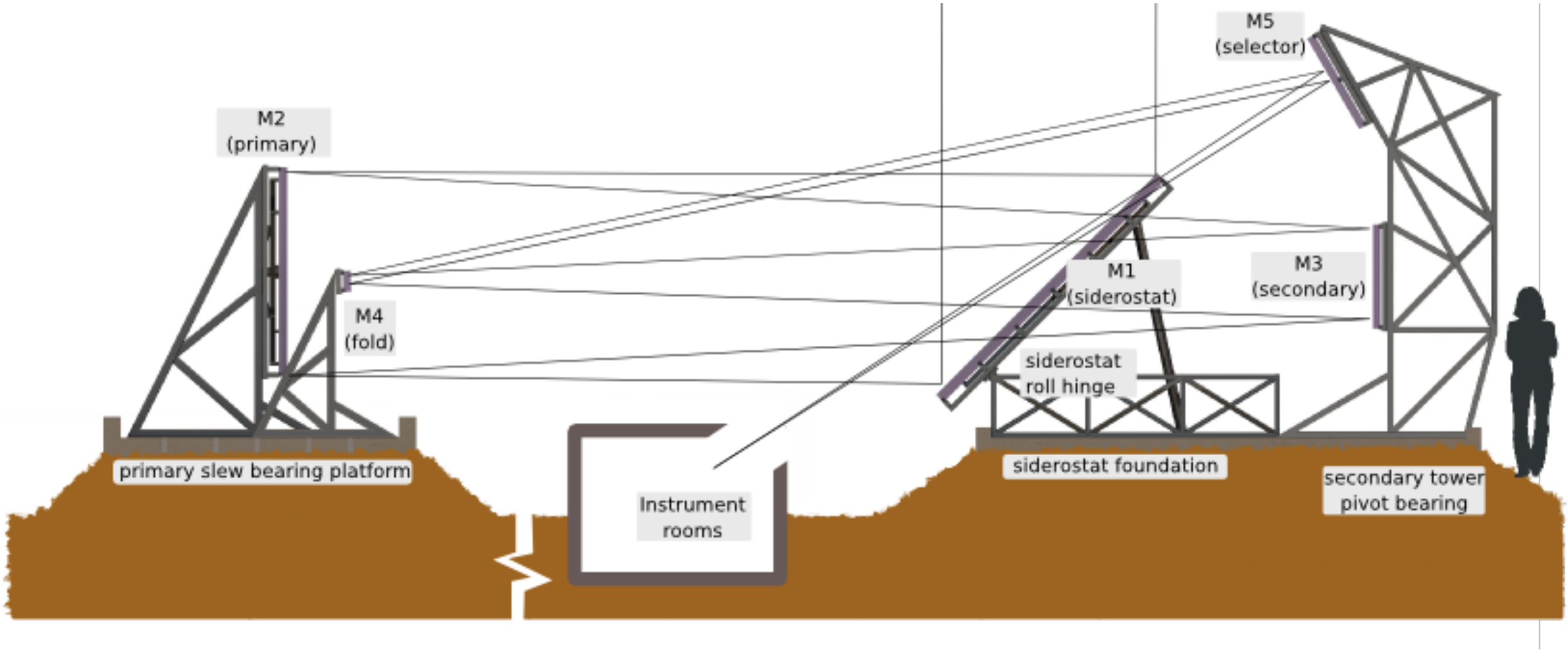
some other industries are better about public cost estimation info

hangar and stadium projects



Structural cost advantages:

- Nothing is high up
- Nothing is flexing
- Nothing is high up *and* flexing



b: mount = dome = mirrors

Ray et. al., Proc. SPIE 4004 (2000)

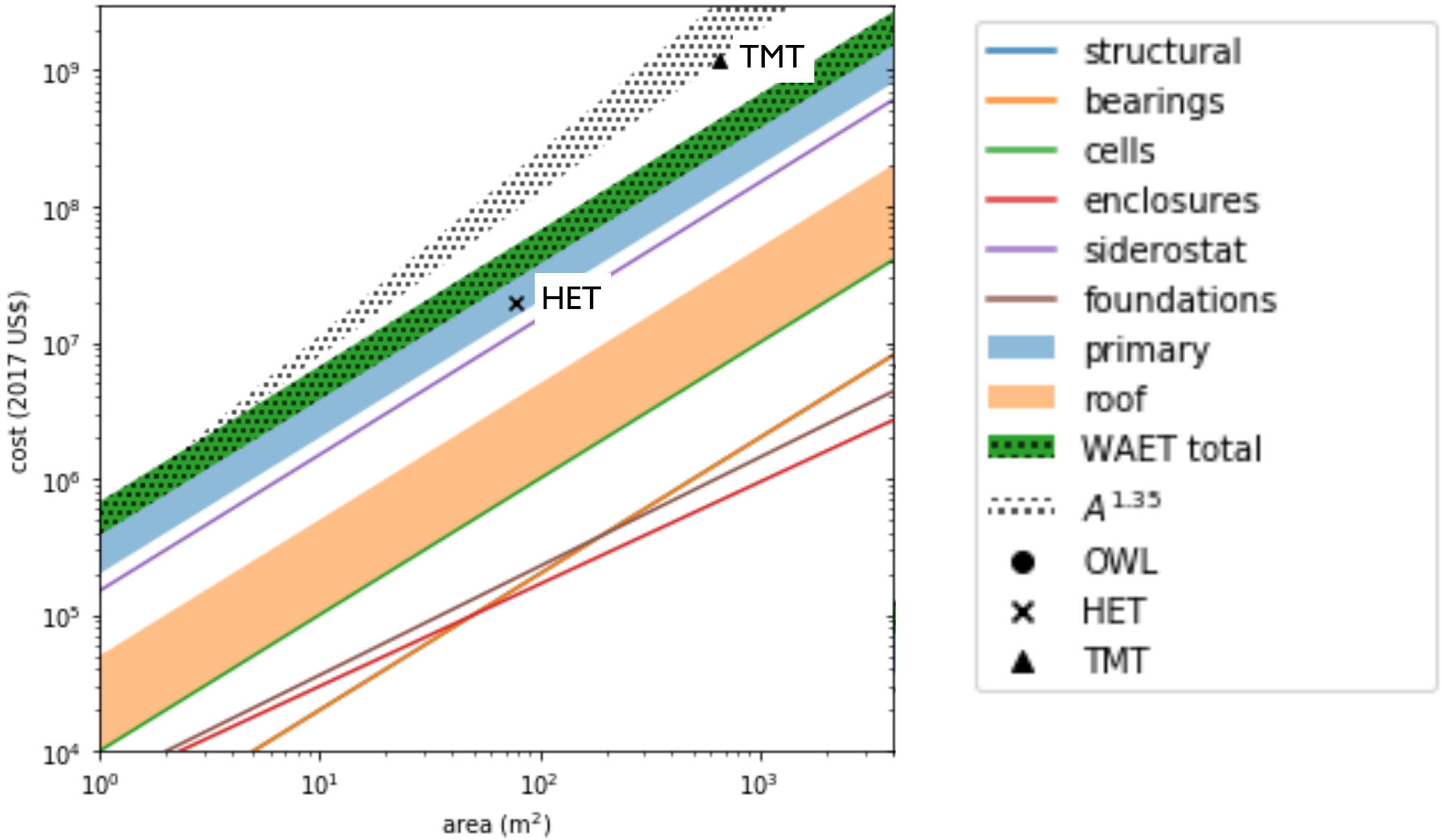
100 m Hobby-Eberly f/1.7

>1.5 α $D^{>3}$

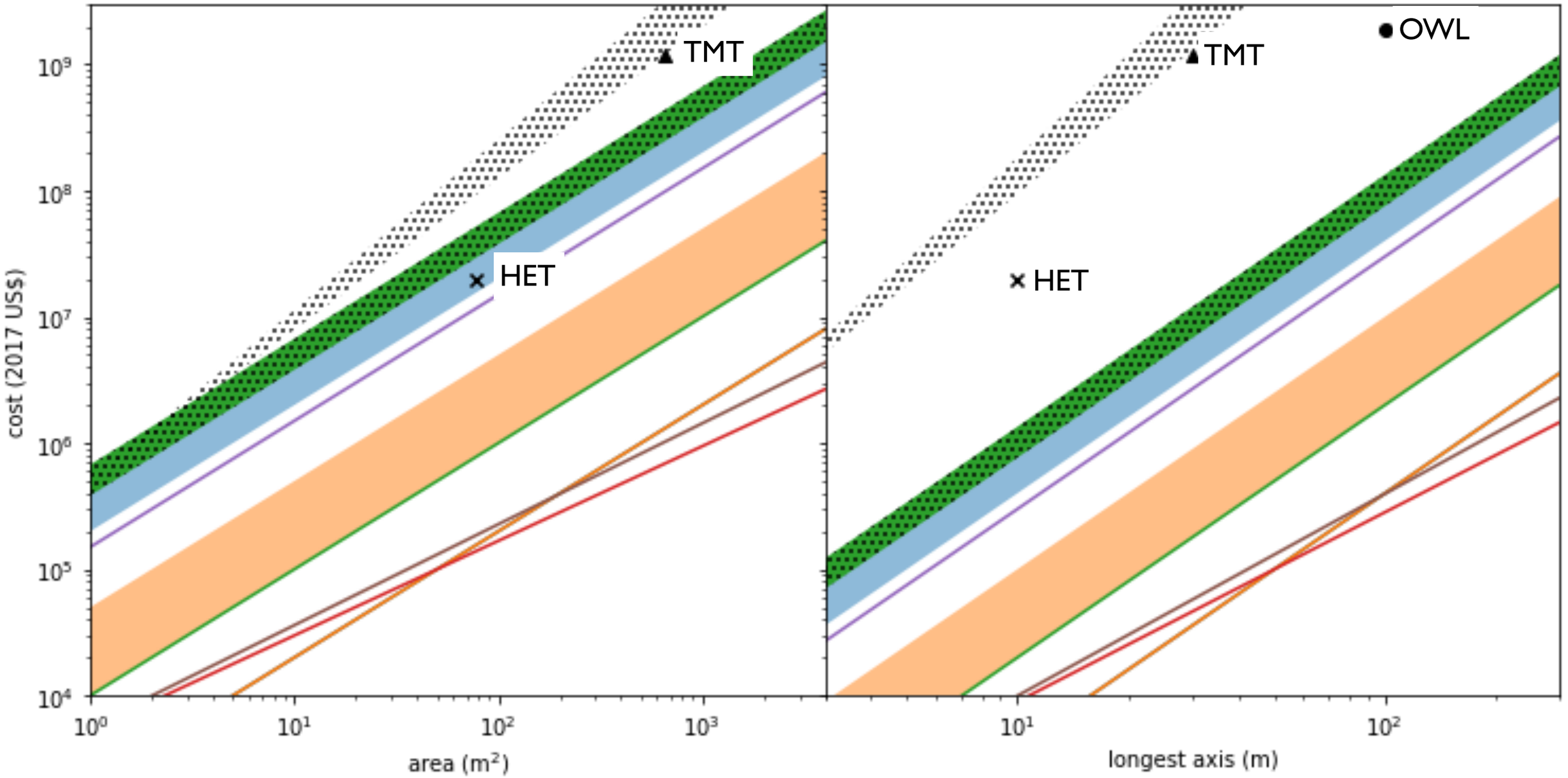
Site/dome

Cost α $A^{1.5}$ α D^{3}

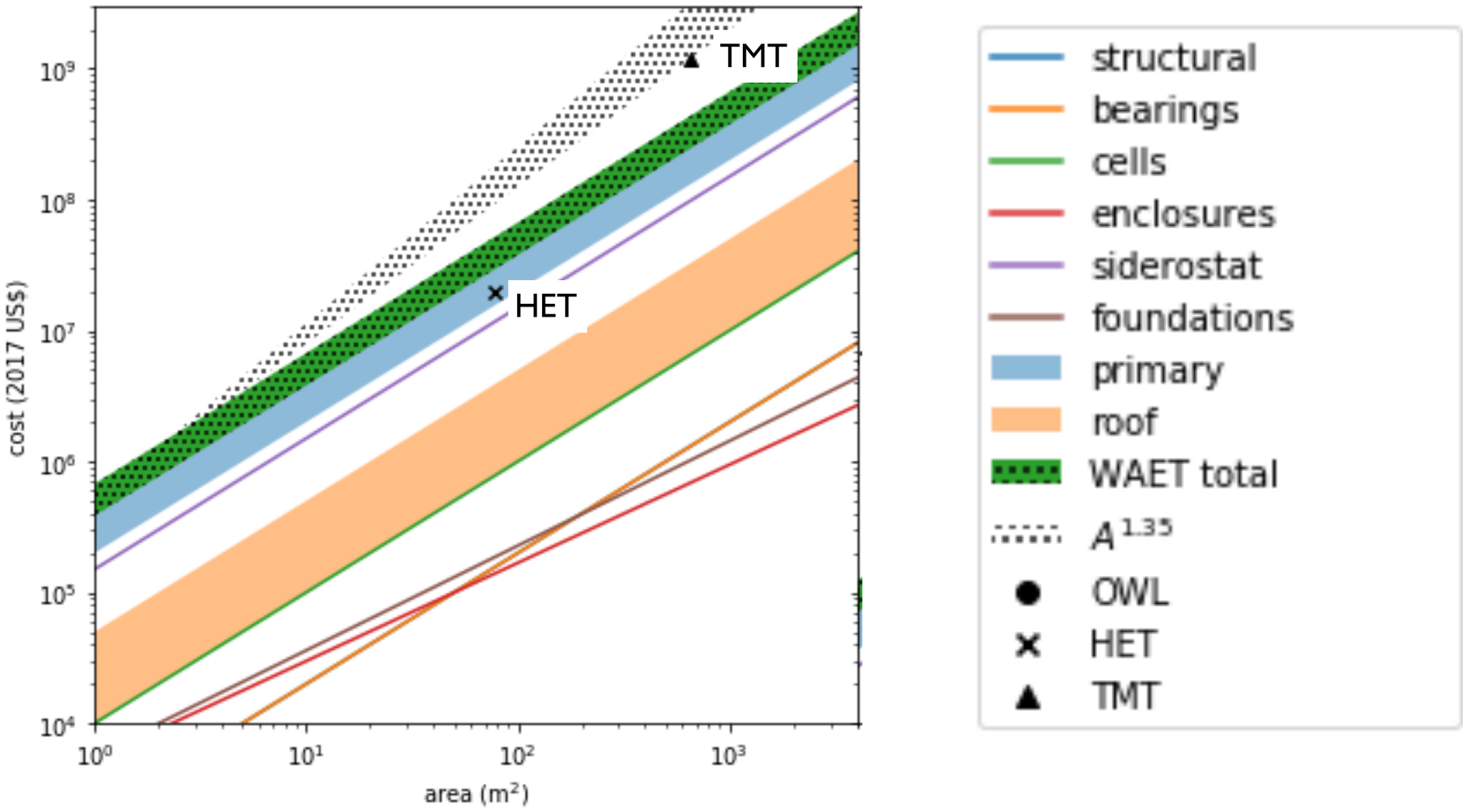
Cost estimation



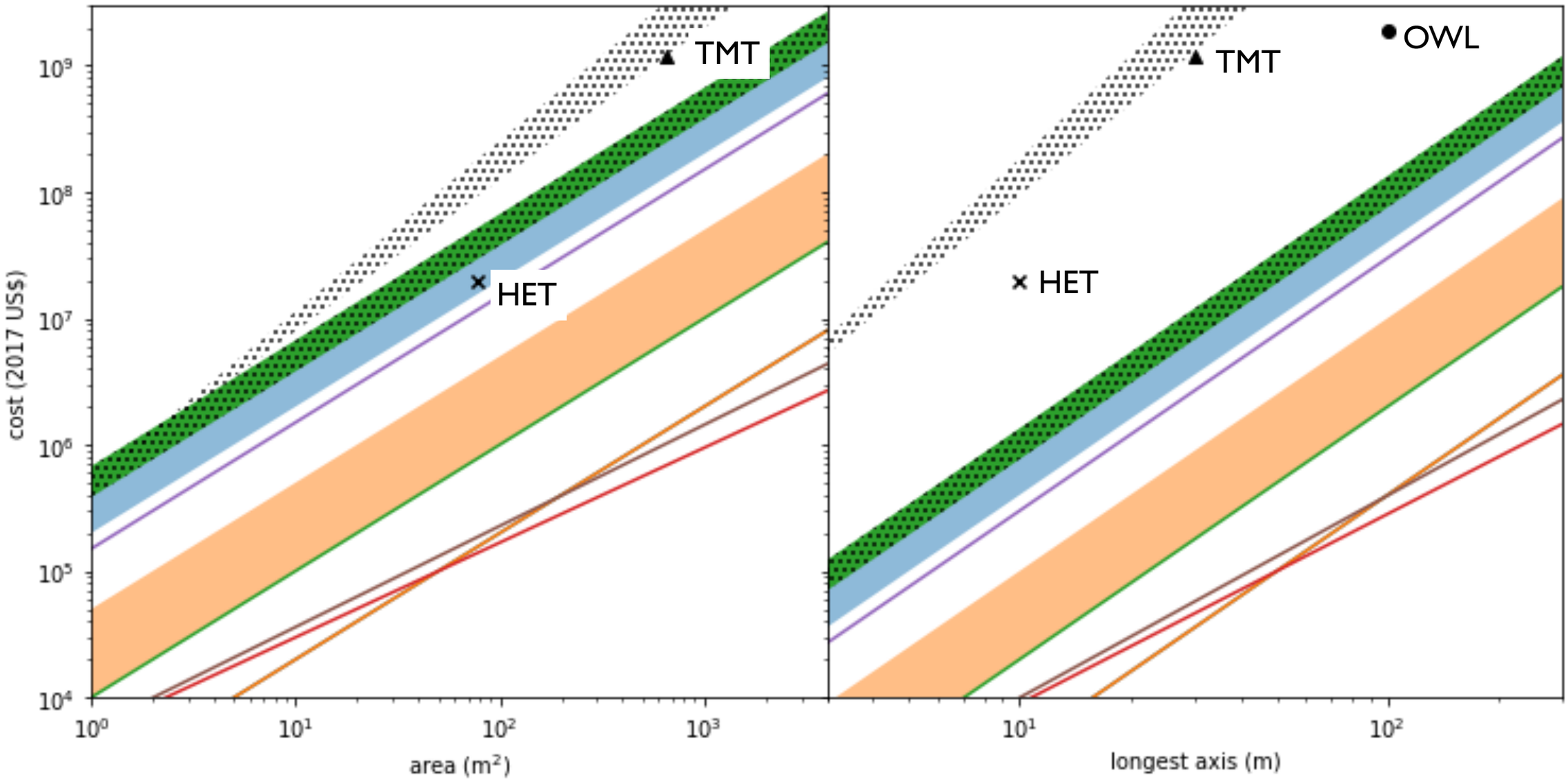
Cost estimation



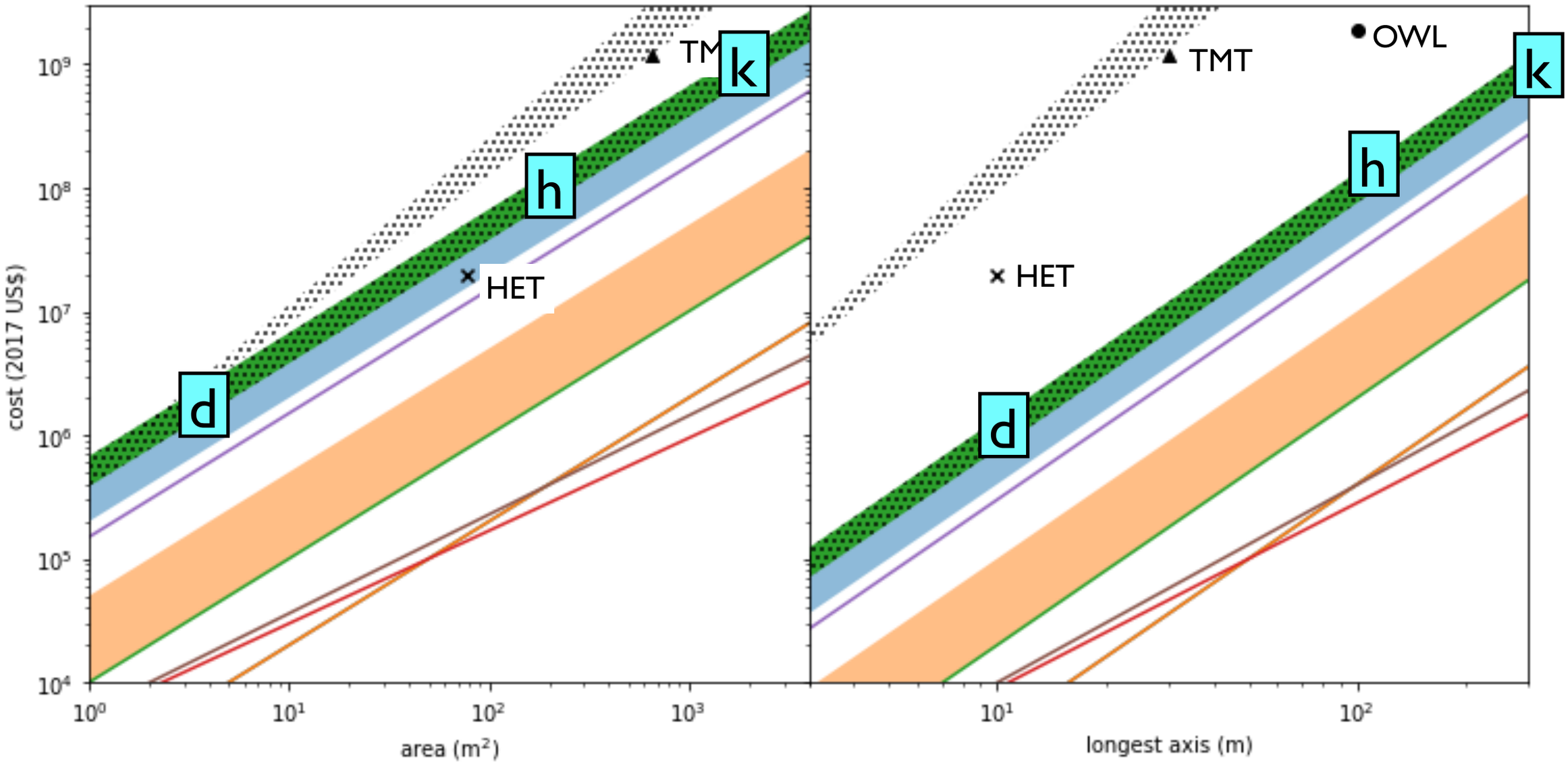
Cost estimation



Cost estimation



Cost estimation

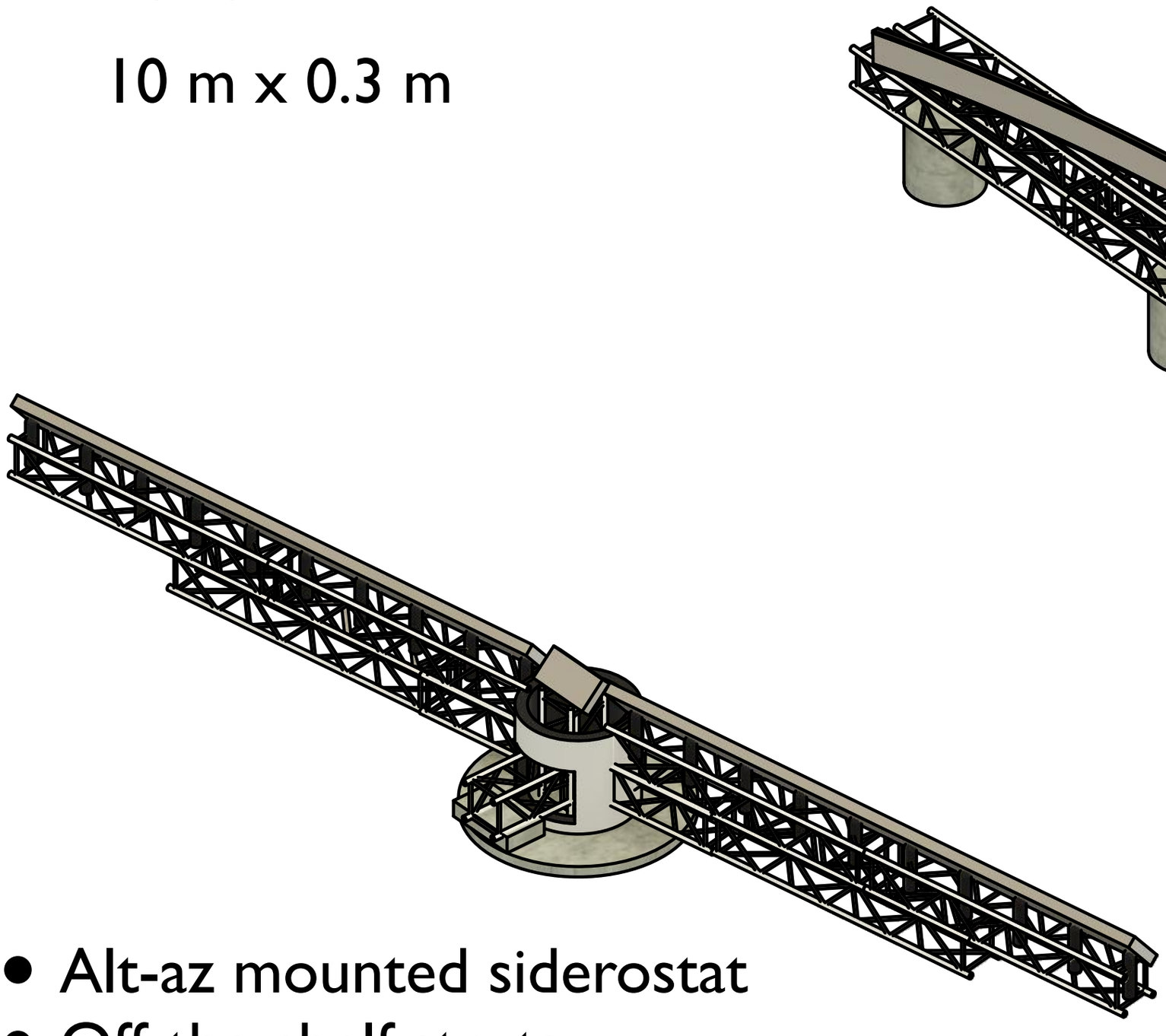


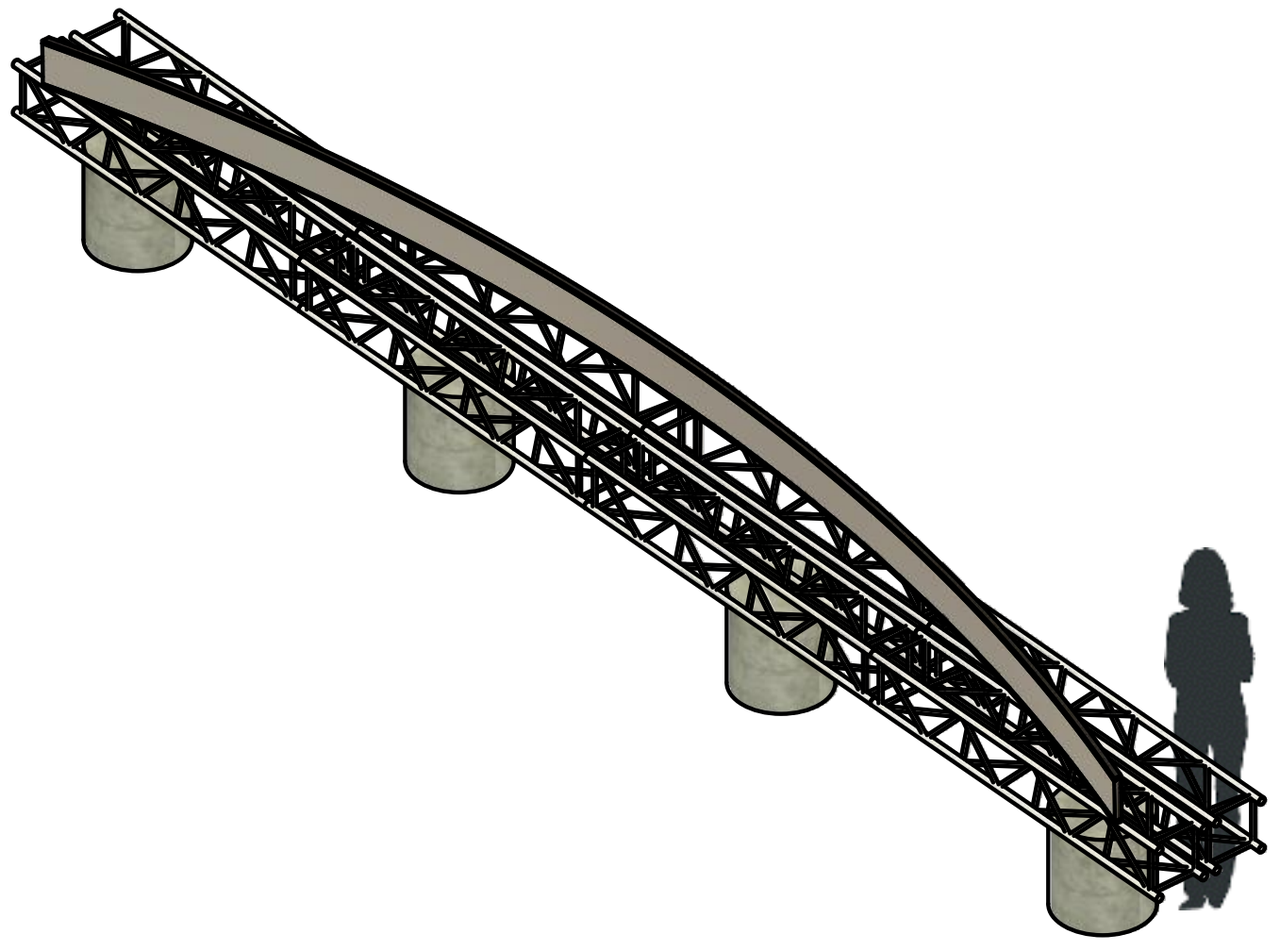
Three example configurations			
	dWAET	hWAET	kWAET
Length (m)	10.0	100	300
Width (m)	0.30	2.0	5.0
Aperture (m^2)	3.0	200	1500
λ/d @1μm (as)	21m	2.1m	690μ
Cost estimates ($)			
Primary mirror	1.50M	100M	450M
Siderostat mirror	760k	51M	380M
Supports	43000	2.8M	21M
Foundation/sheds	15000	760k	5.1M
Thermal	4000	10.0M	18.0M
Total	2.3M	153M	850M
Cost/m^2	770k	770k	560k

dWAET

10 m x 0.3 m

- Area and cost of a 2m
- Resolution of a 10m

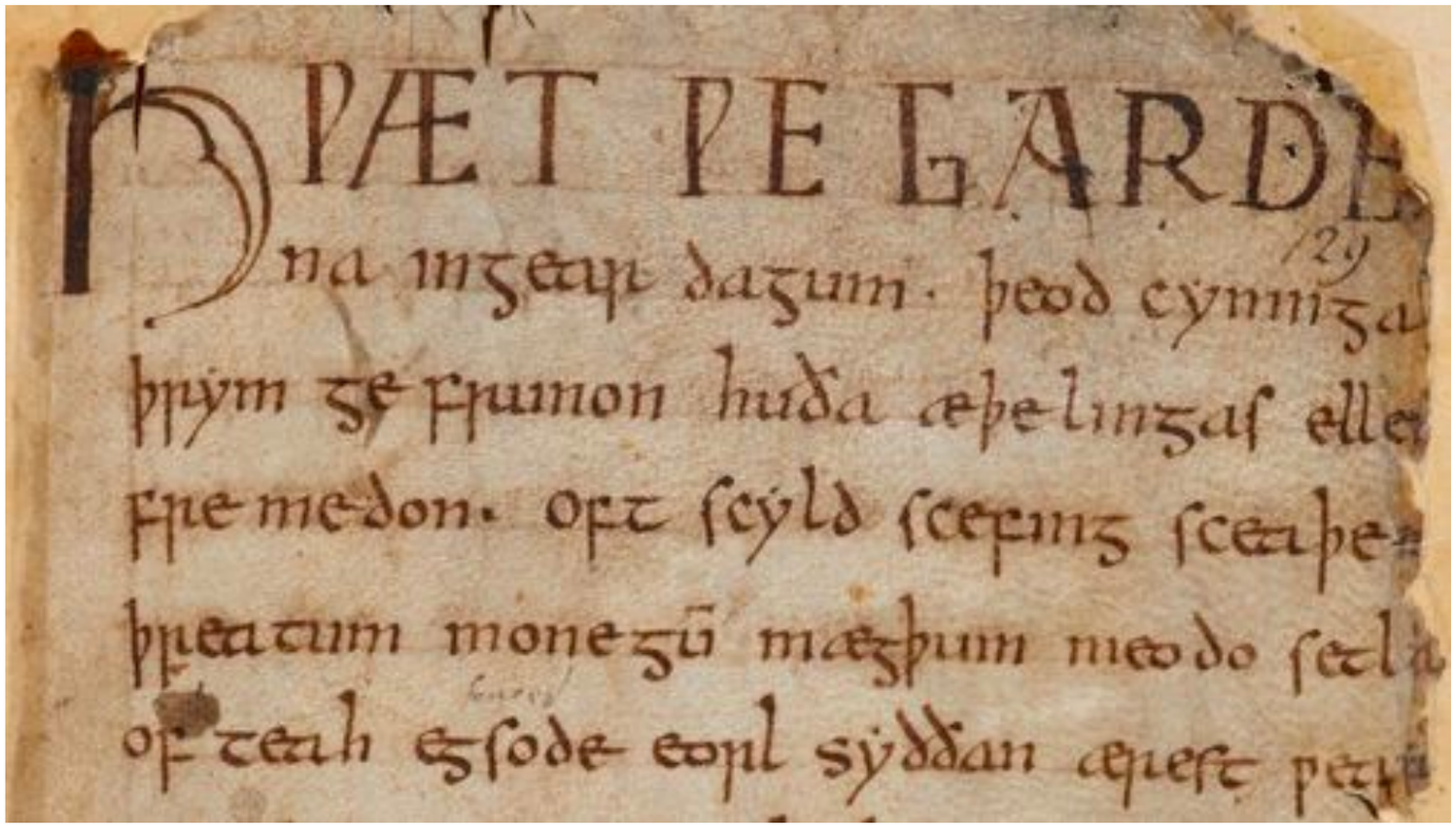




- Alt-az mounted siderostat
- Off-the-shelf struts
- Whole system fits in a 40’ truck or container

hWAET

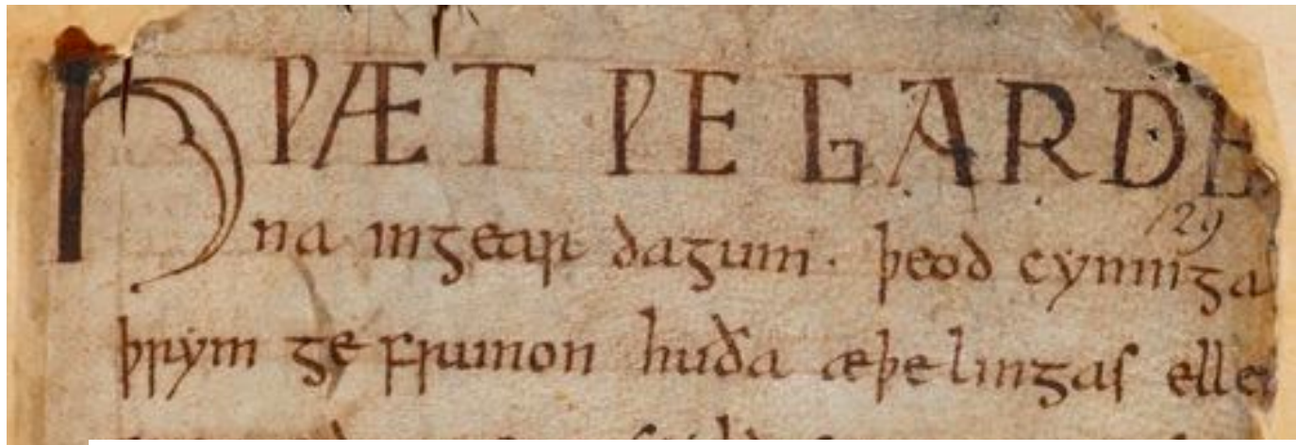
100 m x 2 m



Hwæt! We Gardena in geardagum, þeodcyninga …
So. The Spear-Danes in days gone by … [Heaney]
Lo, praise of the prowess of people-kings … [Gummere]
Hear me! We've heard of Danish heroes … [Raffel]

hWAET

100 m x 2 m

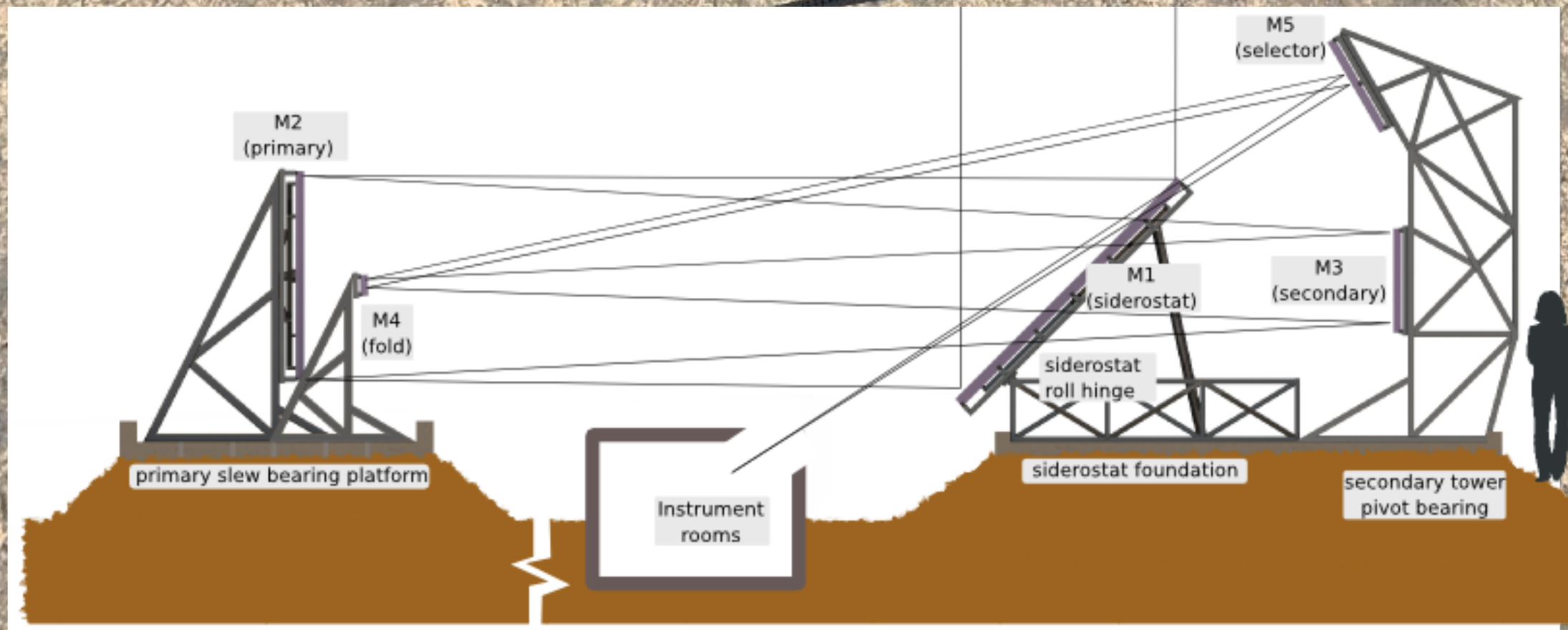


Hwæt! We Gardena in geardagum, þeodcyninga …
So. The Spear-Danes in days gone by … [Heaney]
Lo, praise of the prowess of people-kings … [Gummere]
Hear me! We've heard of Danish heroes … [Raffel]

hWAET

100 m x 2 m

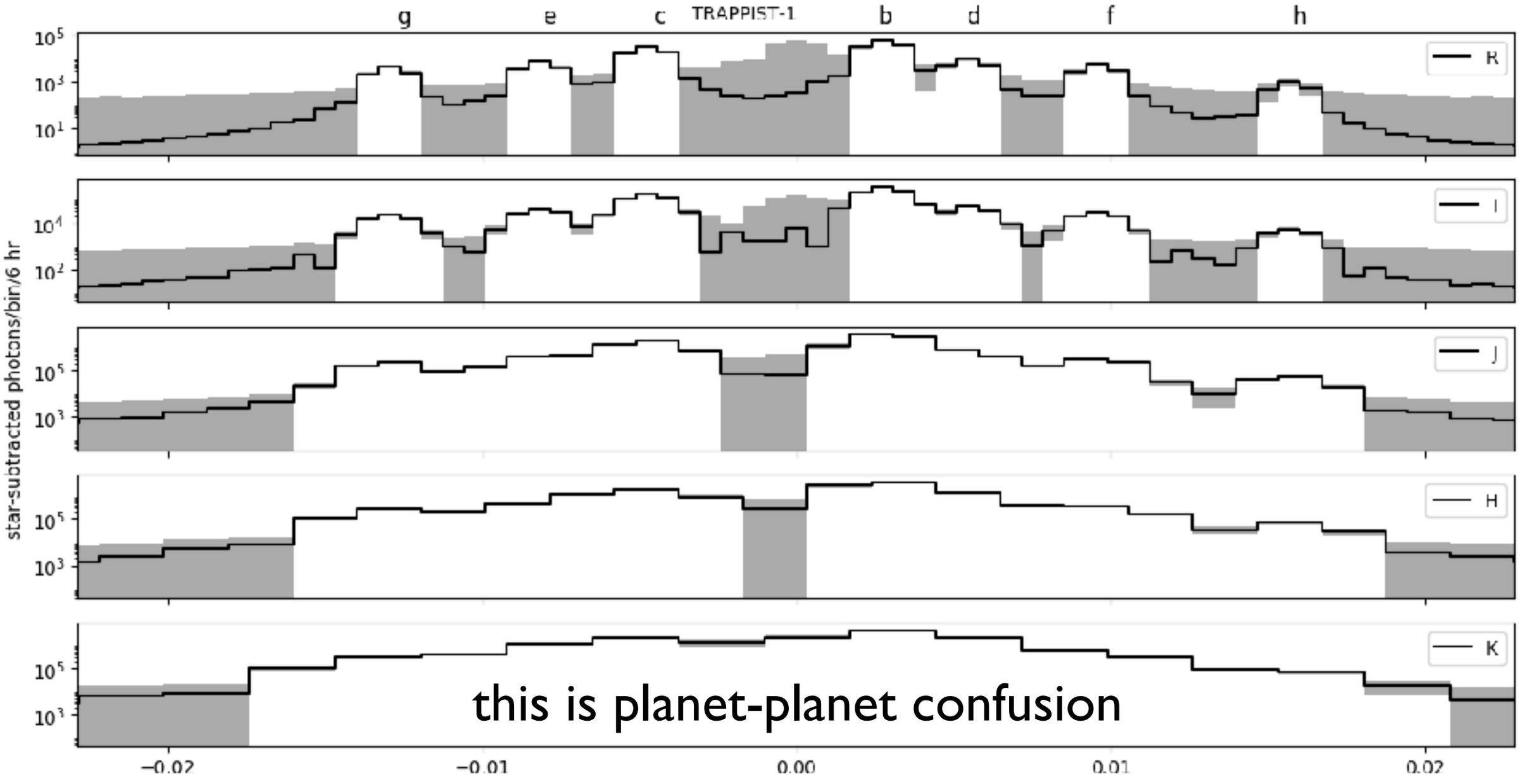
		Keck	TMT	OWL
Area	200 m^2	2.5x	1/3	1/40
L	100 m	10x	3x	1x
Cost	$150M	1x	1/8	1/10



hWAET

100 m x 2 m

Trappist-1 system in reflected light
five bands, 6h exposure
all albedos 1.0
star subtraction, no coronagraph

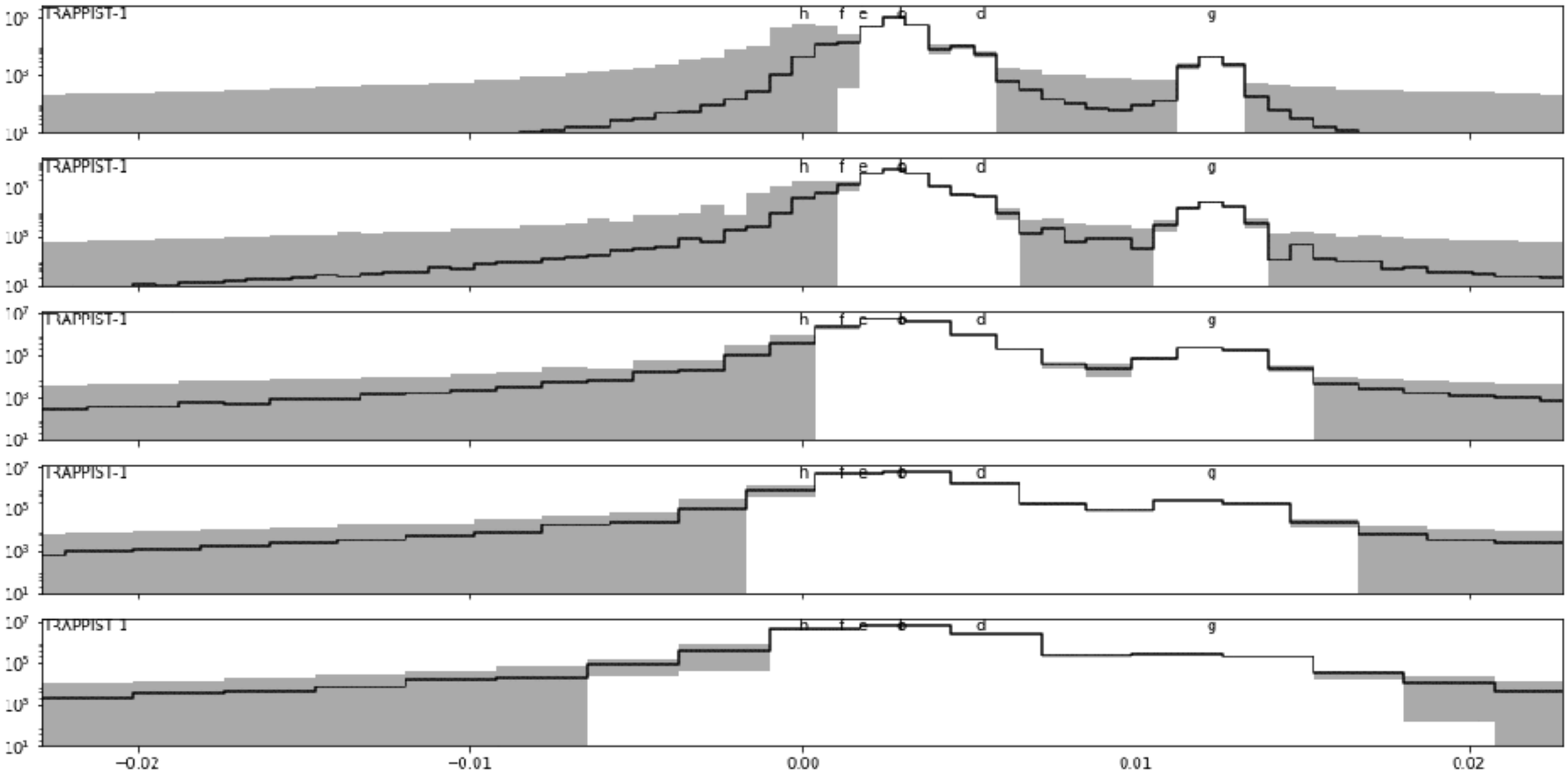


this is planet-planet confusion

PSFs by Rob Halliday

hWAET

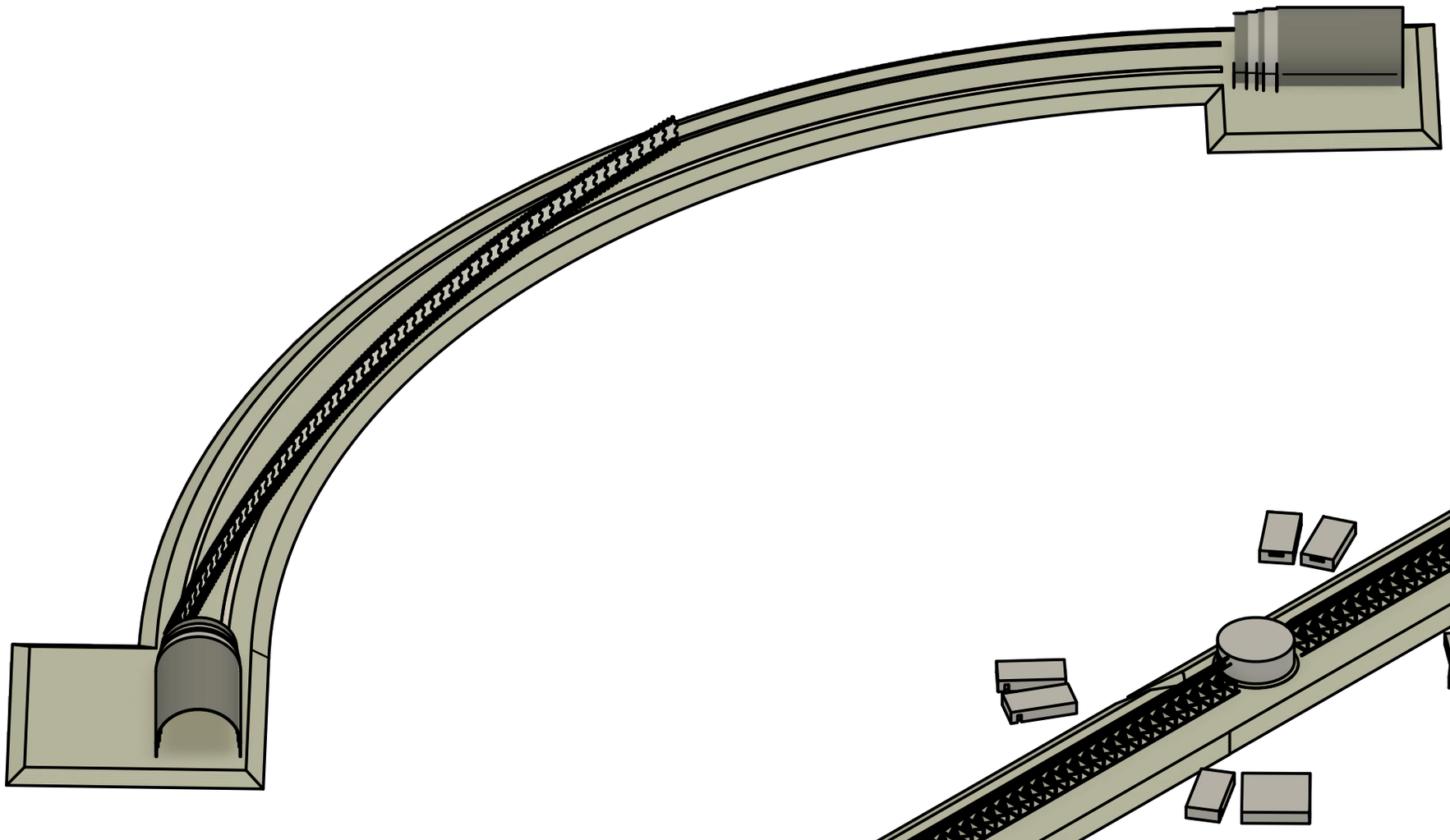
Trappist-1 system in reflected light
five bands, 6h exposure
all albedos 1.0
star subtraction, no coronagraph

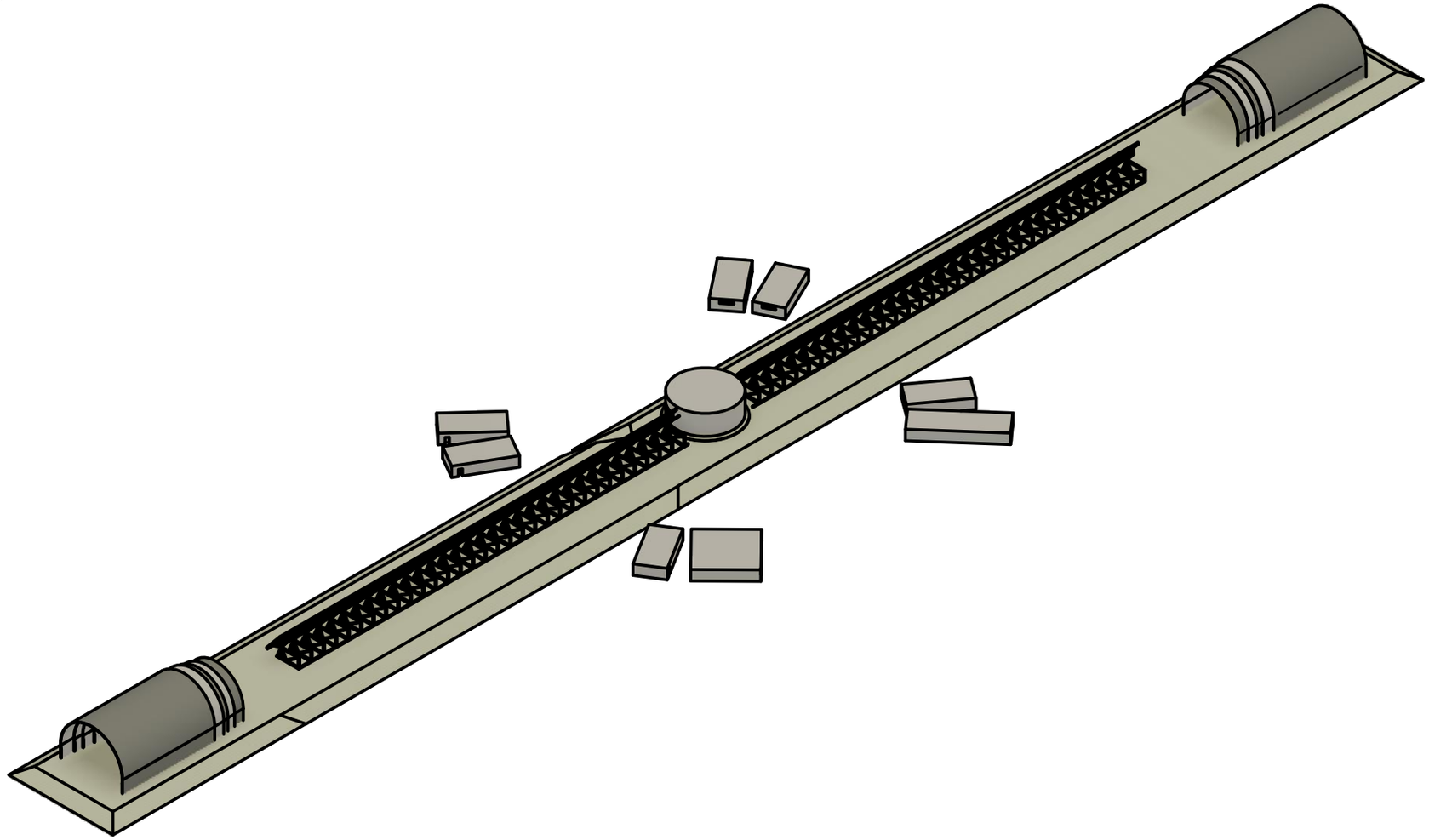


kWAET

300 m x 5 m

		Keck	TMT	OWL
Area	1500 m^2	20x	2x	1/5
L	300 m	30x	10x	3x
Cost	????	more	less	less





kWAET cost particularly uncertain

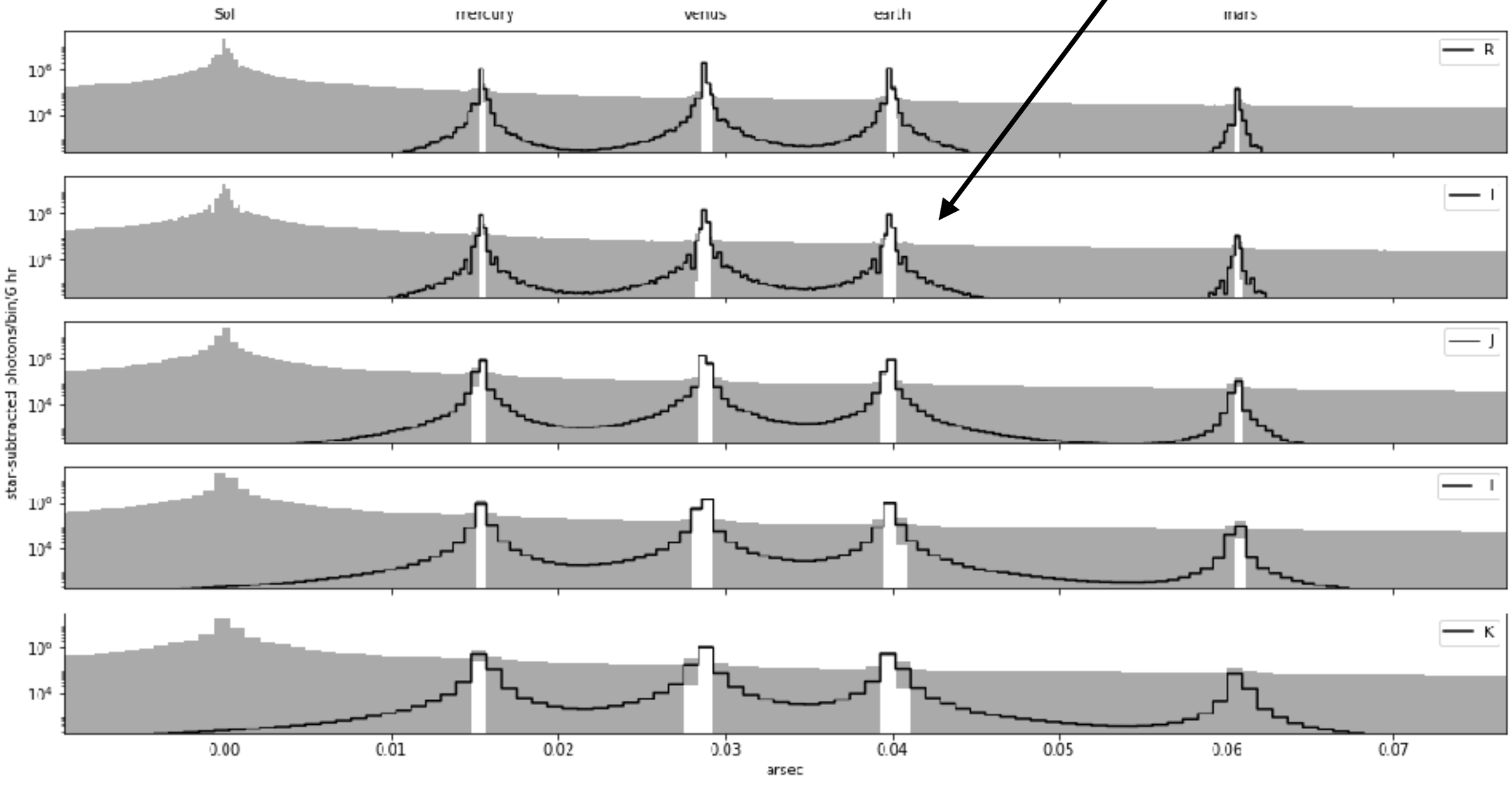
- What do mirrors really cost at this scale?
  - "Standard scaling" = $850M
  - 20 copies of entire HET = $600M
  - Gilmozzi et. al. published OWL cost estimator (virtually the only public domain literature at this detail)
    - Zerodur, shipping, slicing, etc..
    - OWL: $1.2B and kWAET : $150M (!?)

kWAET

300 m x 5 m

the solar system
seen from 25pc
(rectangular aperture!)
(no coronagraph!)
(all albedos = 1.0)

~20 sigma
detection of Earth



Conclusions

- No showstoppers yet; many questions
- My wish list:
  - More people involved
  - Fluid / AO model for hWAET, kWAET
  - Optical design constraints for hWAET
  - Mirror cost model
  - Engineering design of roof
  - Big wish: decadal survey
  - Bigger wish: actually build it

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