Exoplanet detection & characterization with coronagraphic imaging

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Subaru Extreme-AO Coronagraphic System

Subaru AO188 project:
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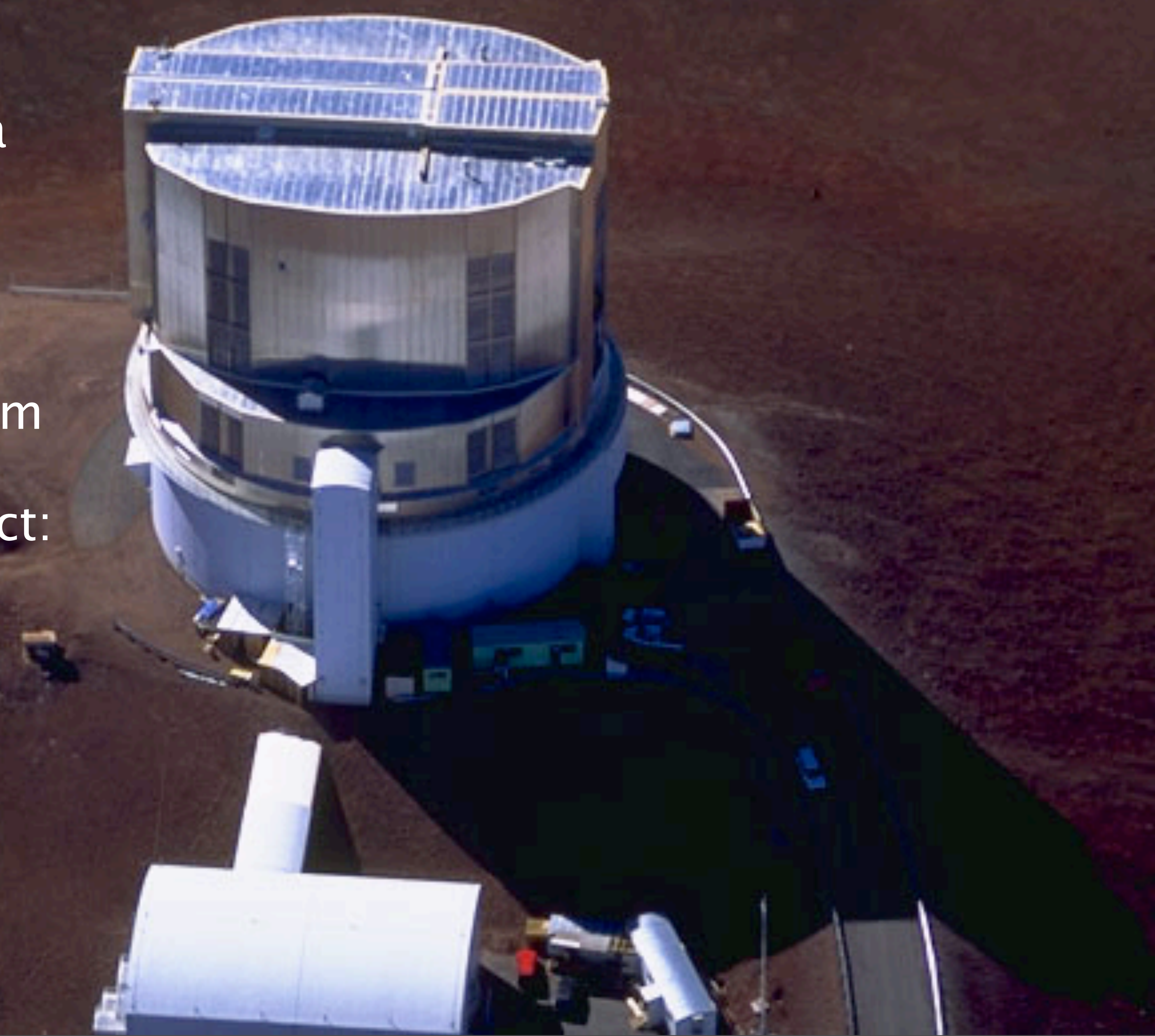
Hideki Takami



Outline

Science goals

- ground: Massive exoplanets -> planetary systems architecture, formation
  - young (self-emitting) / old (reflected light)
- Space: Earth-like planets -> habitability, life ?

Technology

- coronagraphy
- wavefront control

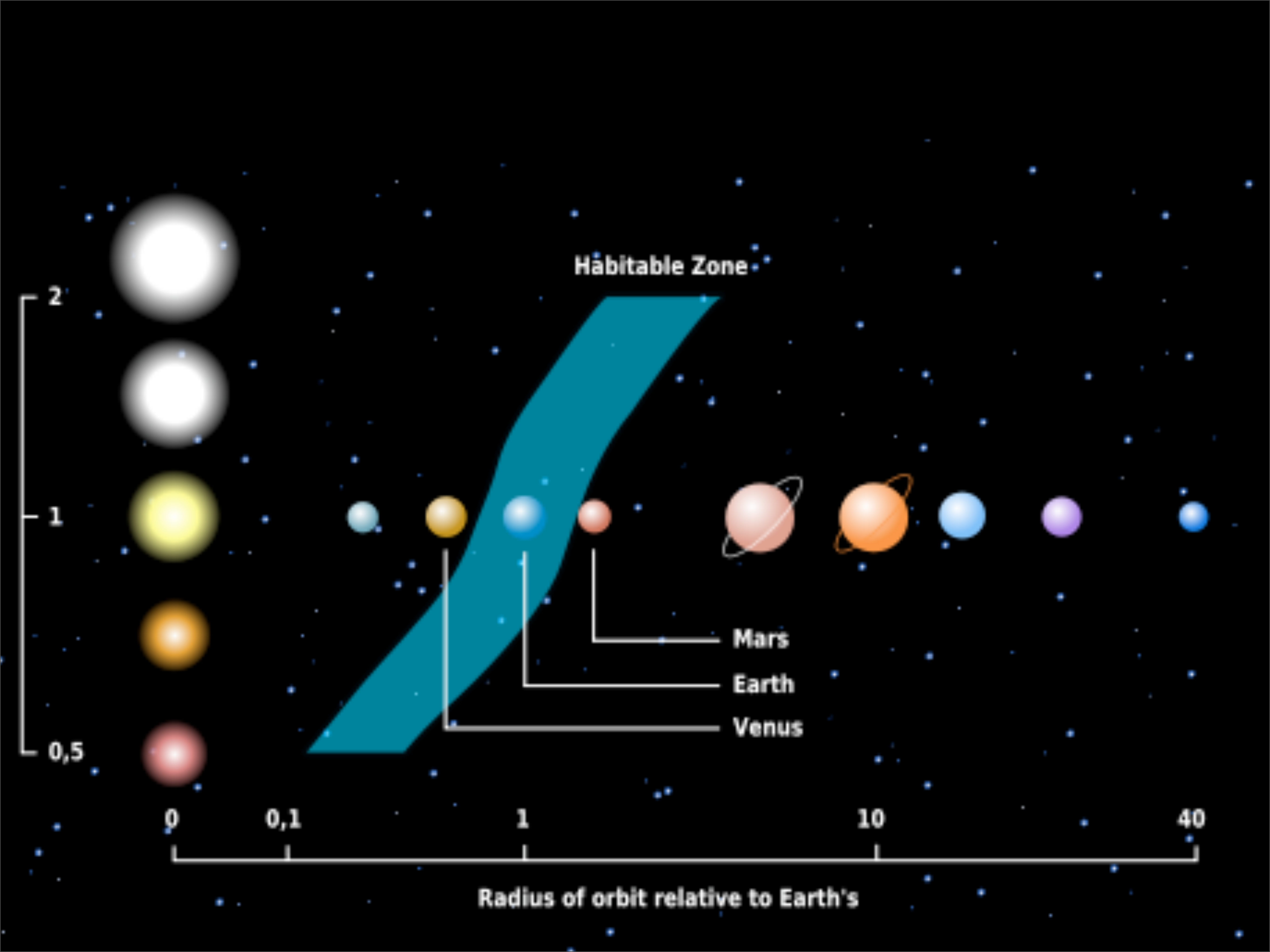
Projects

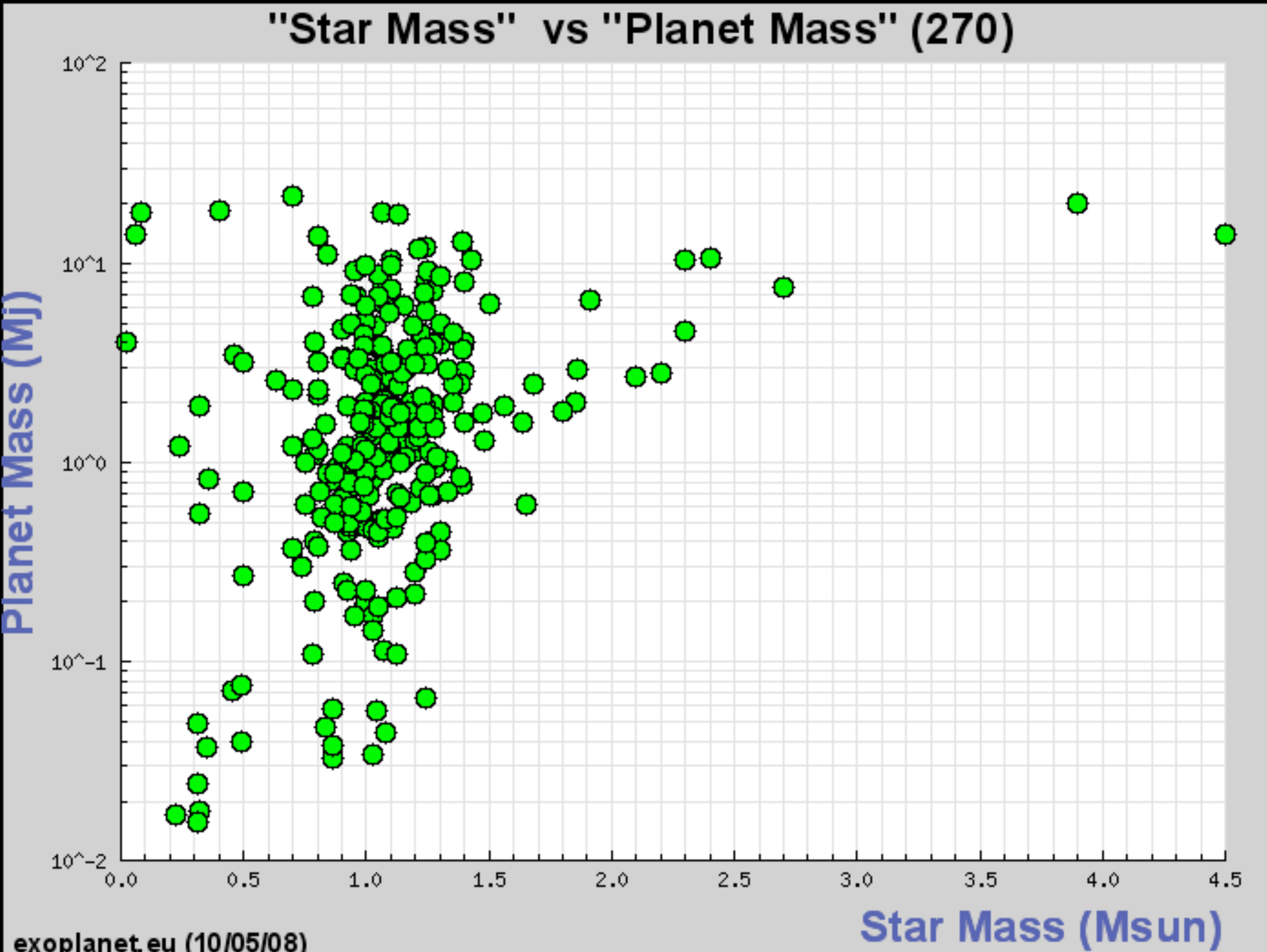
- ground & space

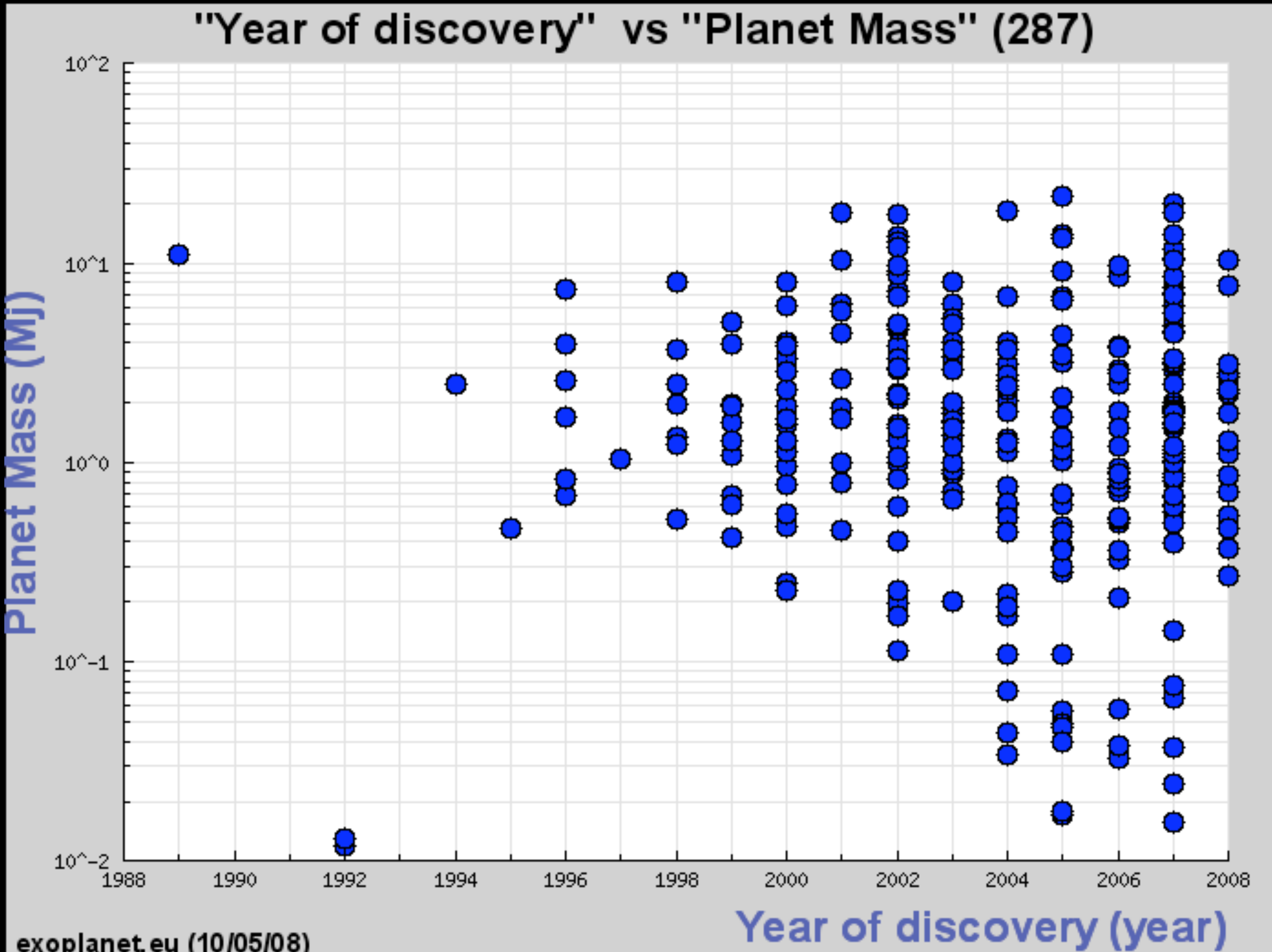
Exoplanets

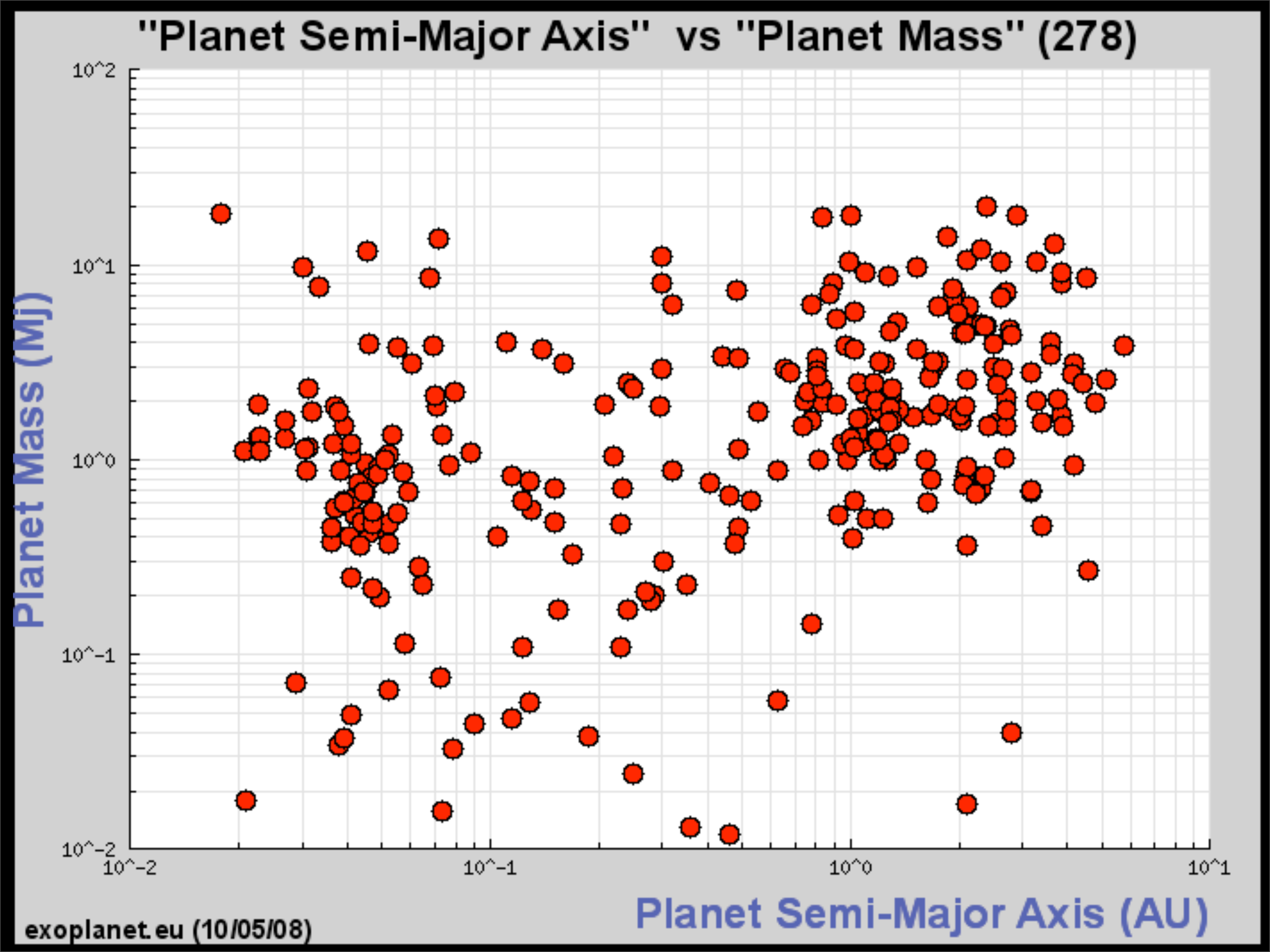
How many planets around other stars ?
How do they form, evolved ?
Mass, size, composition ?
Rocky planets with atmospheres ?

Could have life evolved on other planets ?
Intelligent life somewhere else ?


Habitable Zone
2
1
0,5
Mars
Earth
Venus
0
0,1
1
10
40
Radius of orbit relative to Earth's


"Star Mass" vs "Planet Mass" (270)
Planet Mass (Mj)
10^2
10^1
10^0
10^-1
10^-2
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Star Mass (Msun)
exoplanet.eu (10/05/08)


"Year of discovery" vs "Planet Mass" (287)
10^2
10^1
10^0
10^-1
10^-2
Planet Mass (Mj)
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
Year of discovery (year)
exoplanet.eu (10/05/08)

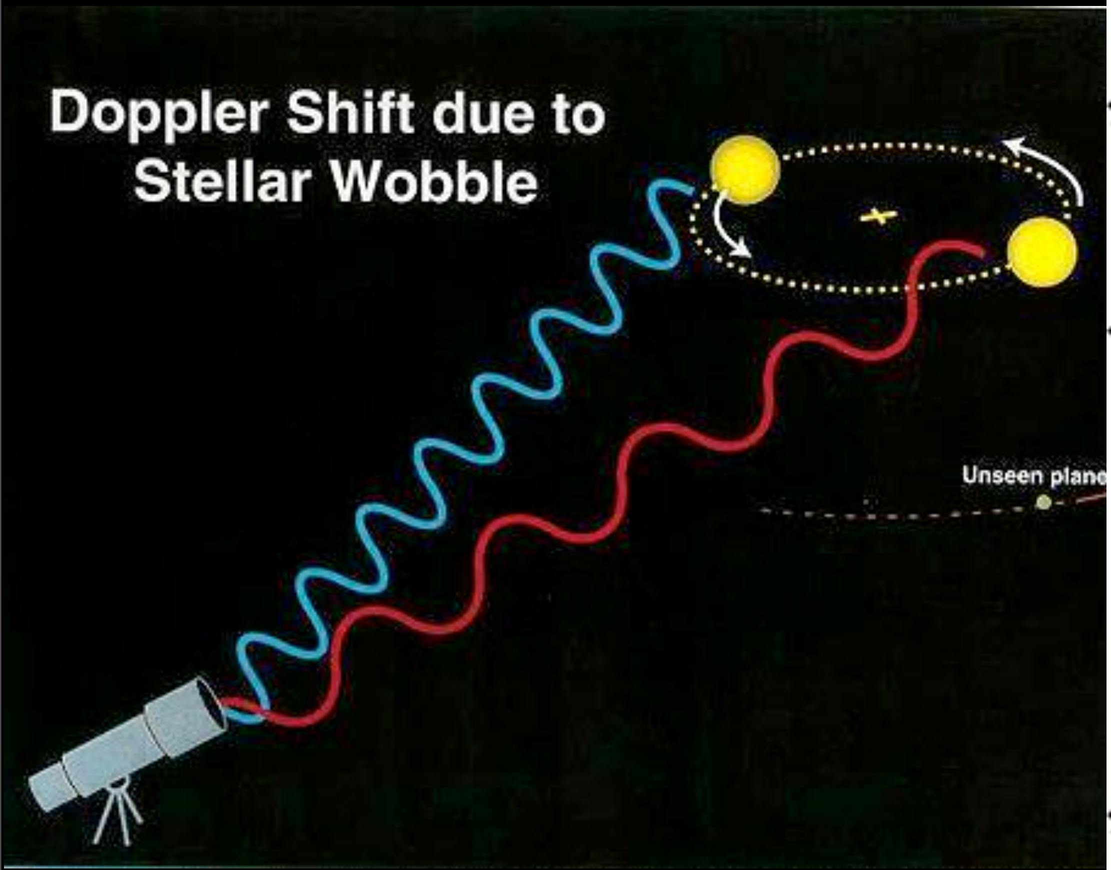

"Planet Semi-Major Axis" vs "Planet Mass" (278)
10^2
10^1
10^0
10^-1
10^-2
Planet Mass (Mj)
10^-2
10^-1
10^0
10^1
Planet Semi-Major Axis (AU)
exoplanet.eu (10/05/08)

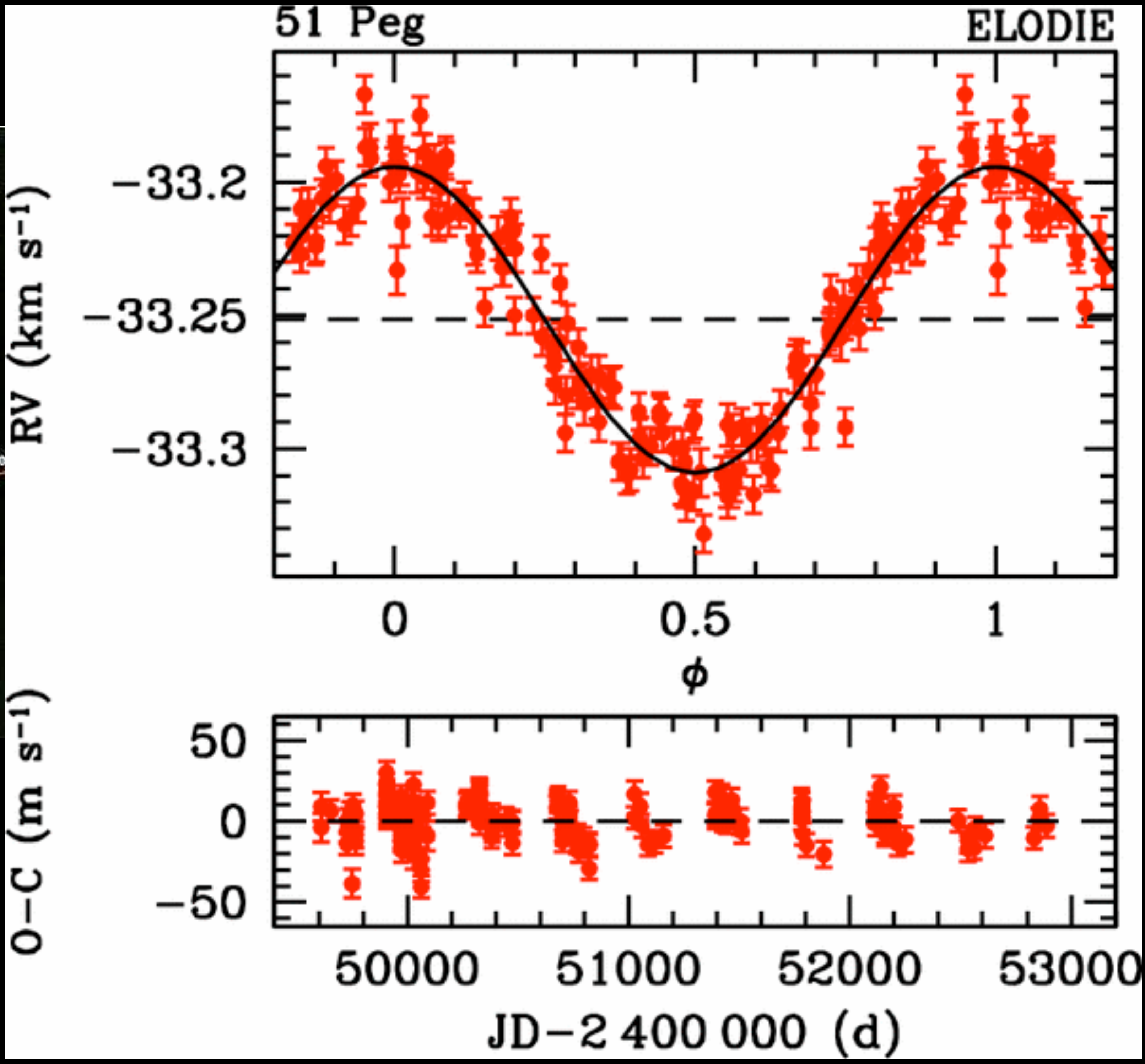
Earth like planets ?

We can't detect them yet, but there is every indication there are many many Earth-like planets:

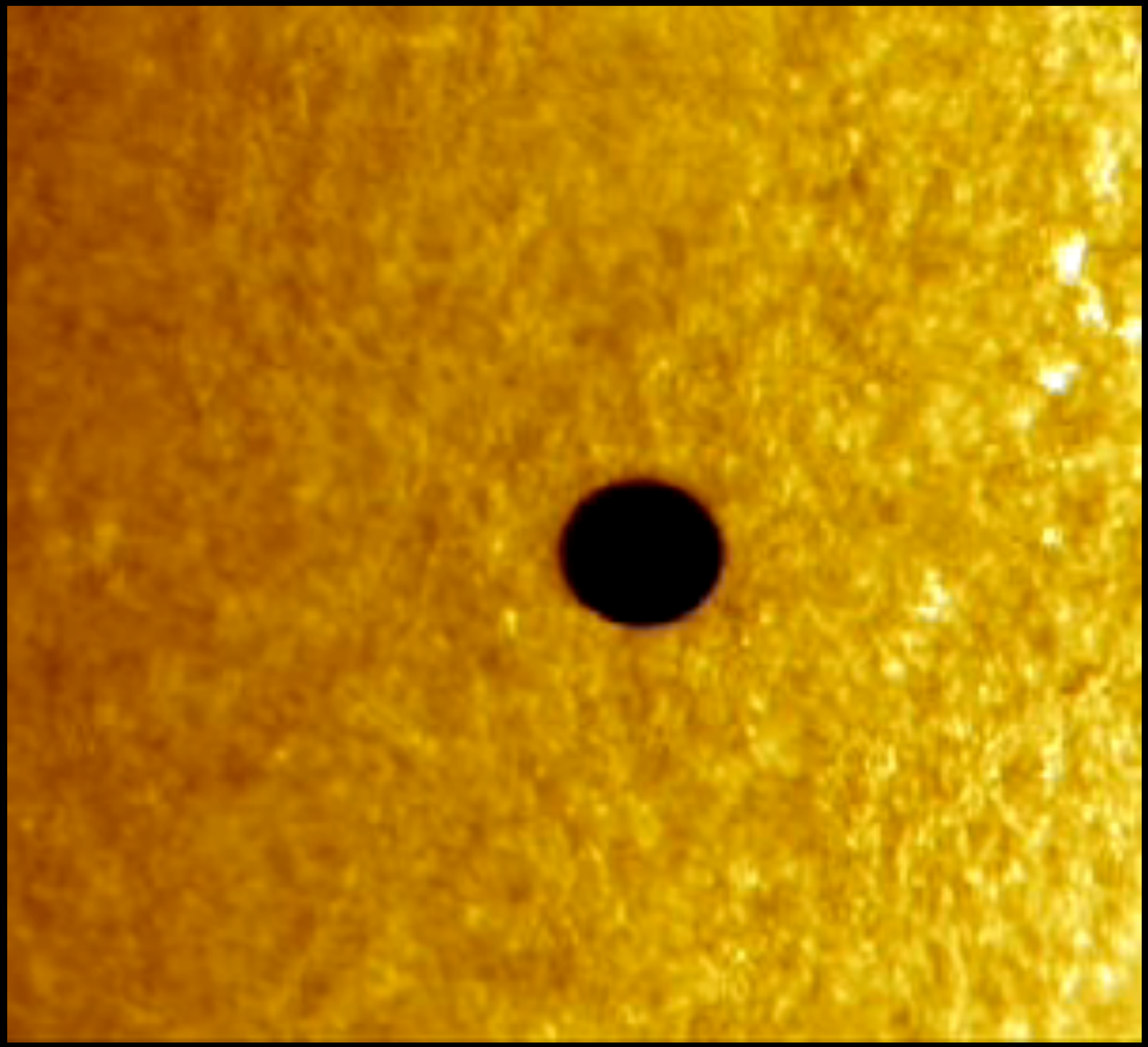
1. Formation models show that several rocky planets form in solar systems through collisions. Small rocks collide to form fewer large rocks .... -> planets
2. It's hard to form large planets and no small one !
3. Our solar system is "dynamically full", confirming the argument (1)

Radial velocity





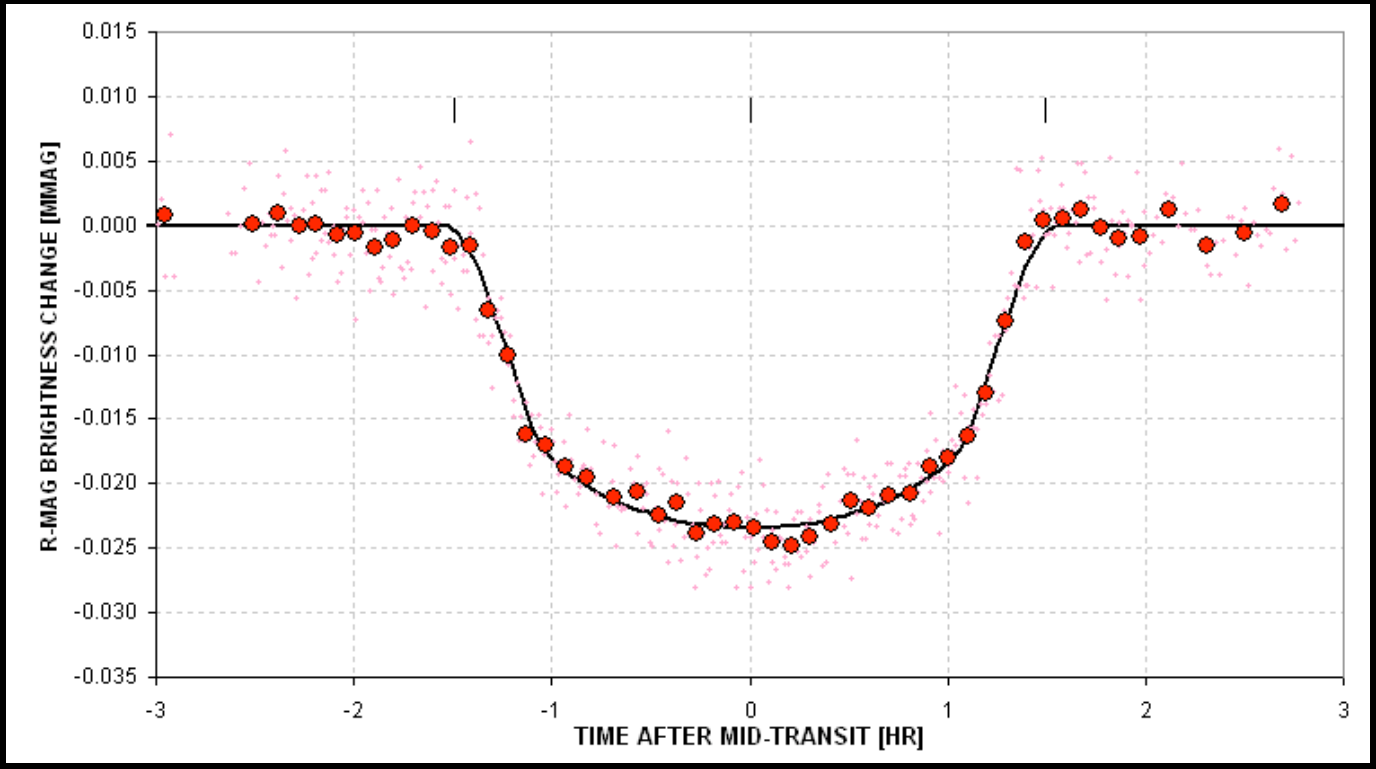
Transits



Planet moves in front of star

-> star gets dimmer

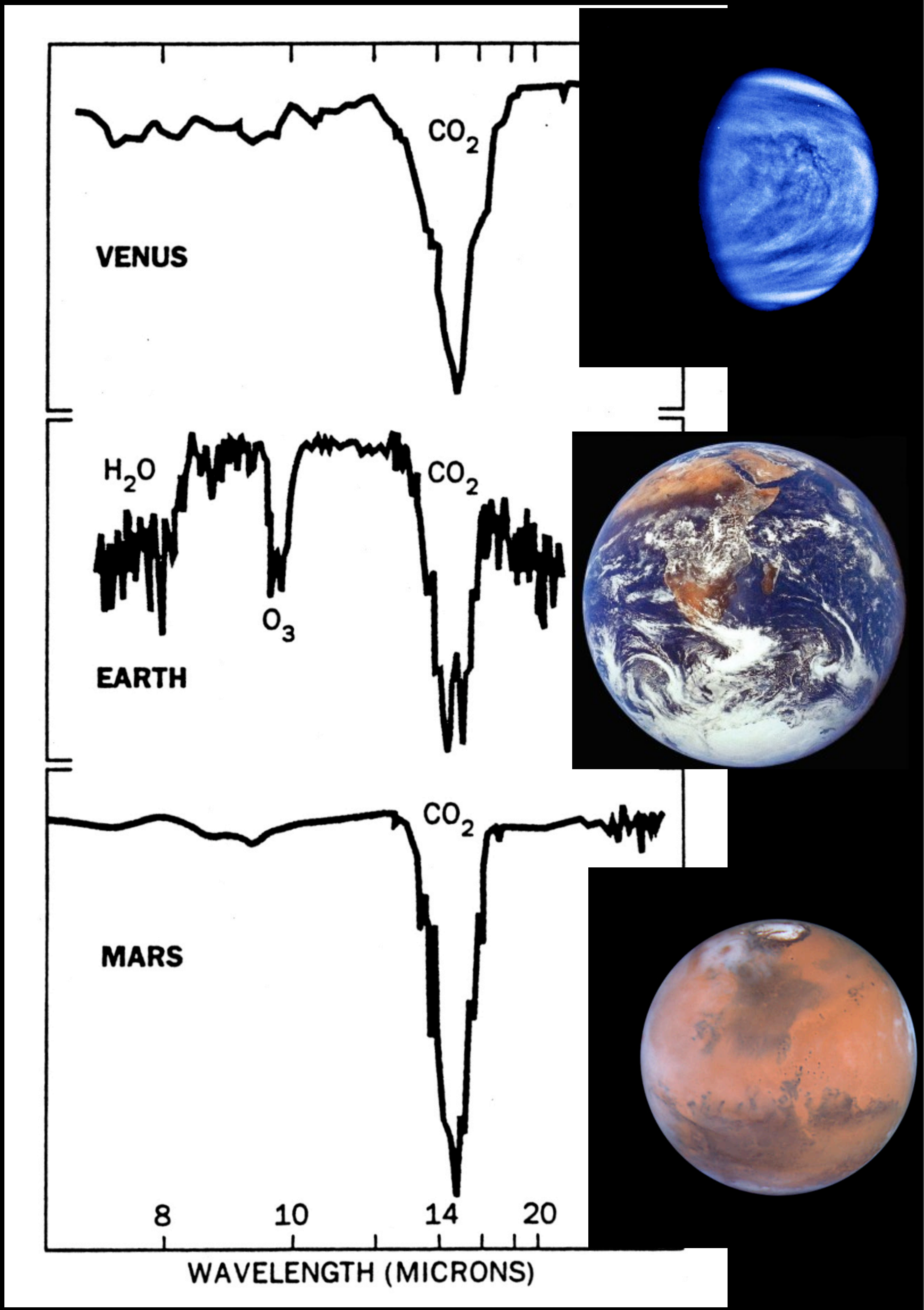
- Planet size
- Planet orbit
- Large atmosphere ?



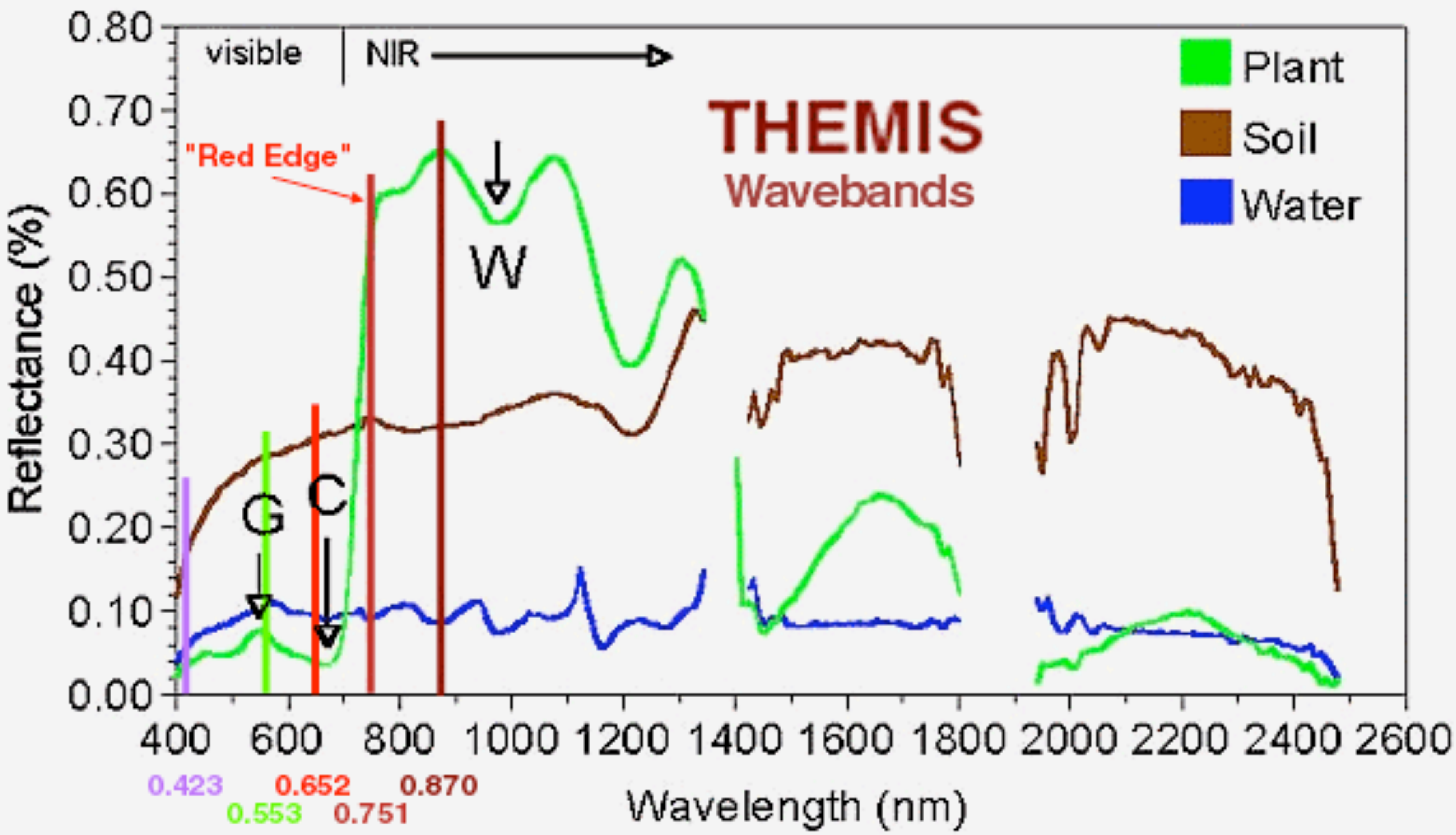
Imaging

- Orbit
- Atmosphere composition
- Continents vs. Oceans ?
- Rotation period
- Weather patterns
- Planetary environment :

  Planets + dust



"Red Edge"



Plant, soil, and water spectra. Letters G, C, and W refers to green peak, chlorophyll absorption, and water absorption features.

Spectral signatures of plants: "Red edge"

Earthshine

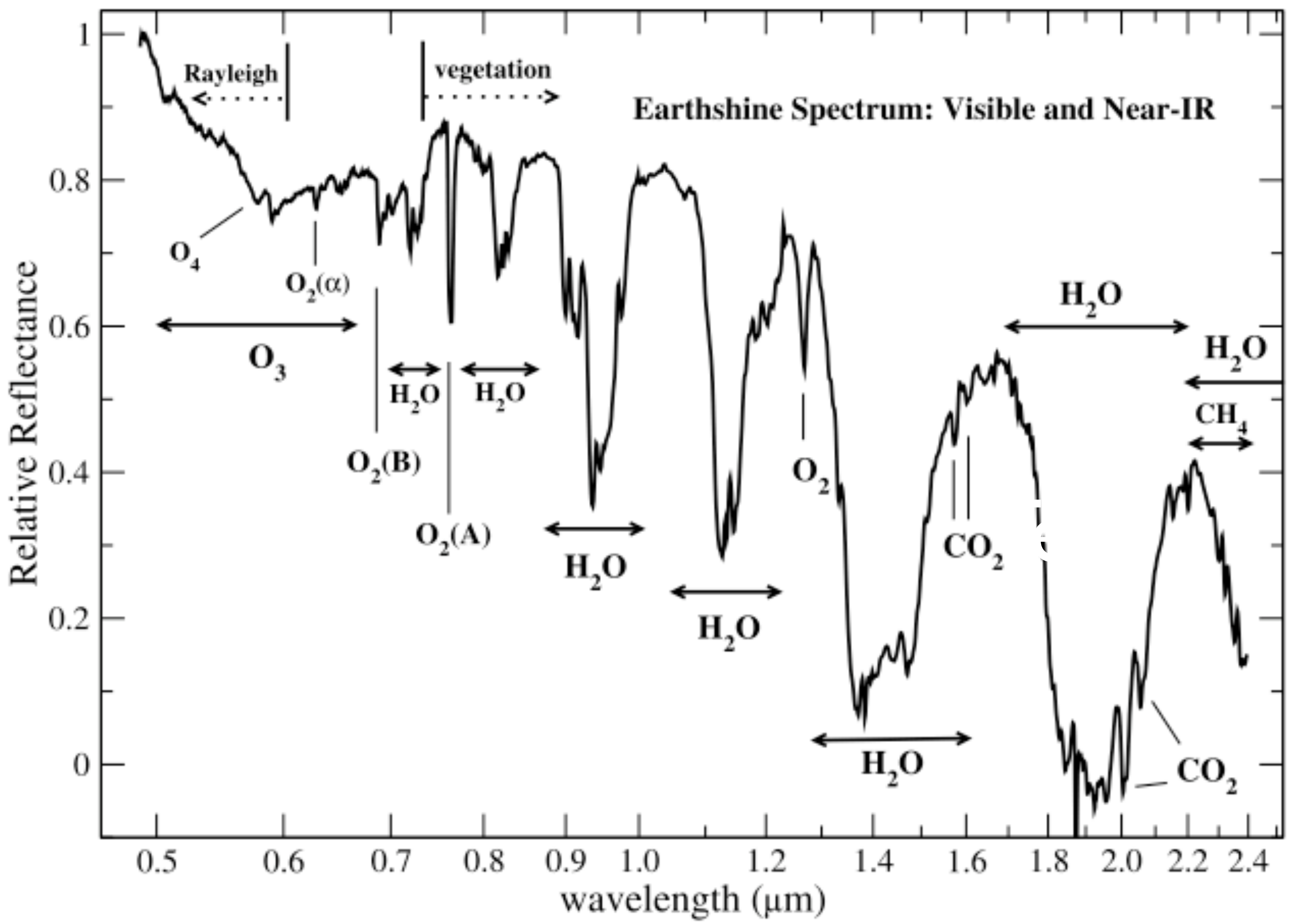
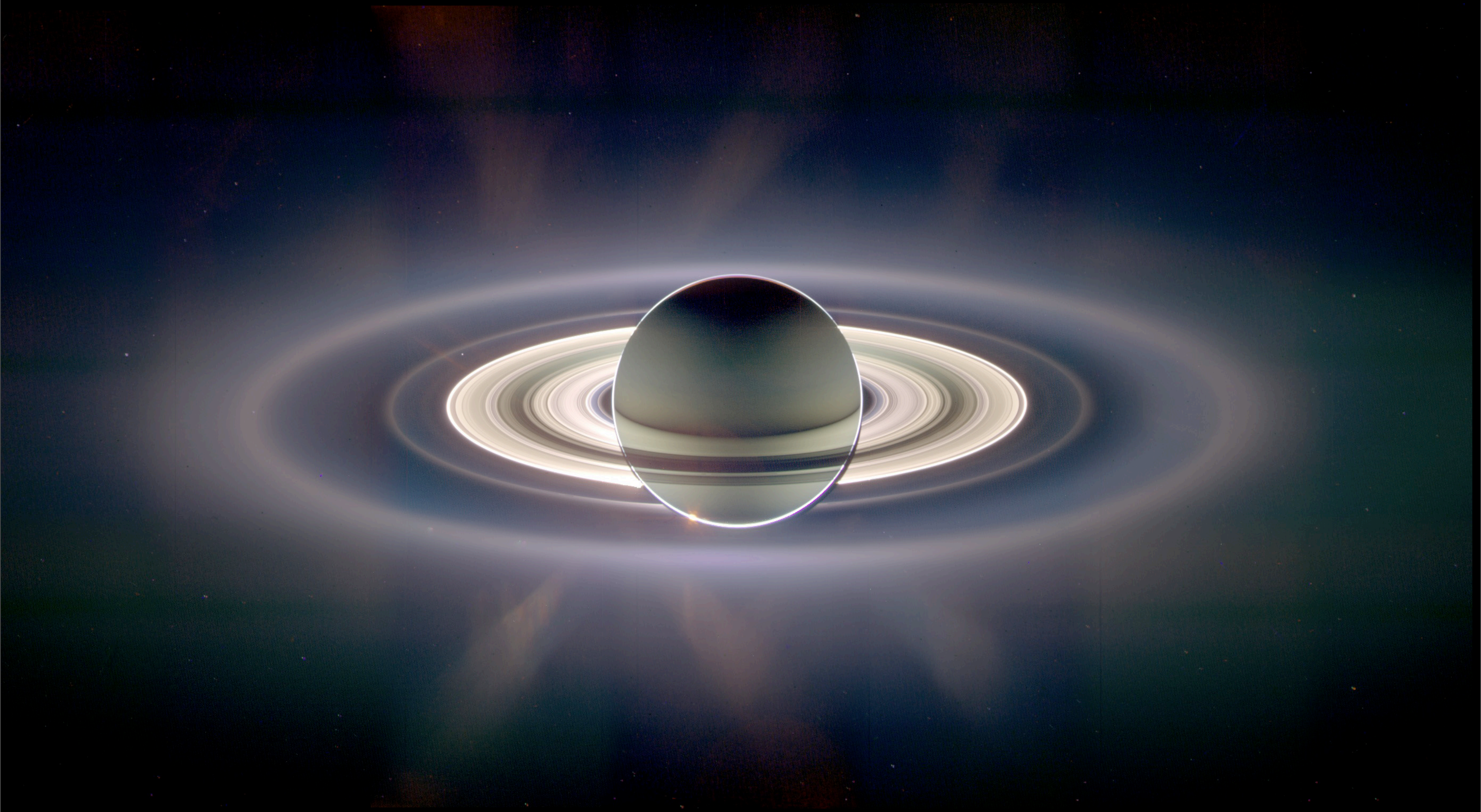


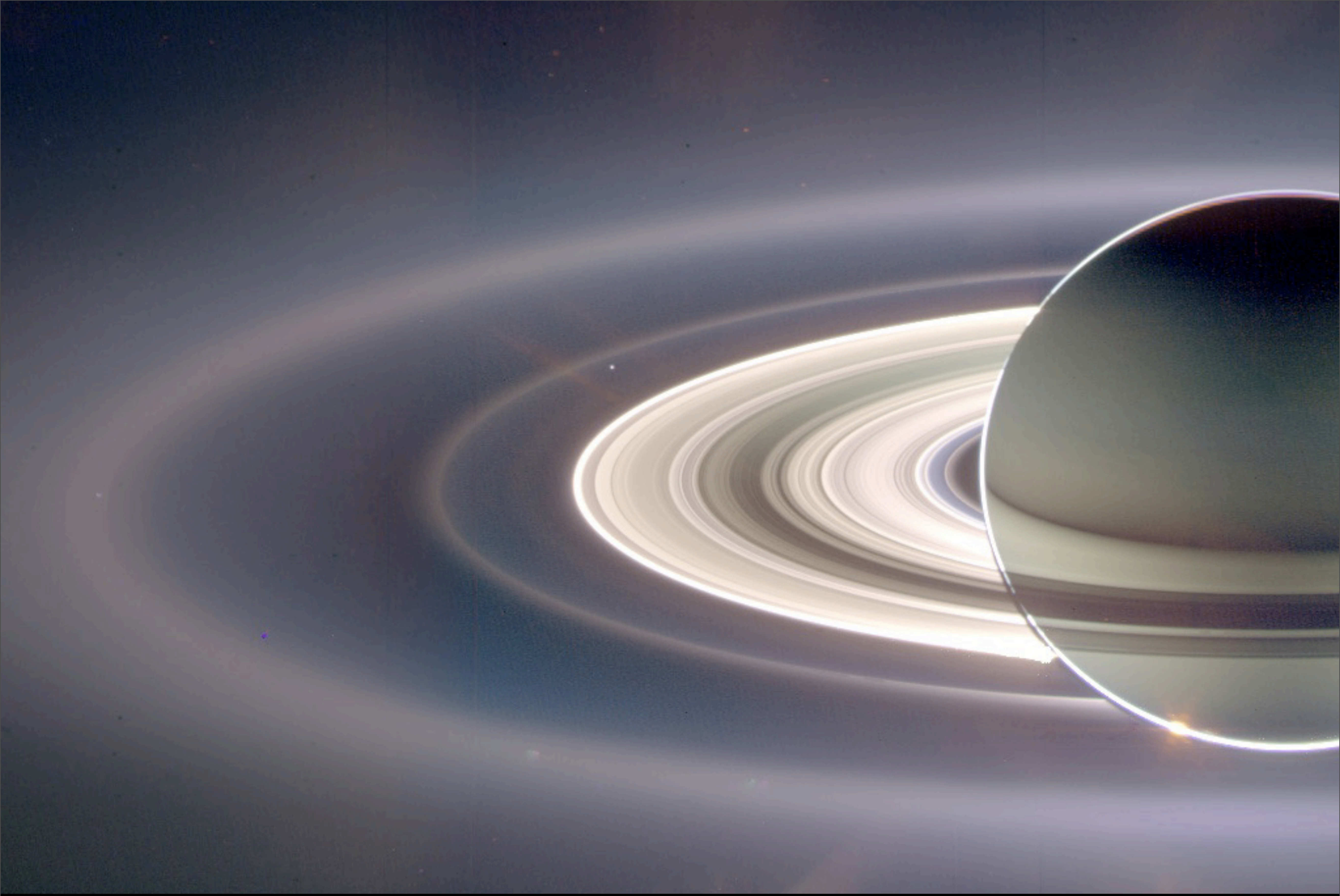
FIG. 7.—Earth's observed reflectance spectrum, at visible and near-infrared wavelengths, created from a composite of the data in this paper (0.8–2.4 μm) and the data presented in Paper I (0.5–0.8 μm). The strongest molecular signatures are indicated, as are the wavelengths where Rayleigh scattering and vegetation reflection are most significant.

Turnbull et al. 2006

Why haven't we imaged Earth-like planets yet ?

- They are very very faint compared to their star (10 billion times), and also very close (0.1" = hair thickness 150 yards away)
- Star is not a point, it's a small disk
- There is a lot of Exozodiacal light around, and probably several planets





Exoplanet science with direct imaging

- Ground based telescopes:

  Near-IR with adaptive optics and coronagraphy

  Image disks around stars and young giant planets (Jupiters with age less than 1 Gyr)

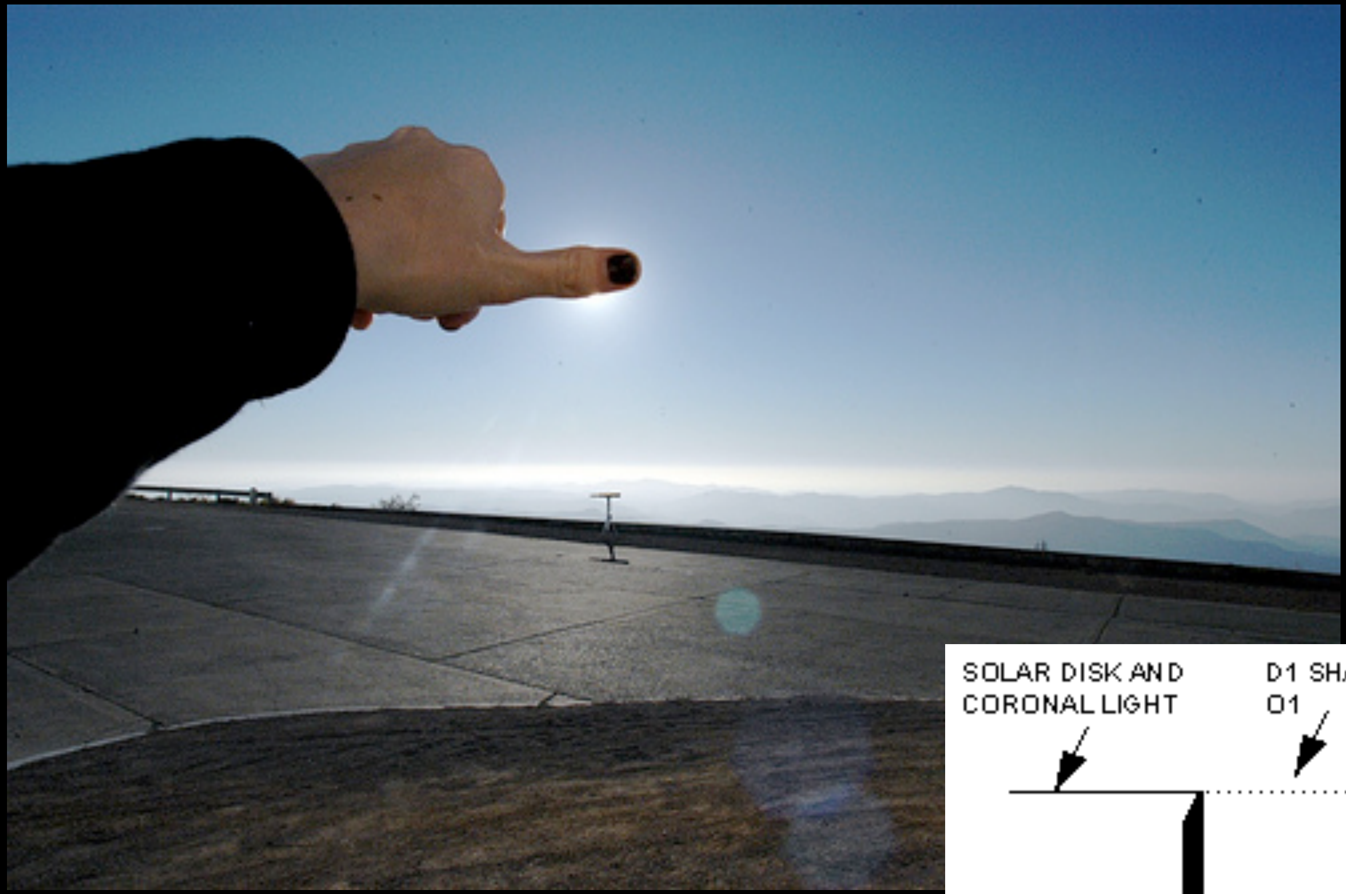
  Prepare and test techniques for future space use

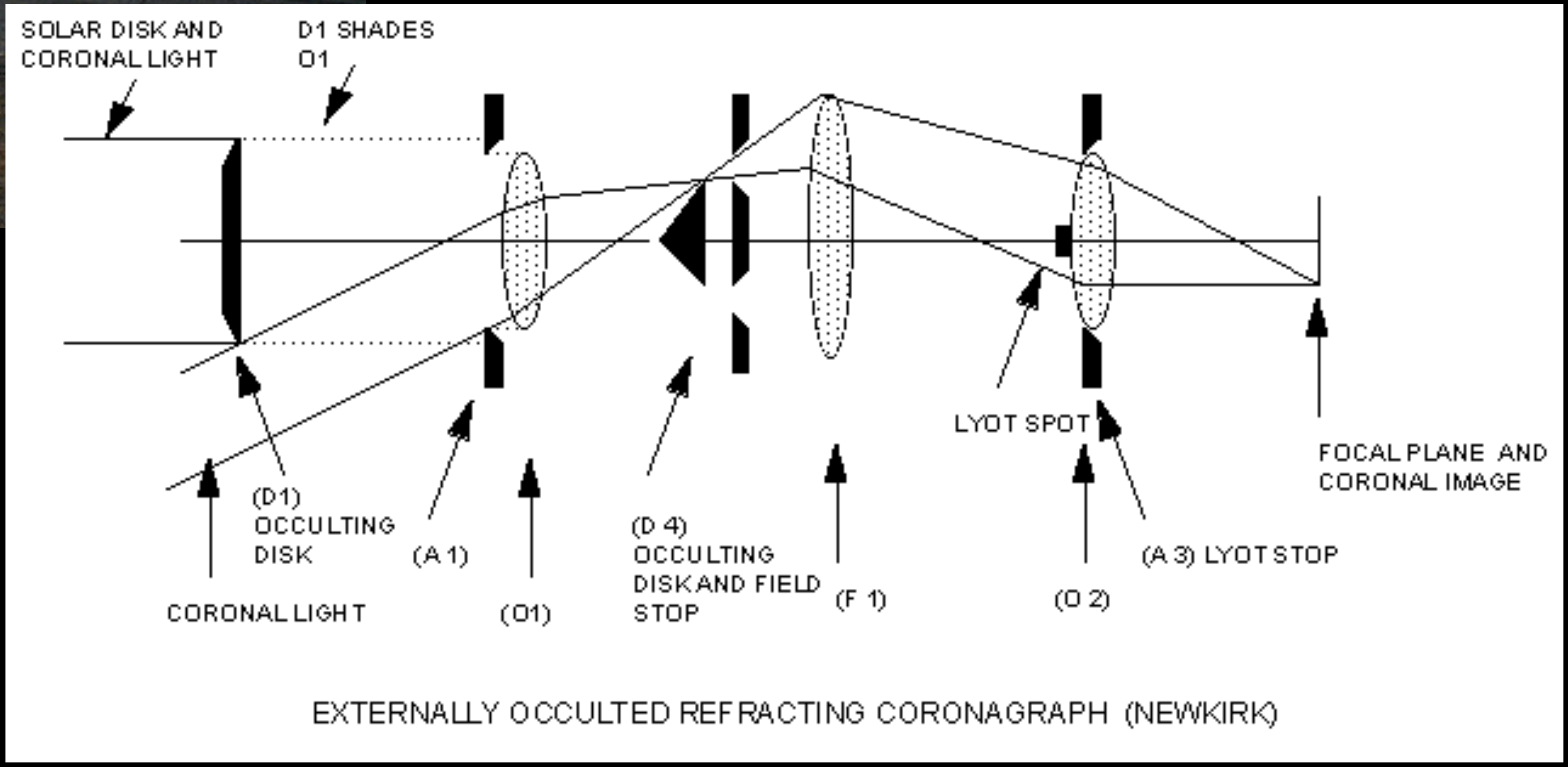
- Space:

  work in visible to image and characterize Earths and "Super-Earths"

Technology

Coronagraphs





Conventional Pupil Apodization (CPA)

Many pupil apodizations have been proposed.

Apodization can be continuous or binary.

\+ Simple, robust, achromatic

\- low efficiency for high contrast

Jacquinot & Roisin-Dossier 1964
Kasdin et al. 2003, ApJ, 582, 1147
Vanderbei et al. 2003, ApJ, 590, 593
Vanderbei et al. 2003, ApJ, 599, 686
Vanderbei et al. 2004, ApJ, 615, 555

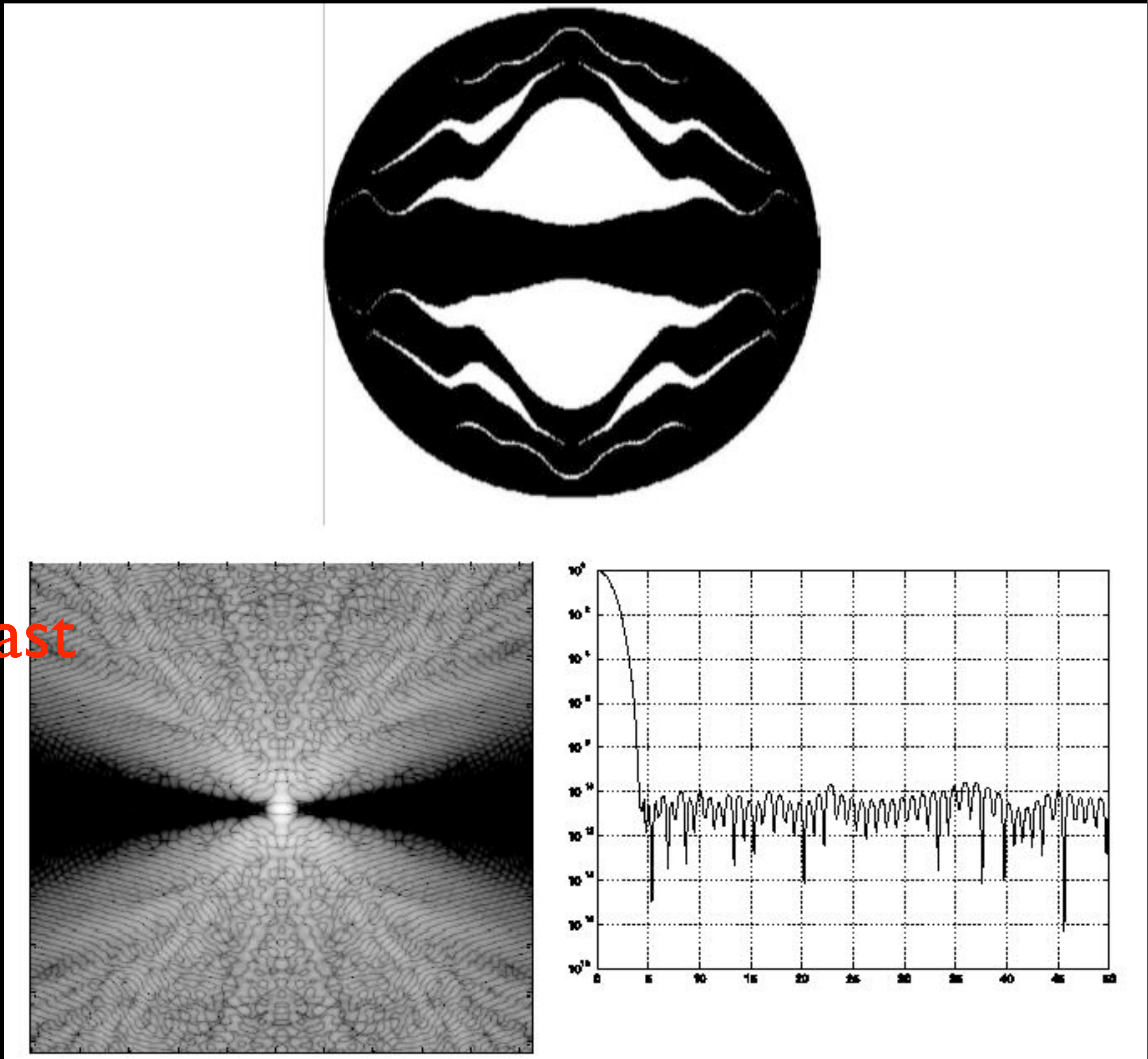


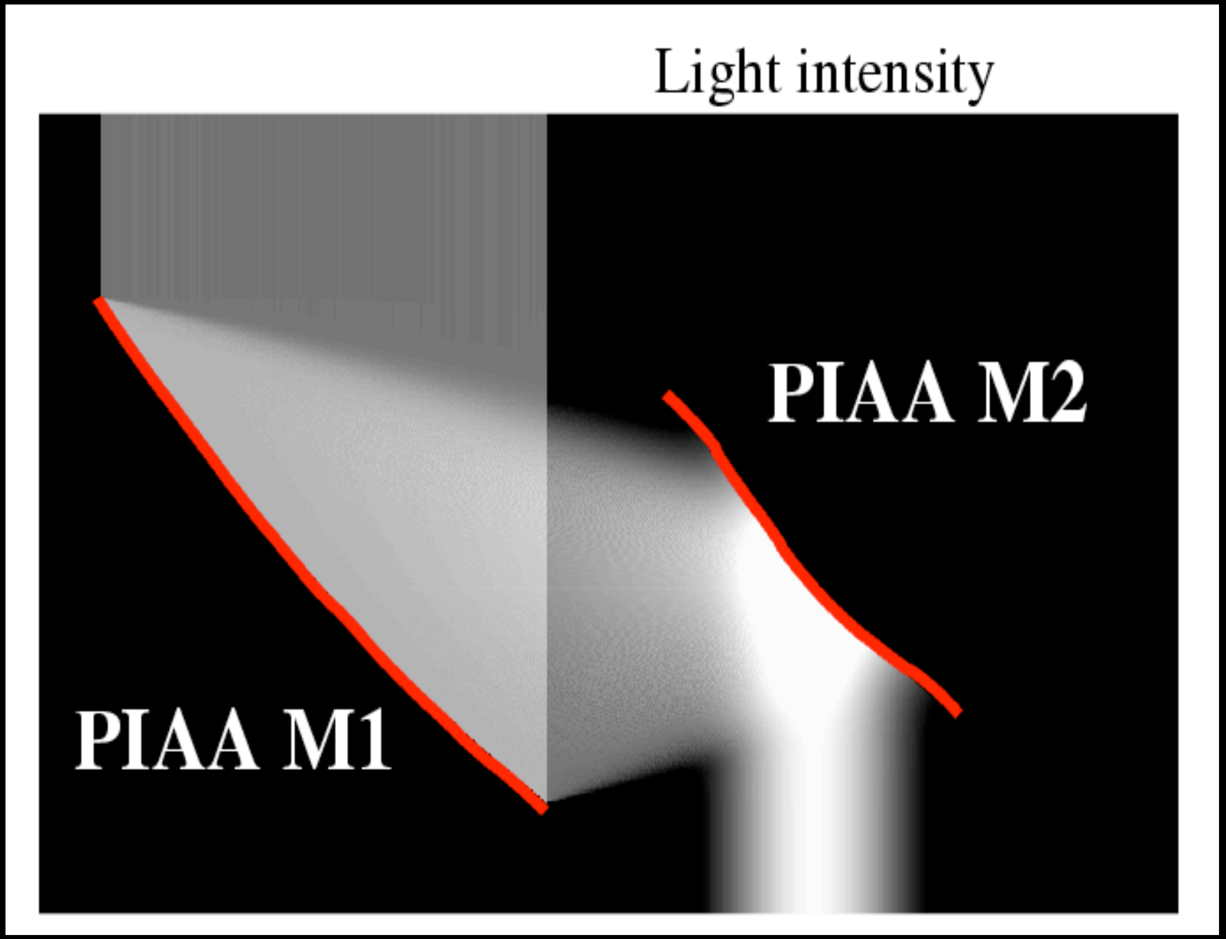
Fig. 9.—*Top*: Asymmetric multiopening mask designed to provide high-contrast, 10^{-10}, from $\lambda/D = 4$ to $\lambda/D = 100$ in two angular sectors centered on the x-axis. Ten integrations are required to cover all angles. Total throughput and pseudoarea are 24.4%. Airy throughput is 11.85%. *Bottom*: Associated PSF. (Note that this mask was originally designed for an elliptical mirror. It has been rescaled to fit a circular aperture.)

PIAA coronagraph development at Subaru

co-funded by JPL and Subaru/NAOJ

Utilizes lossless beam apodization with aspheric optics (mirrors or lenses) to concentrate starlight is single diffraction peak (no Airy rings).

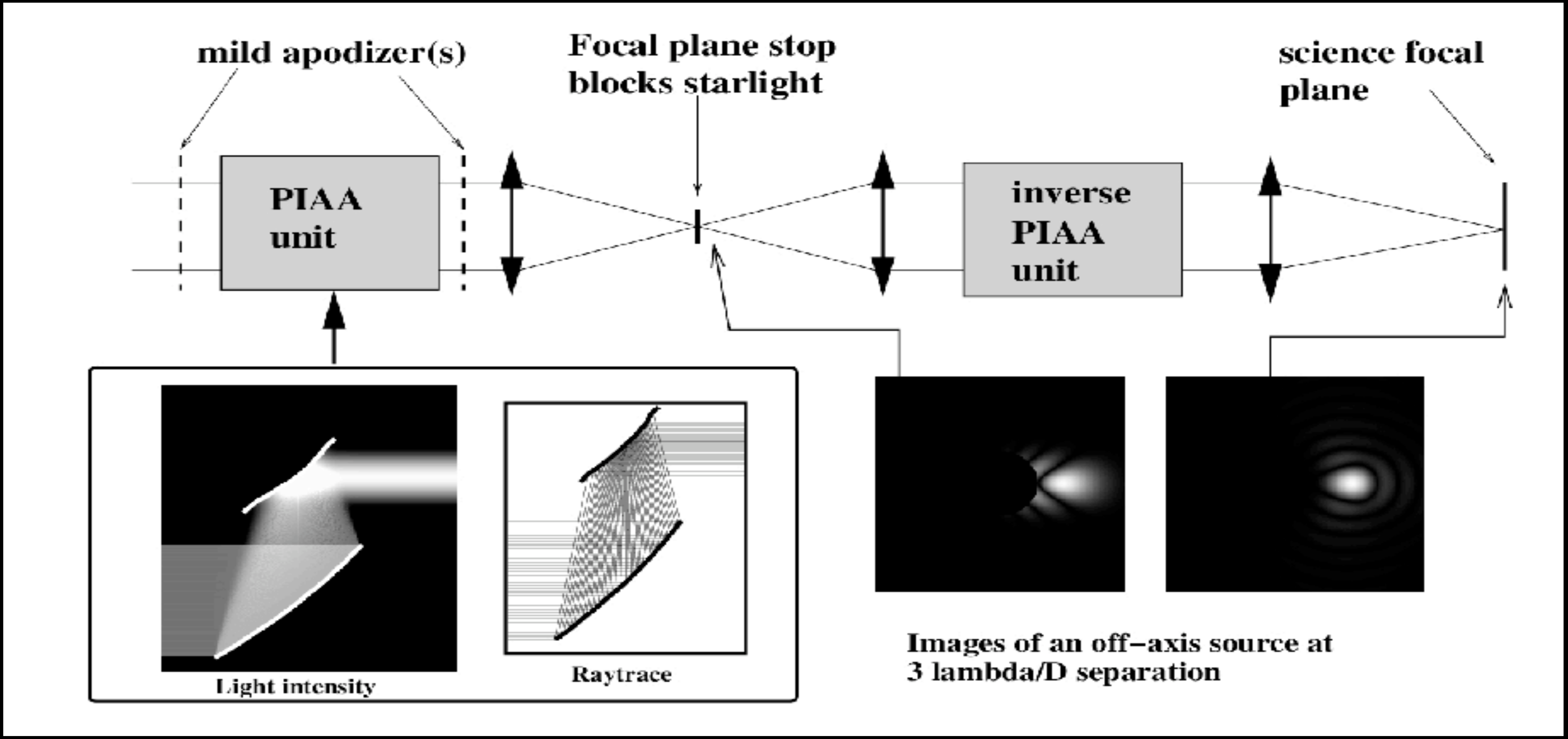
- high contrast
- Nearly 100% throughput
- IWA ~1.5 l/d
- 100% search area
- no loss in angular resol.
- can remove central obsc. and spiders
- achromatic (with mirrors)



For Subaru, Lyot Coronagraph with PIAA- apodized input pupil. IWA ~ 1 lambda/d

Phase-Induced Amplitude Apodization Coronagraph (PIAAC)

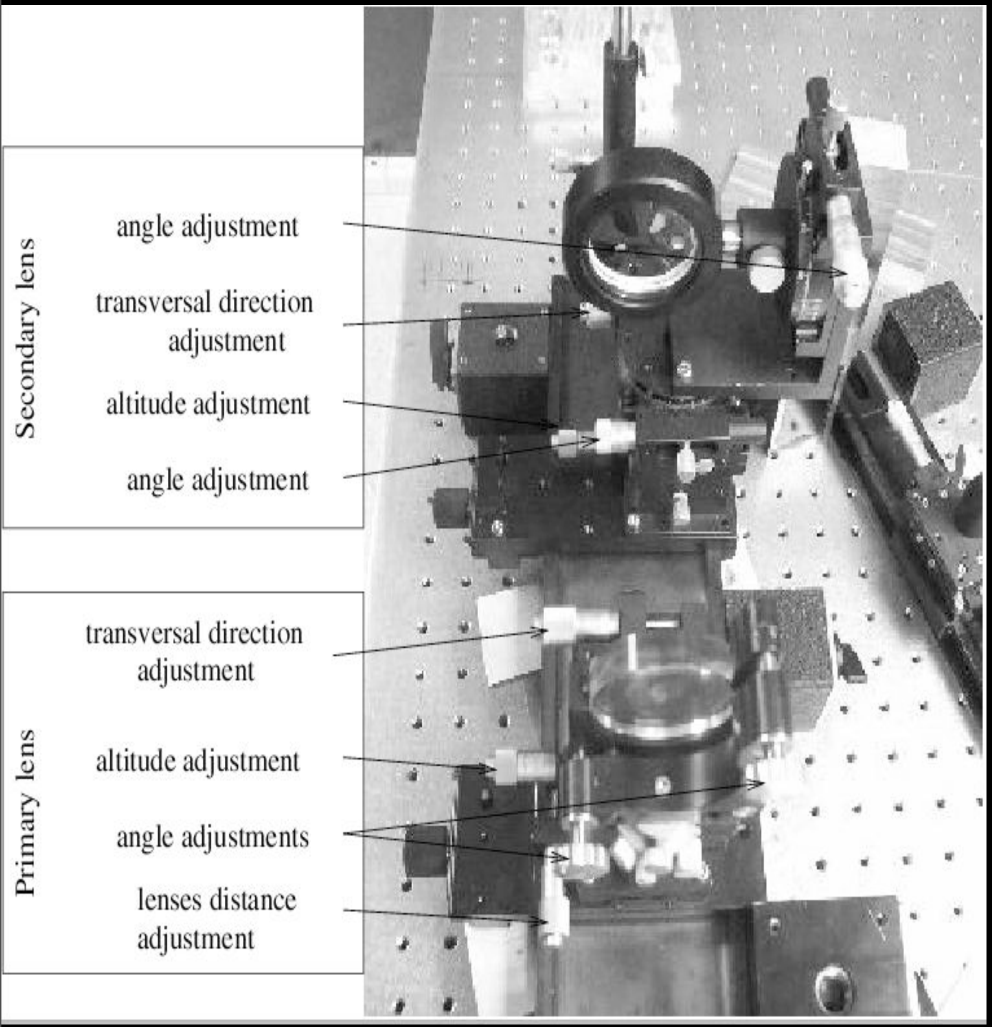
Lossless apodization by aspheric optics.

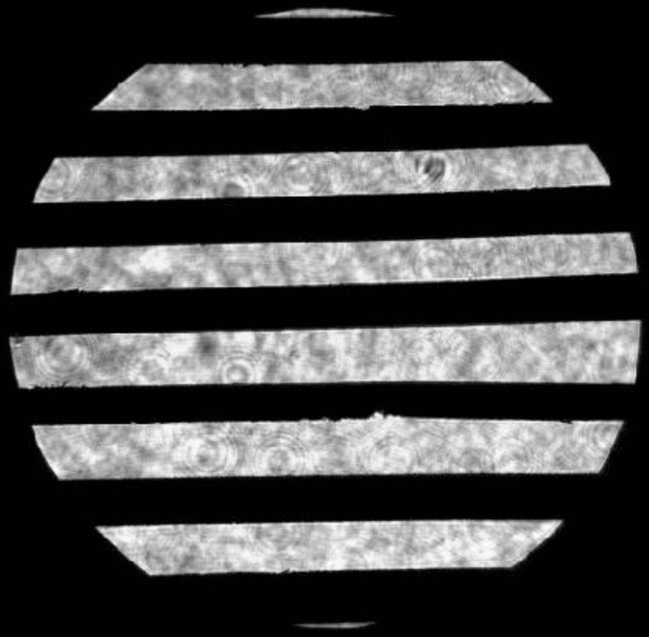


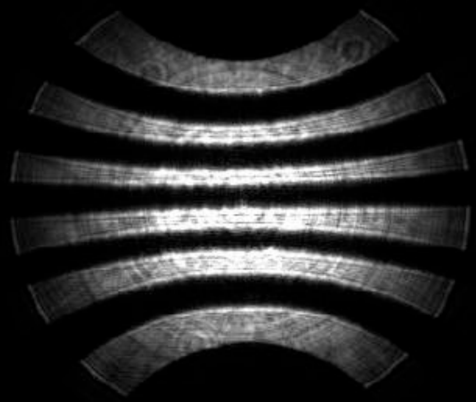
Guyon, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-2006

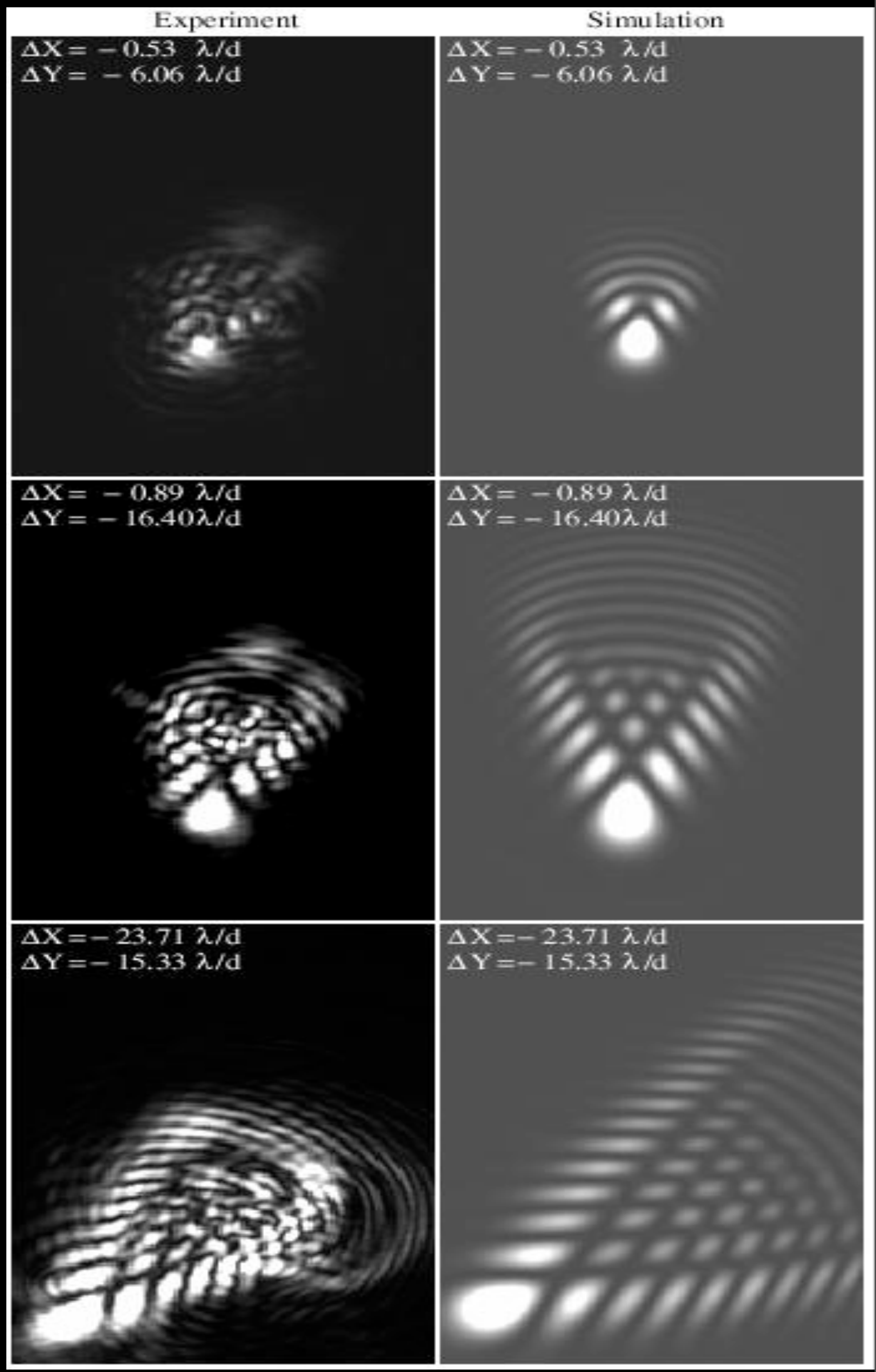
Early demonstration in lab

Lenses made by Masashi Otsubo (ATC, NAOJ)









(Galicher et al. 2005)

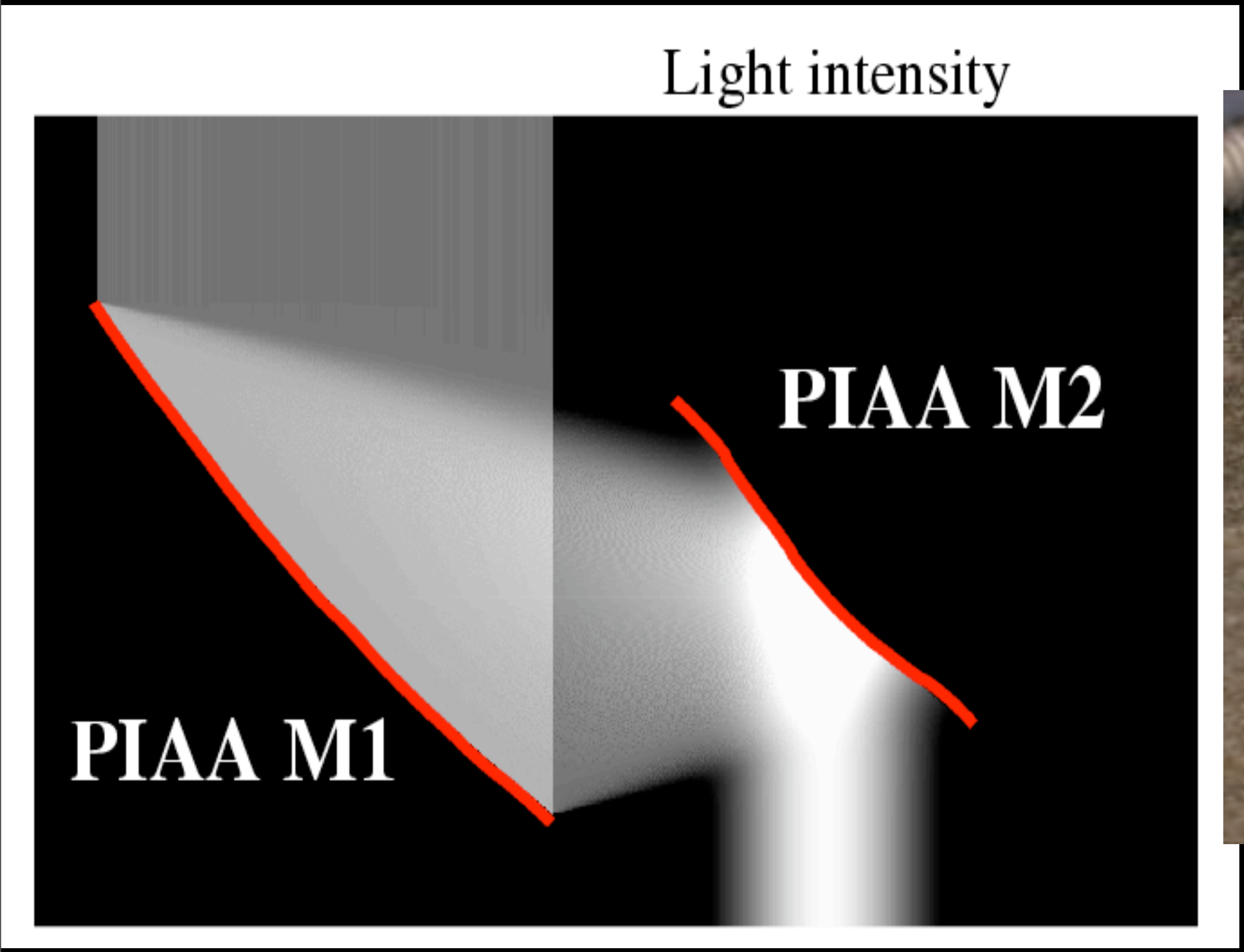
PIAA Coronagraph Technology Development

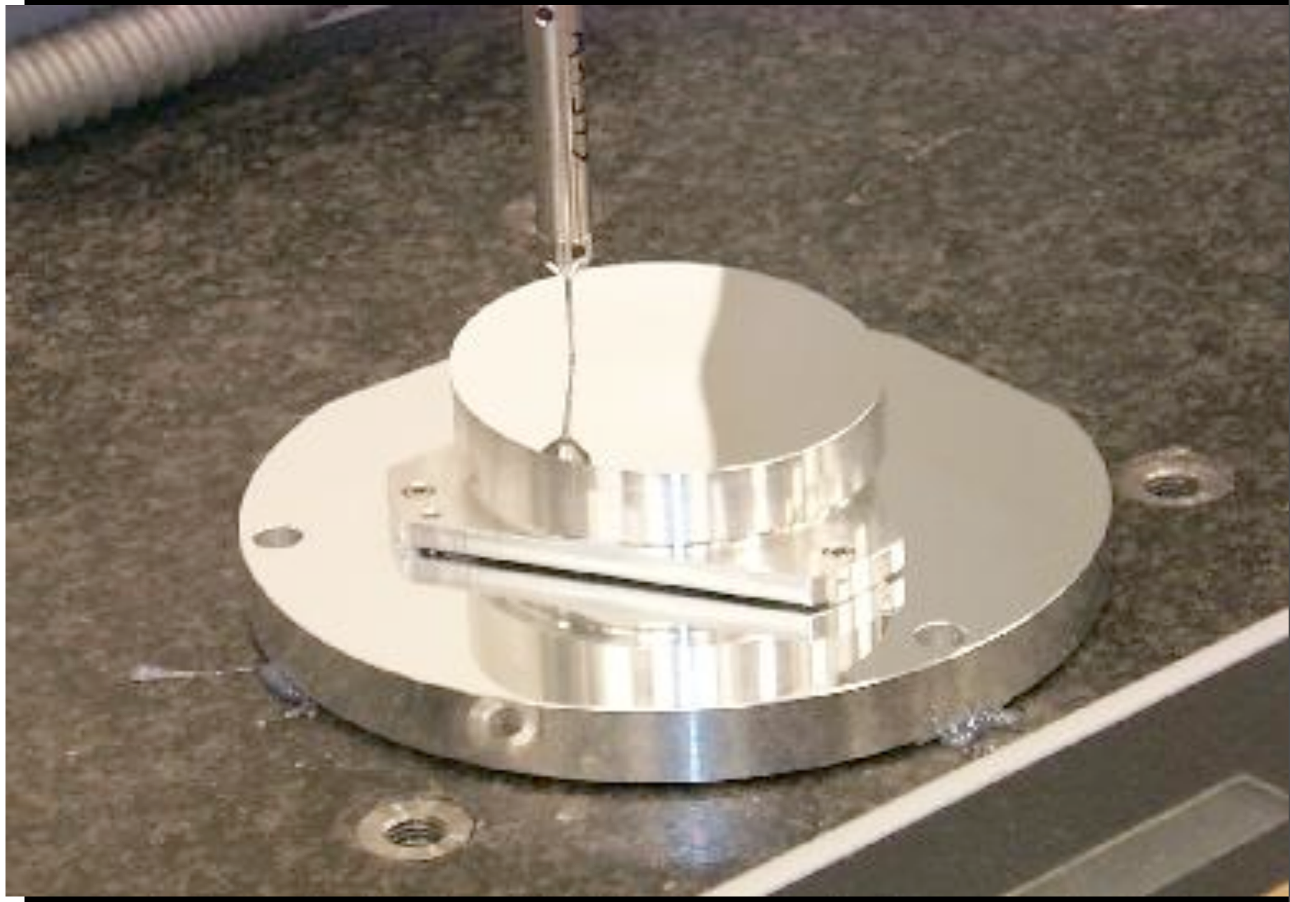
Testbed @ Subaru Telescope
Ground-based coronagraphic ExAO project
2nd generation PIAA design & manufacturing
Space projects studies: TOPS -> PECO, EXCEDE, TPF-C, SPICA

Main funding sources

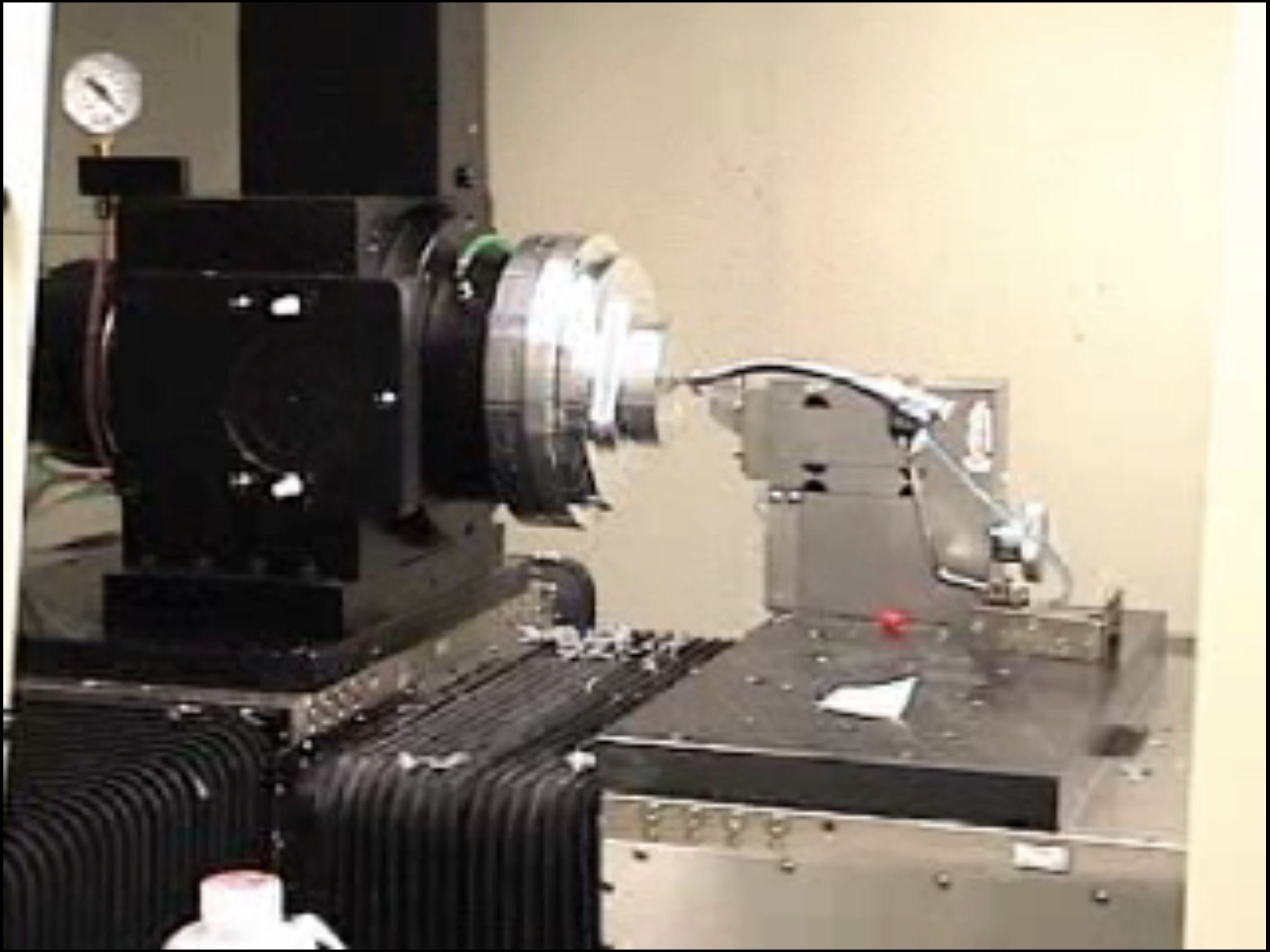
Ground-based	Space
	NASA JPL Navigator program
Subaru Telescope/NAOJ	Subaru Telescope/NAOJ
MEXT (Japan)	
	NASA Ames TOPS partnership

Lossless apodization by aspheric optics.

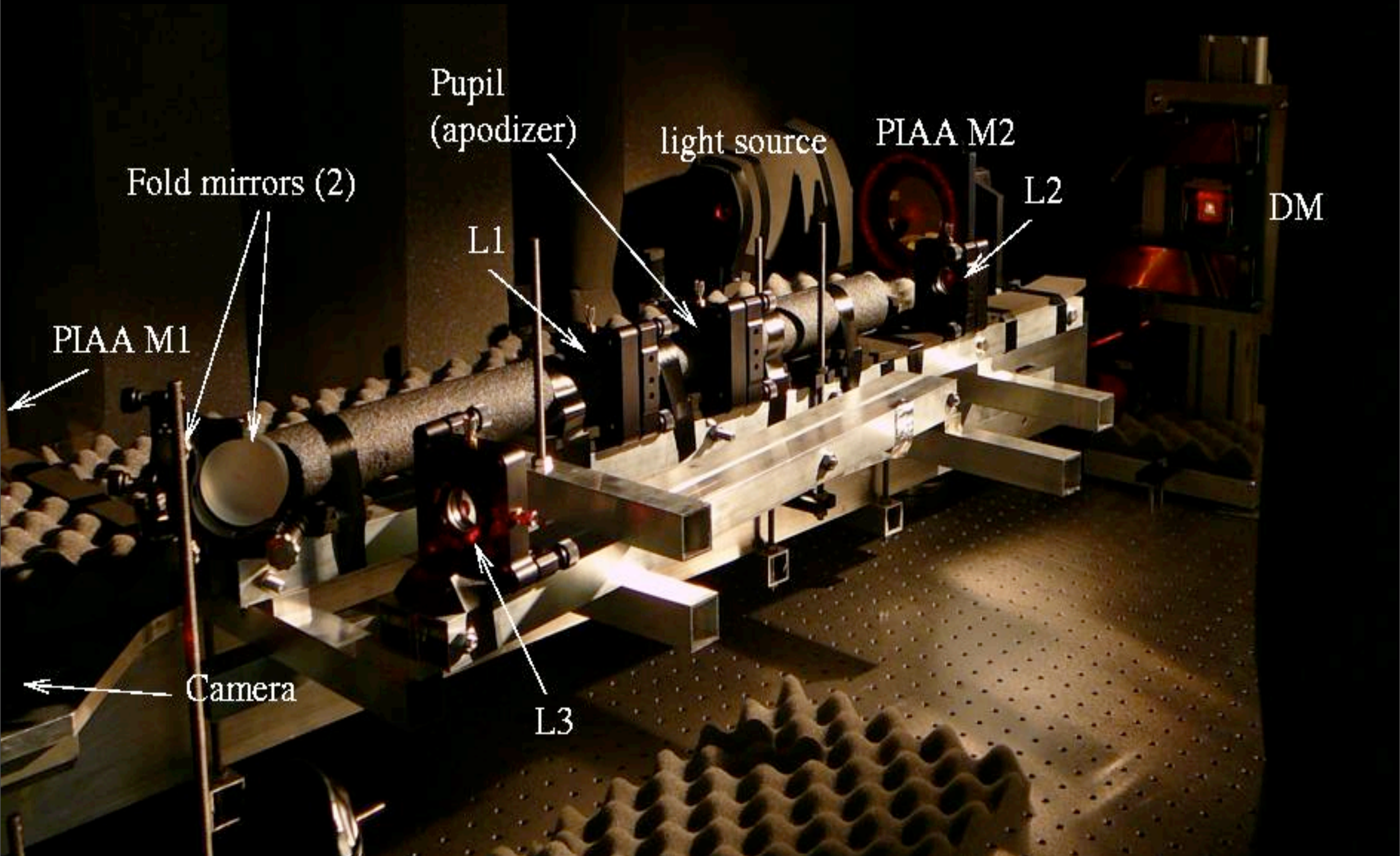


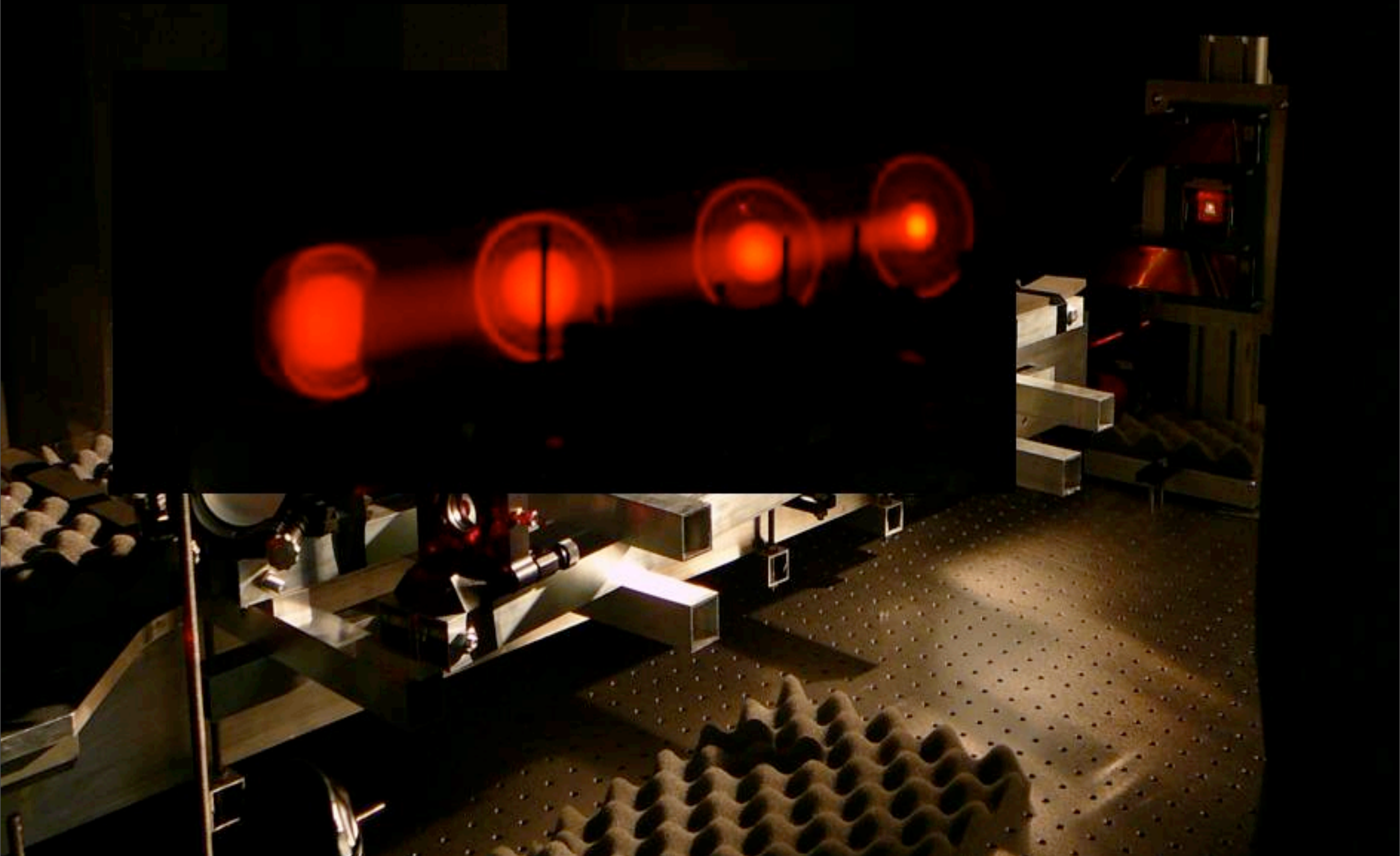


Guyon, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-2006



Subaru lab experiment
co-funded by Subaru/NAOJ & JPL





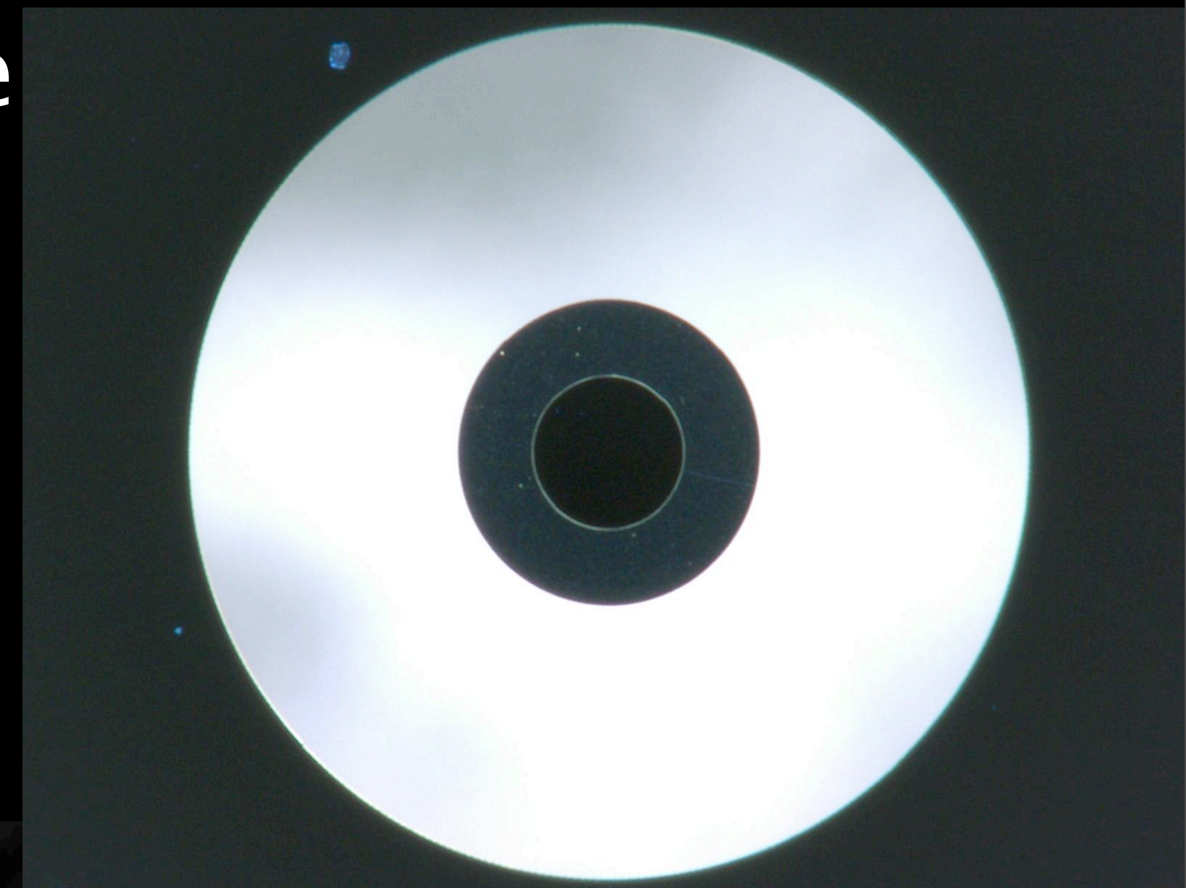
Hybrid PIAA/conventional apodization is best

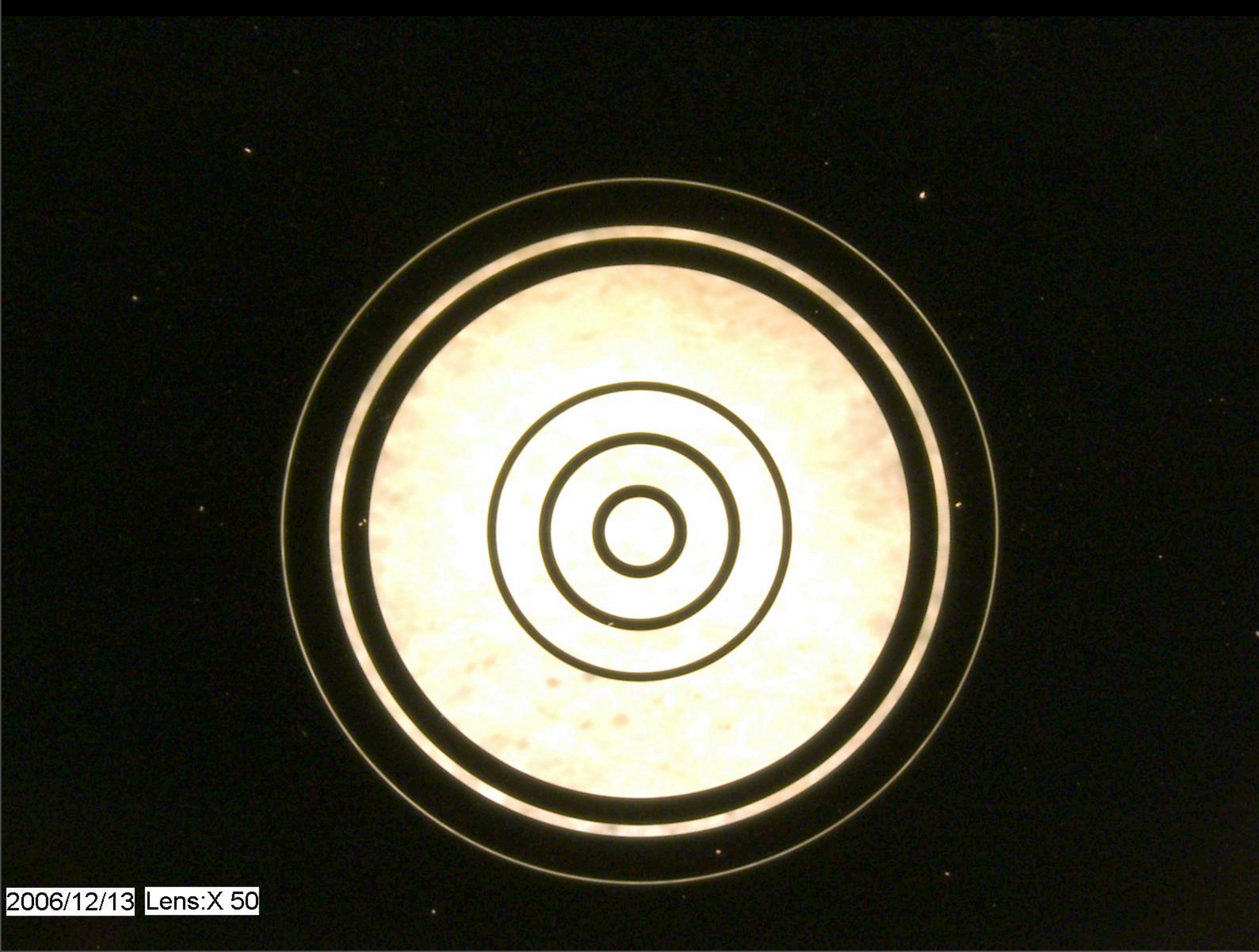
-> Optics easier to manufacture

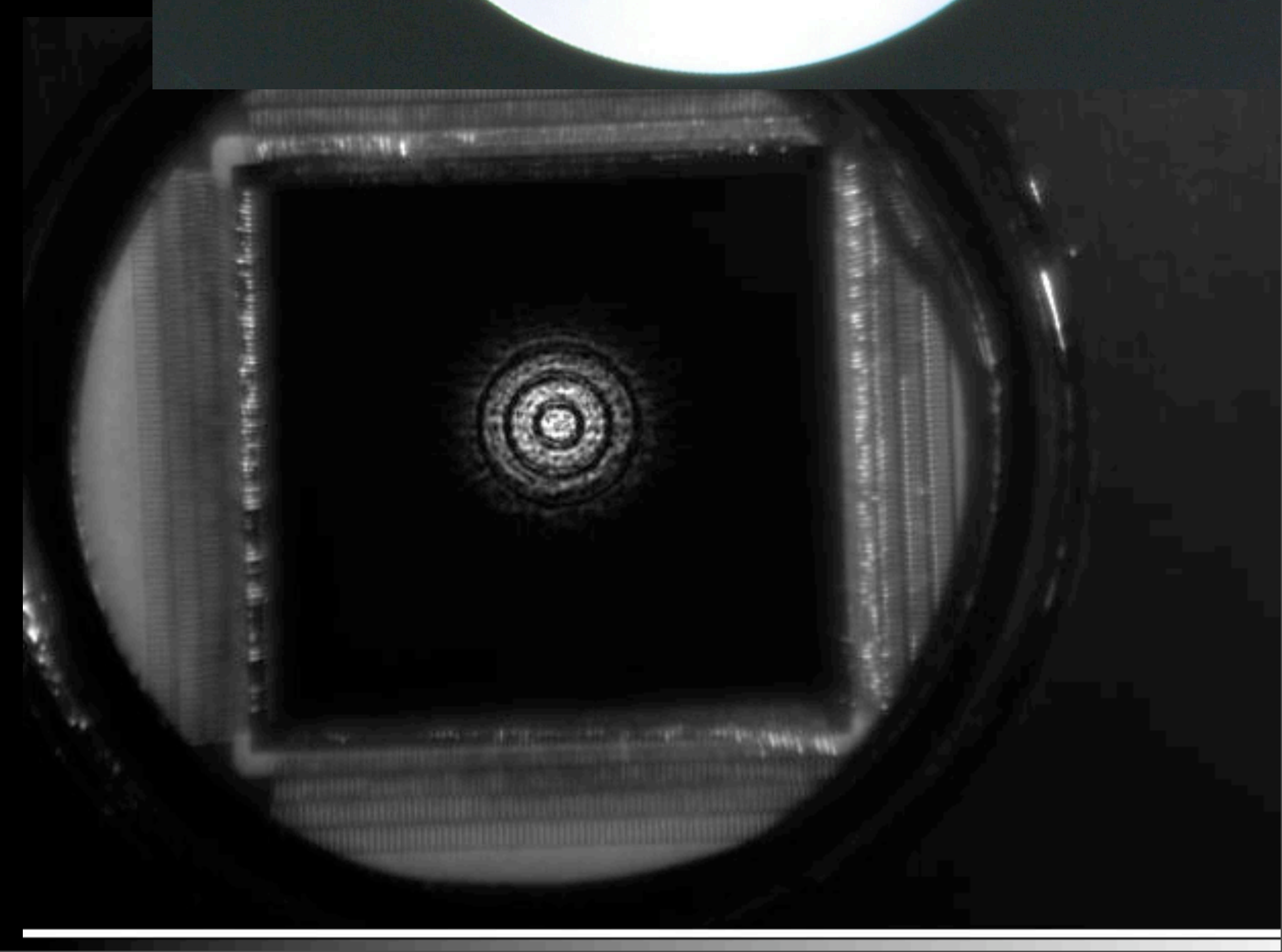
-> Good achromaticity

Pointing is critical

-> Continuous pointing corrections





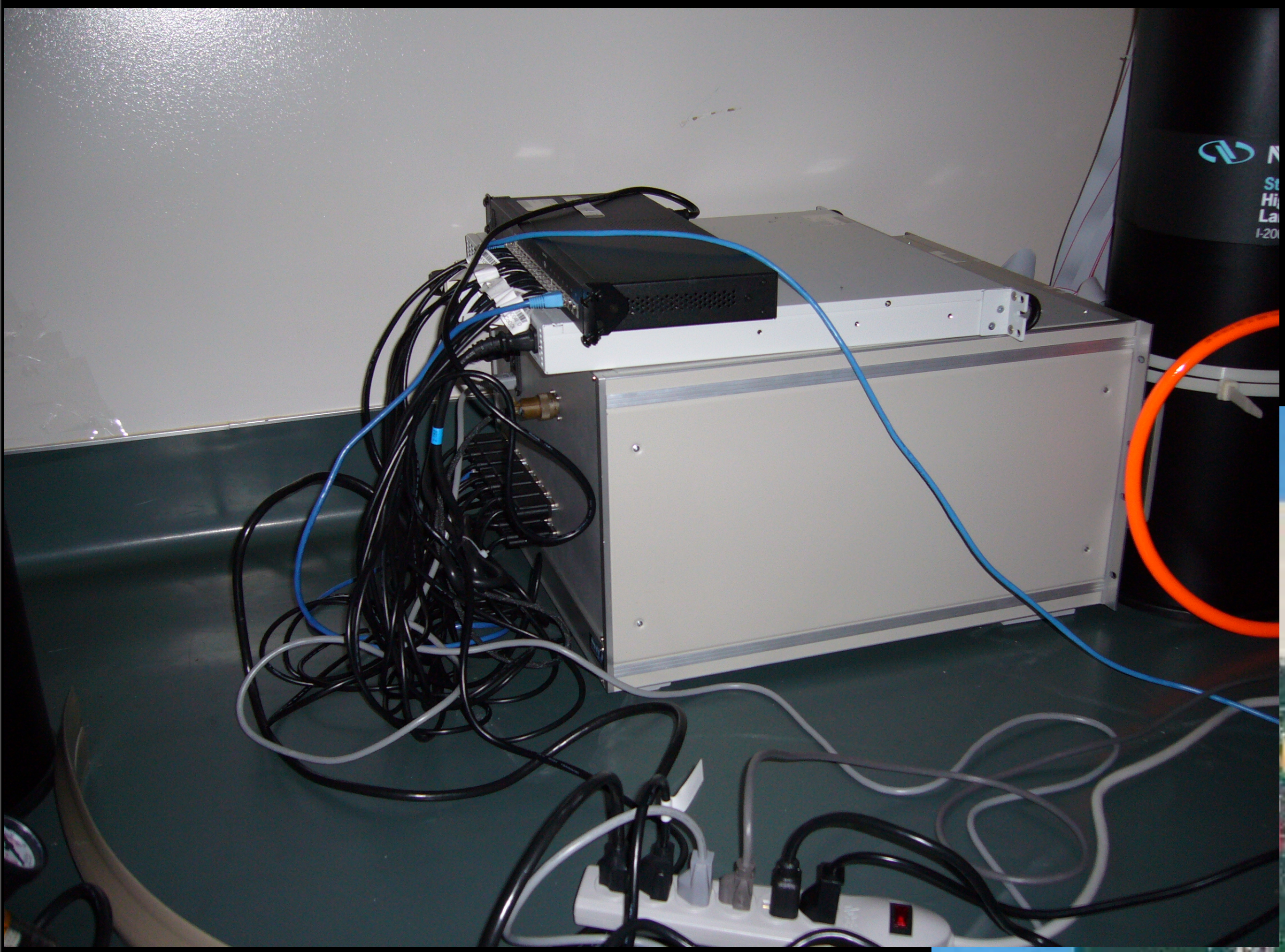


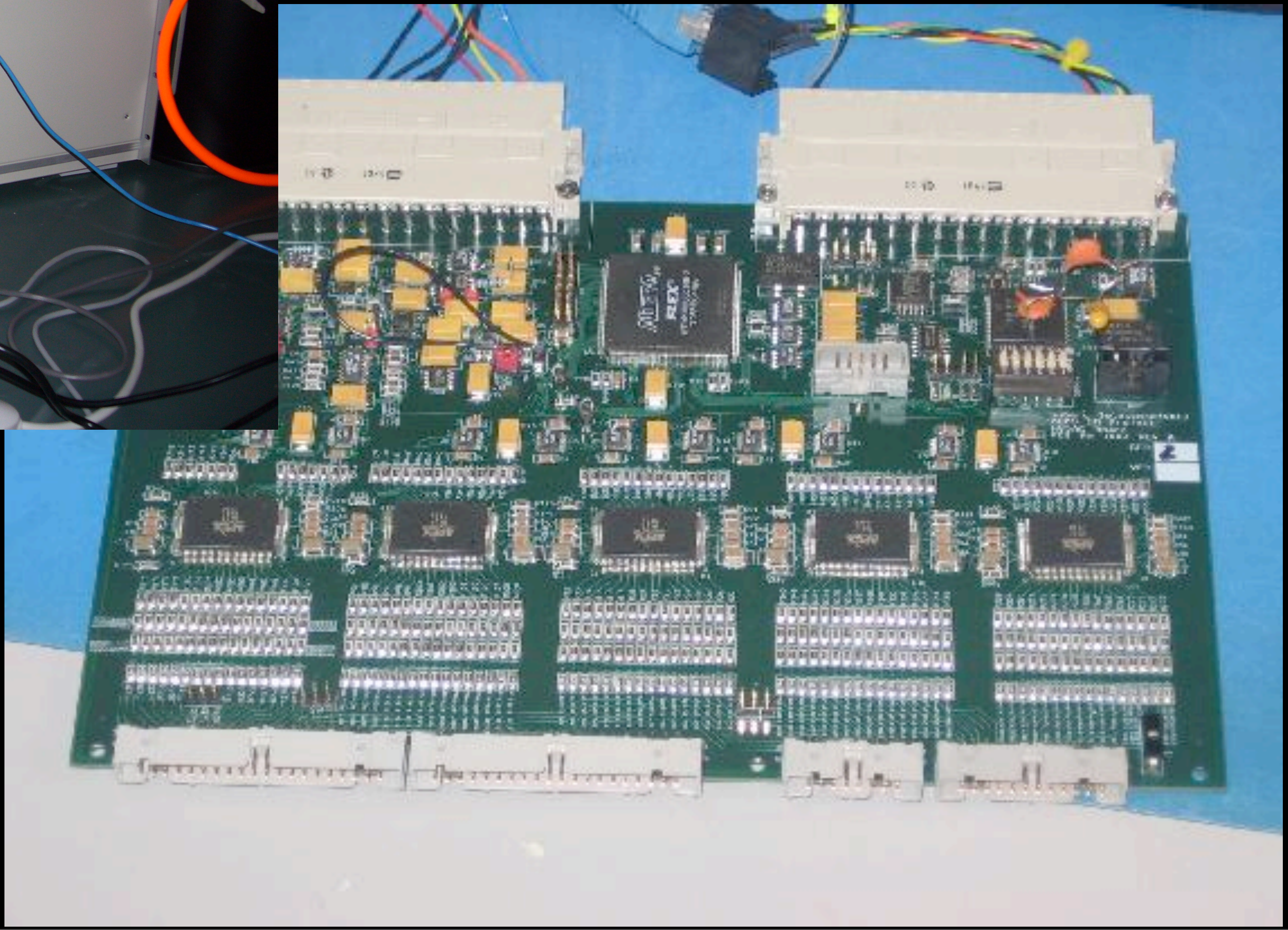
MEMS DM control electronics

16 bit

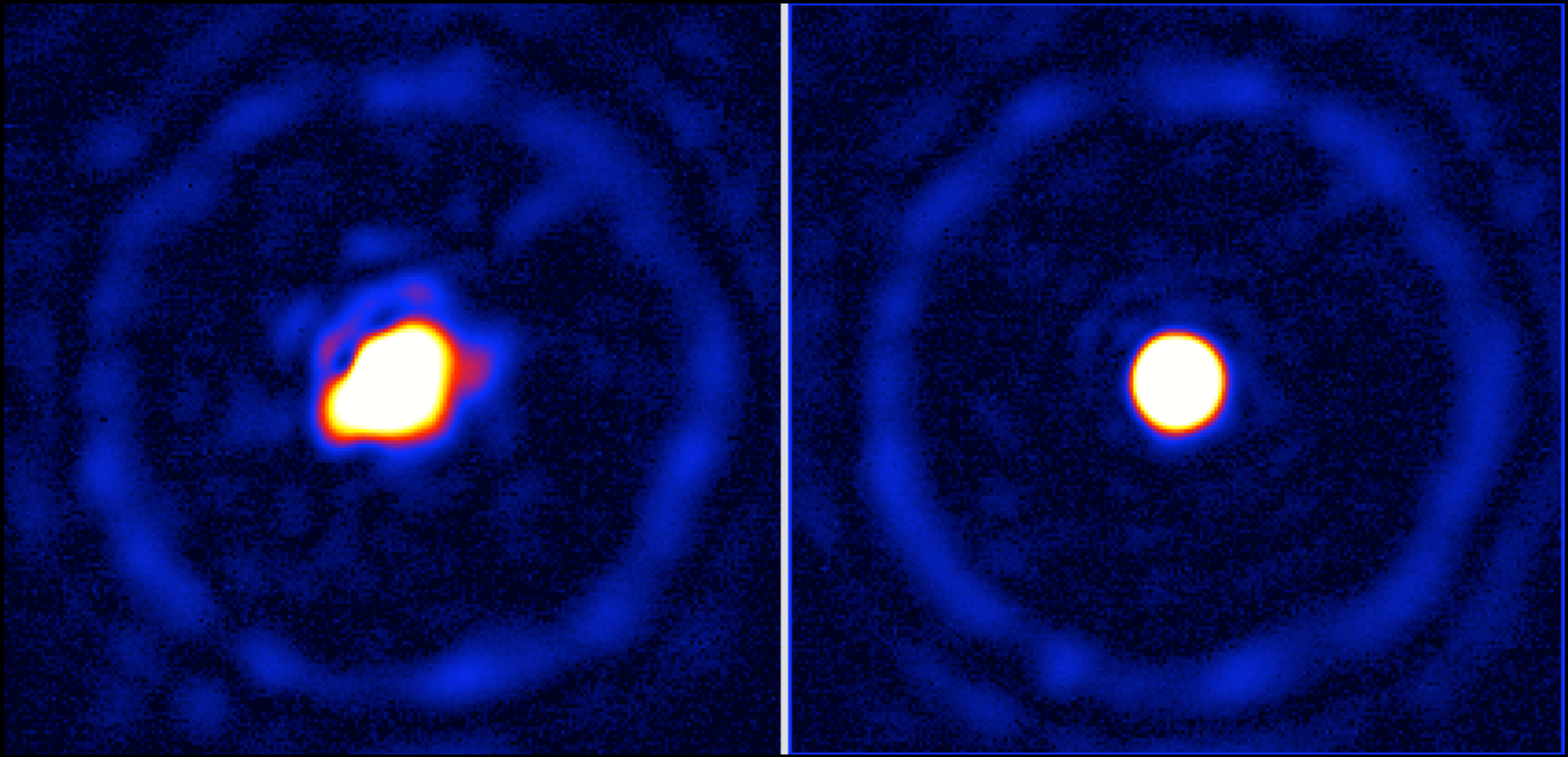
5 kHz update rate of full DM with high speed serial interface

20 Hz update rate with Ethernet



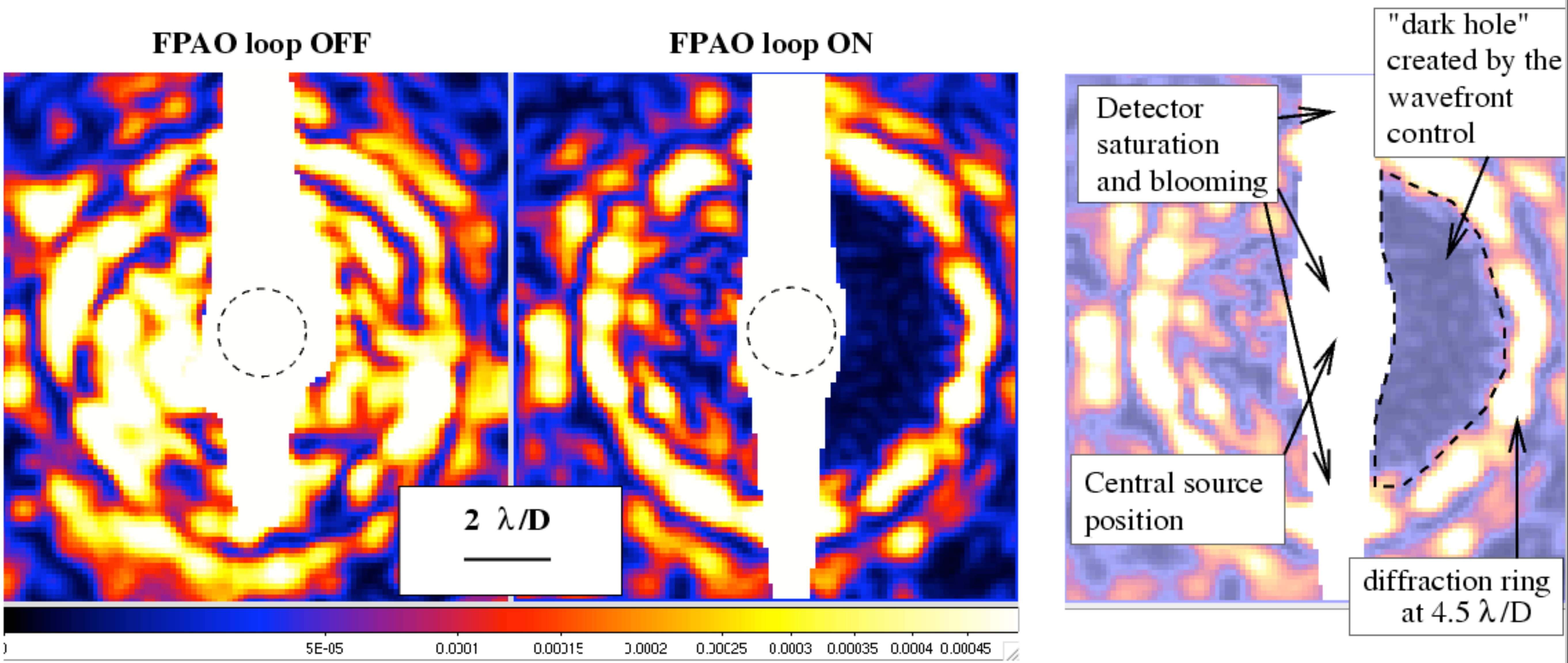


Lab results with PIAA coronagraph + FPAO



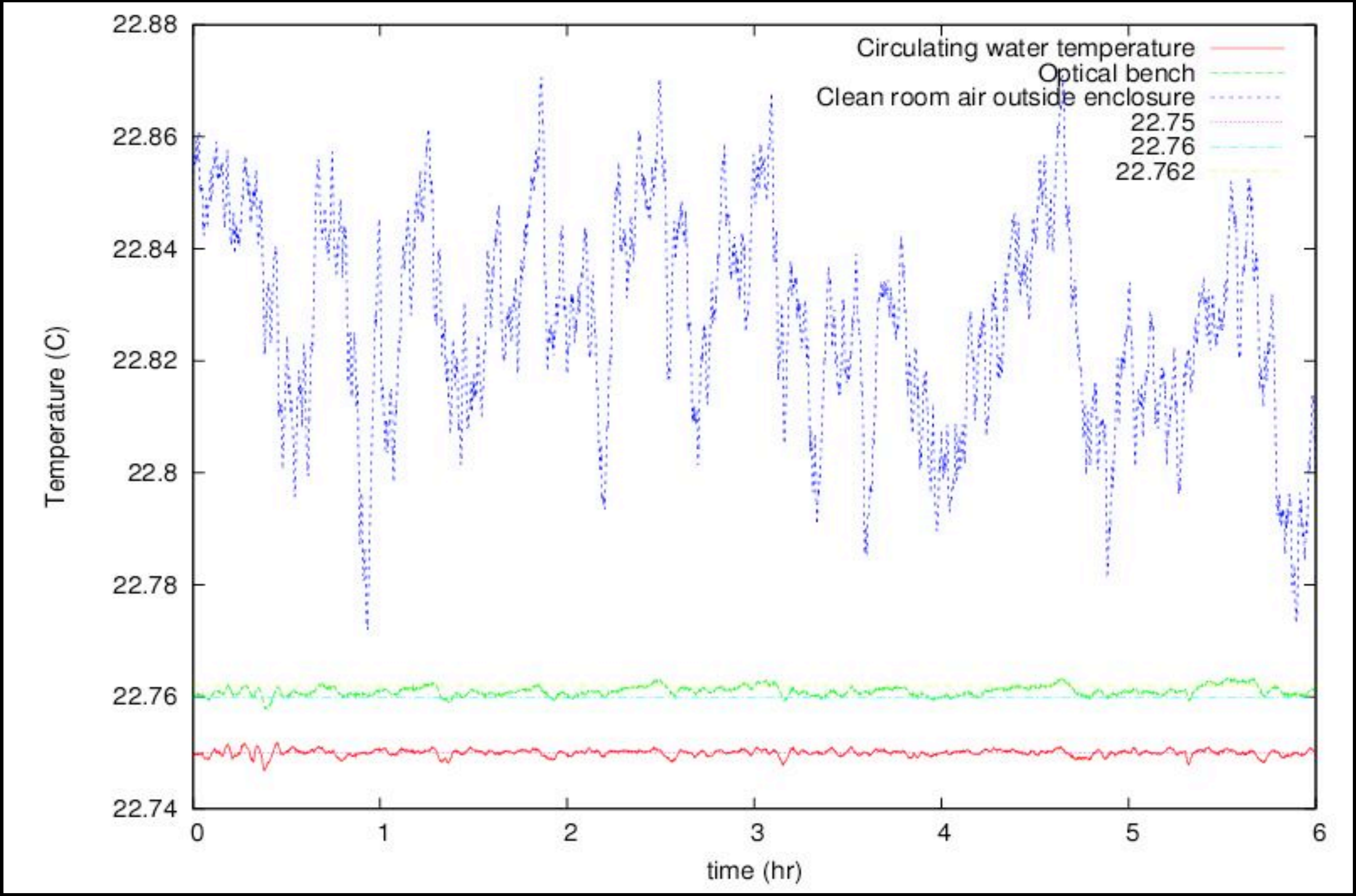
Step 1: phase diversity -> DM correction

Lab results with PIAA coronagraph + FPAO with 32x32 MEMs DM



See also results obtained at JPL HCIT & Princeton
So far, these results are obtained at <1 Hz: making FPAO run at ~kHz is challenging (detector, algorithms)

mK Temperature control
-> greatly improved wavefront stability



Wavefront control

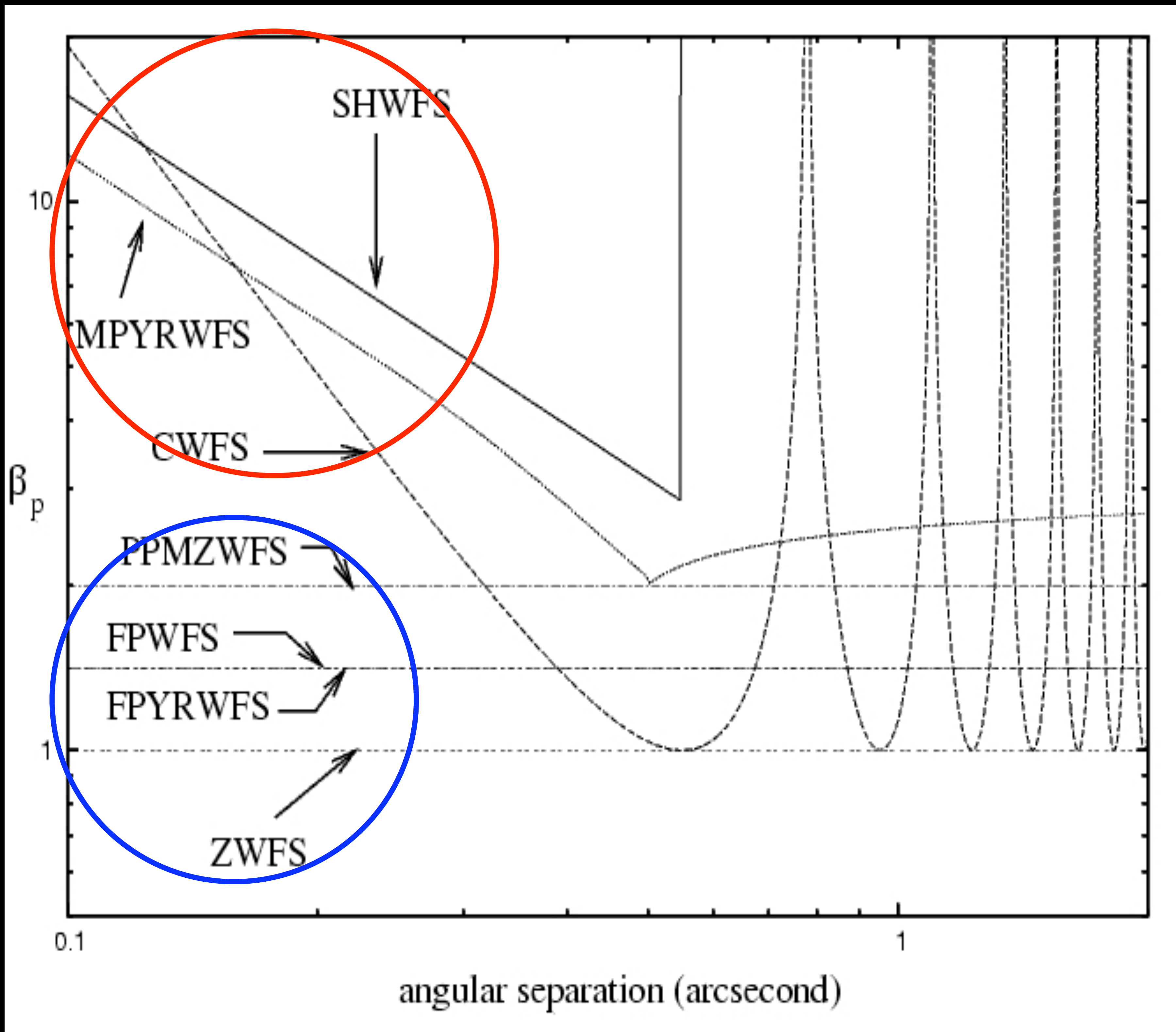
- Adaptive Optics (AO) for ground-based telescopes:

- Measure and correct in REAL TIME (~kHz) wavefront errors induced by atmosphere: goal is ~few x 10nm RMS

- Wavefront correction is space:

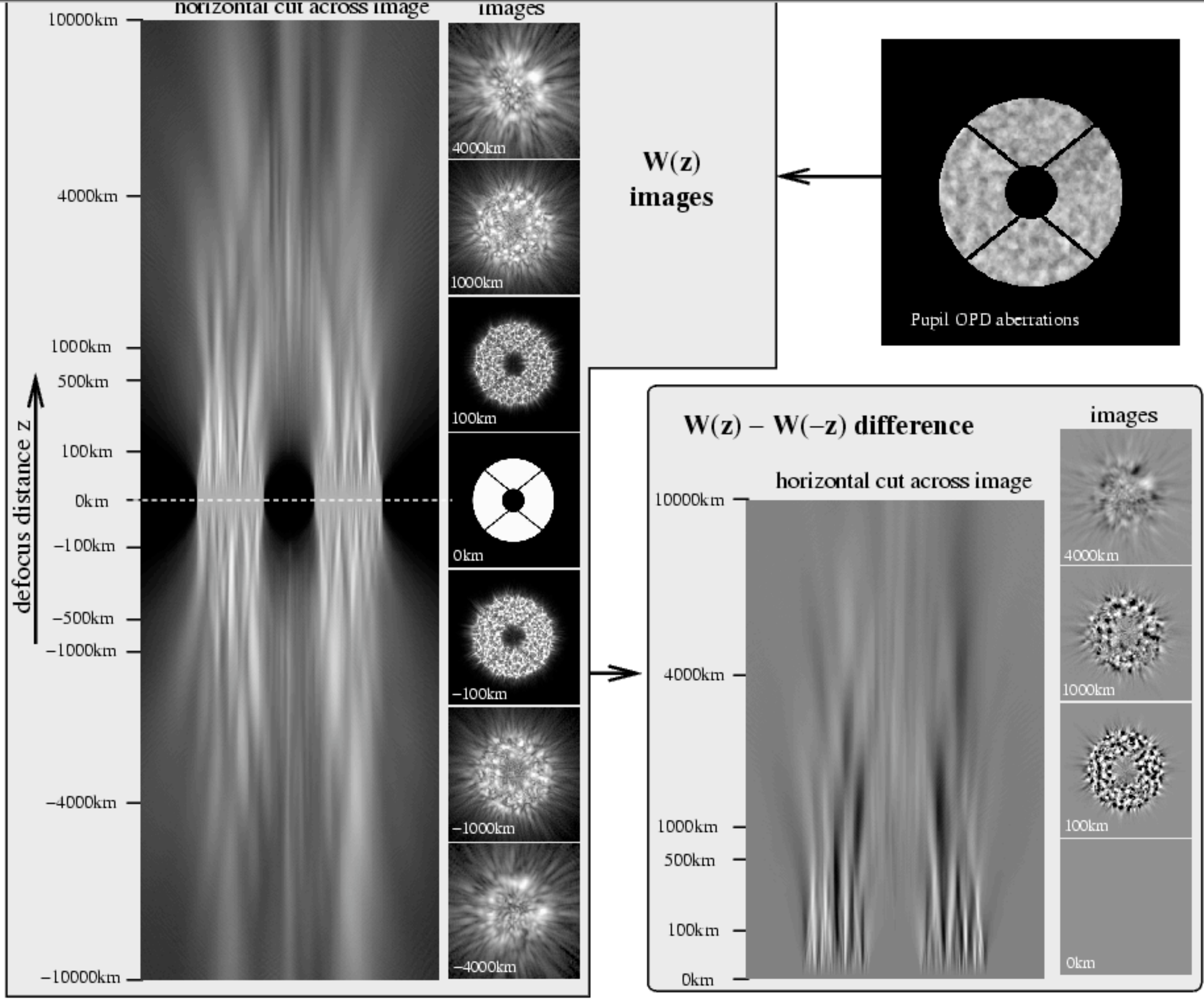
- Accurately measure and correct small wavefront errors due to manufacturing errors and thermal changes: goal is ~0.1 nm RMS

Wavefront sensors "sensitivities" in linear regime with full coherence (Guyon 2005)



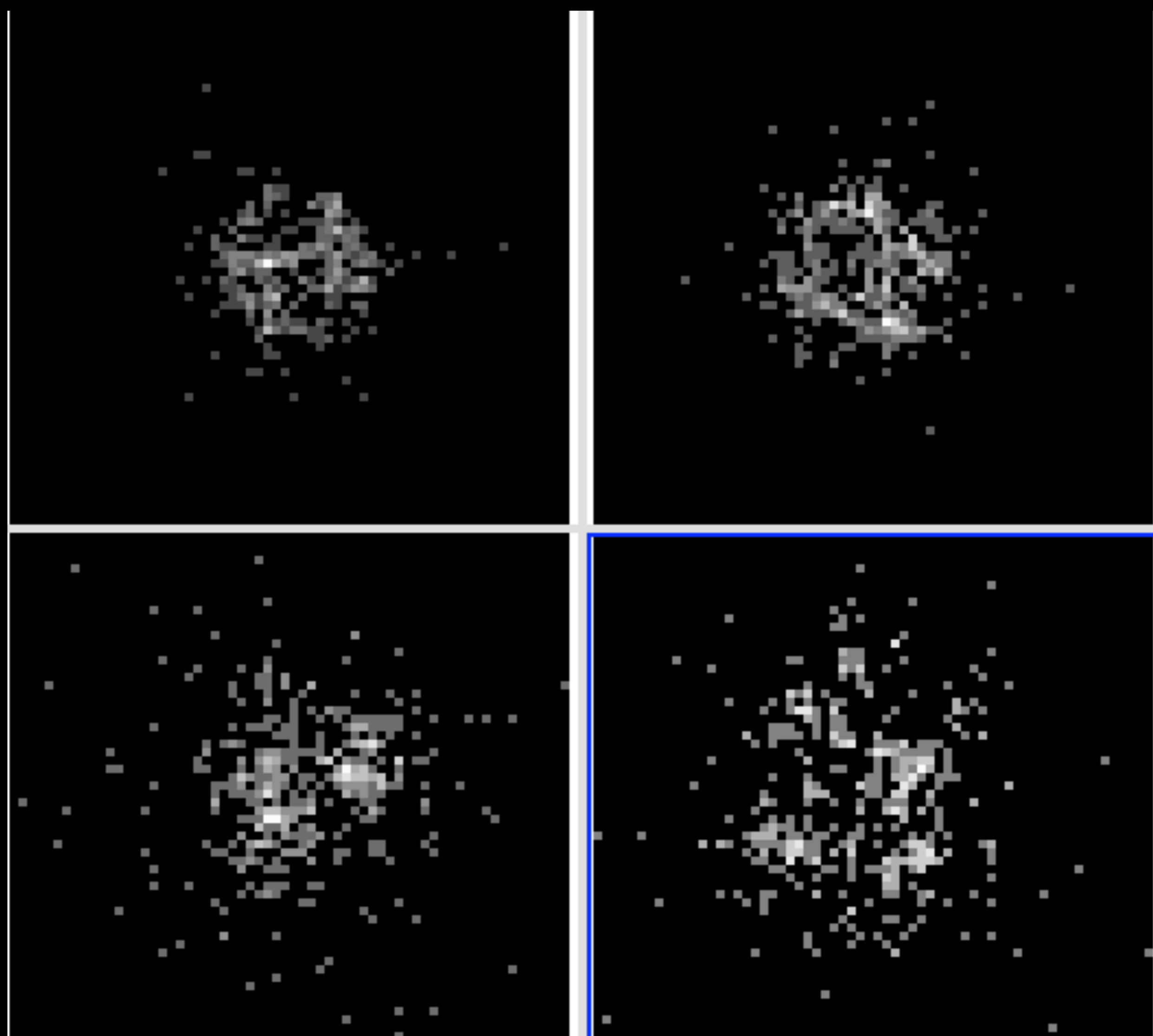
Square root of # of photons required to reach fixed sensing accuracy

plotted here for phase aberrations only, 8m telescope. Tuned for maximum sensitivity at 0.5" from central star.



horizontal cut across image
images
10000km
4000km
1000km
500km
100km
0km
−100km
−500km
−1000km
−4000km
−10000km
defocus distance z
4000km
1000km
100km
0km
−100km
−1000km
−4000km
W(z)
images
Pupil OPD aberrations
W(z) – W(−z) difference
images
horizontal cut across image
10000km
4000km
1000km
500km
100km
0km
4000km
1000km
100km
0km

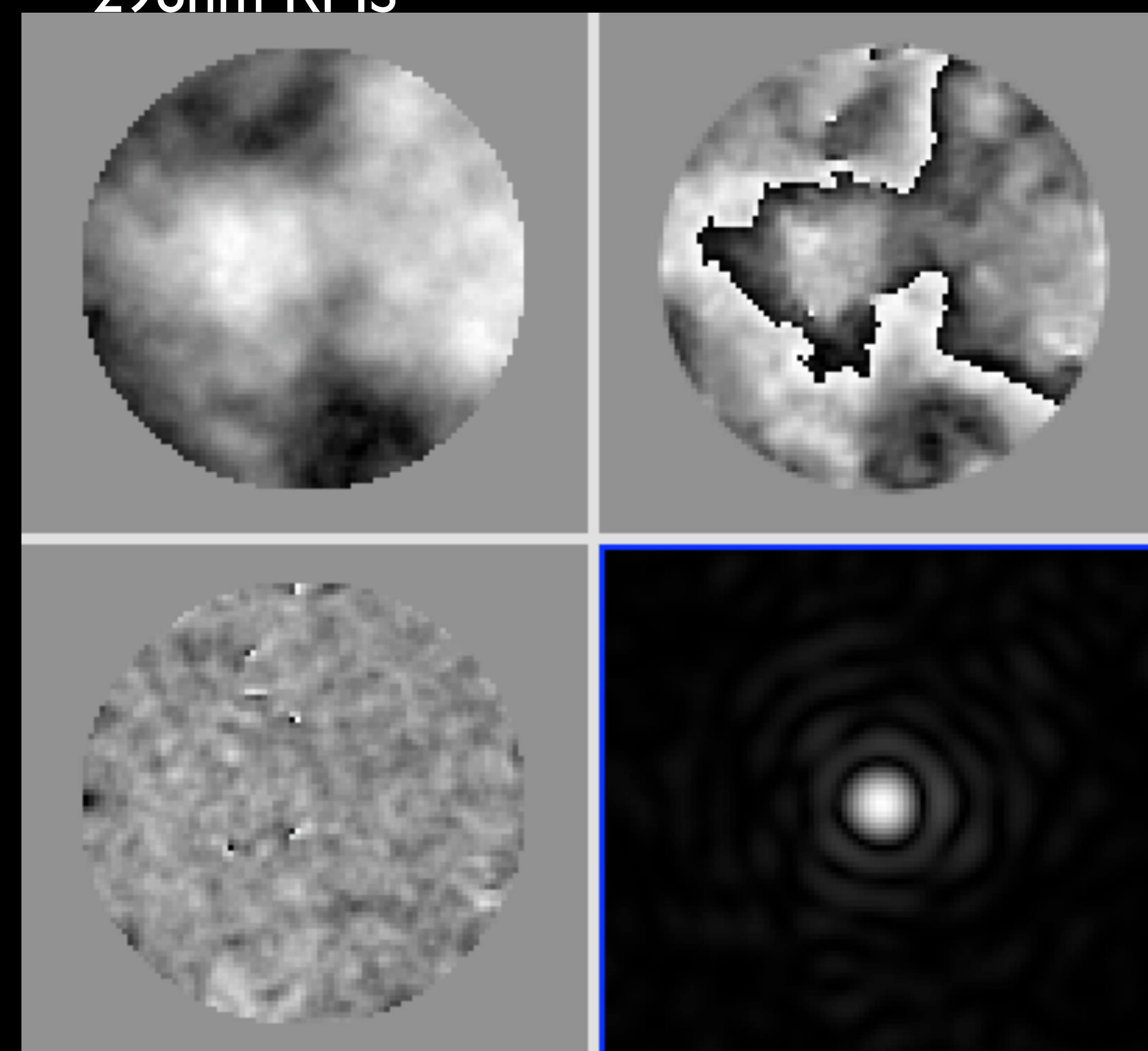
Non linear dual stroke WFS, 2000 ph total
8m telescope, 0.65 mu, 373 ill. subapert.



Defocused pupil images

Input pupil phase
296nm RMS

Reconstructed phase



Residual: 55nm RMS

SR = 0.763
at 0.65 micron

500 ph / frame
Top : +/- 2000km
Bottom: +/- 8000km

Magn 16 source -> 2000 ph/ms on 8m telescope

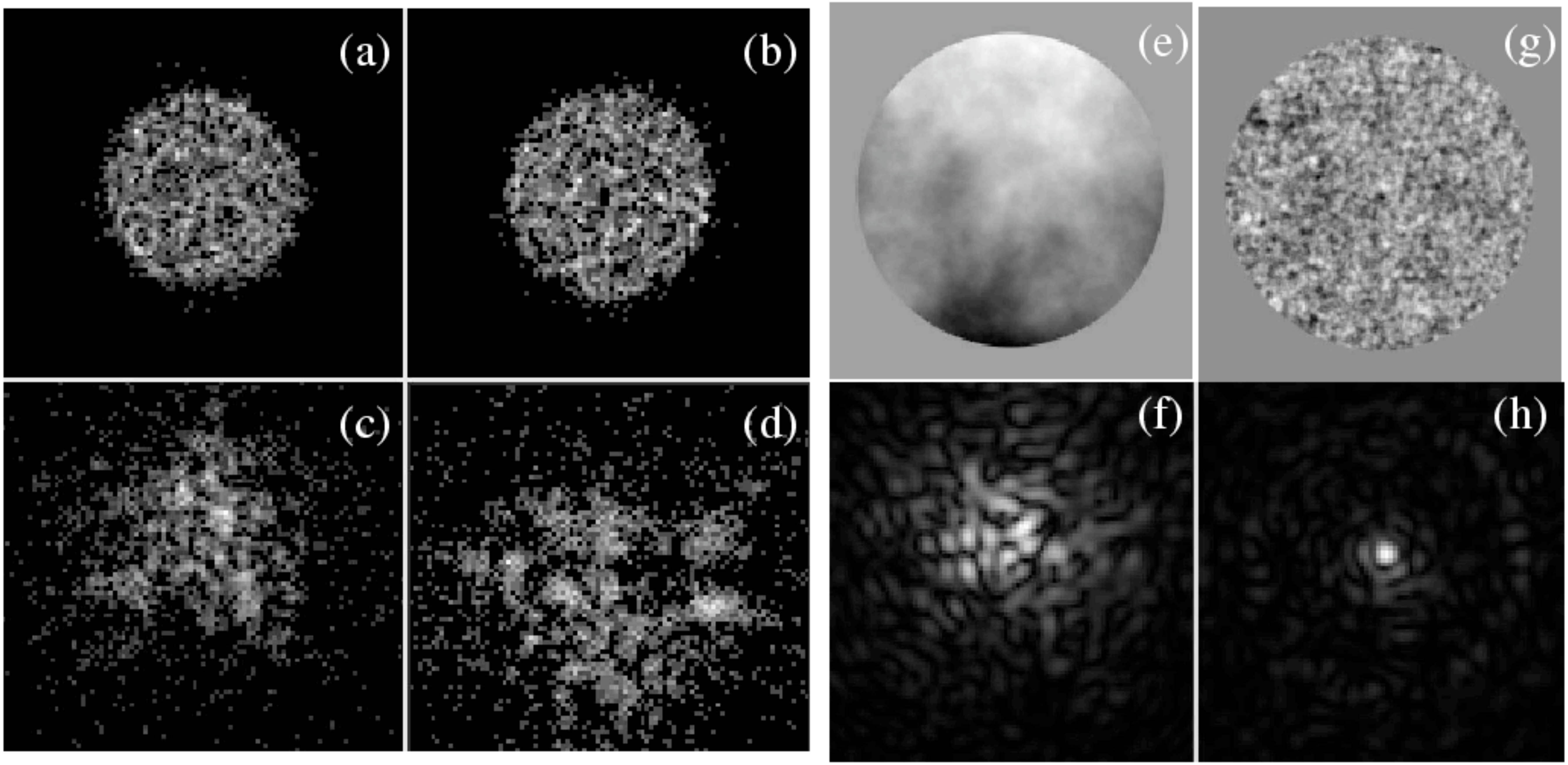


Fig. 9.— Wavefront reconstruction using the algorithm shown in fig. 8. Four noisy defocused pupil images (images (a), (b), (c) and (d)) are acquired to transform the pupil phase aberrations (e) into intensity signals. The input pupil phase is 609 nm RMS, yielding the PSF (f) before correction. After correction, the residual pupil phase aberration (g) is 34.4 nm RMS, allowing high Strehl ratio imaging (h). All images in this figure were obtained at 0.65 μm. The total number of photons available for wavefront sensing in 2e4.

Why is is so good ??? -> uses HSF to infer LSF

6073 ill.
elements

+/- 1000km

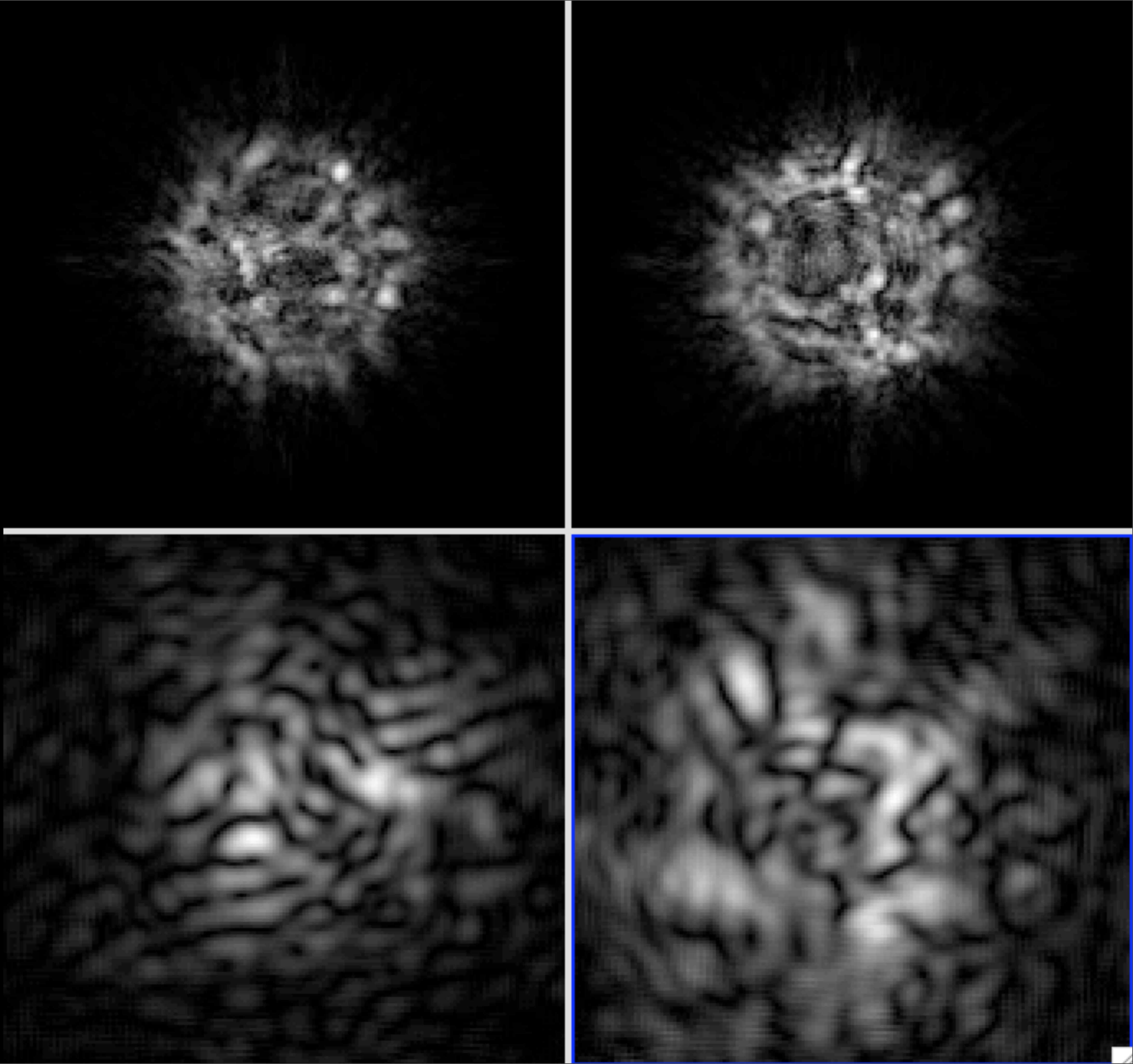
dI/I = 0.0

Nph = 2e8

After
Correction:

SR = 99.3
RMS = 8nm

+/- 8000km

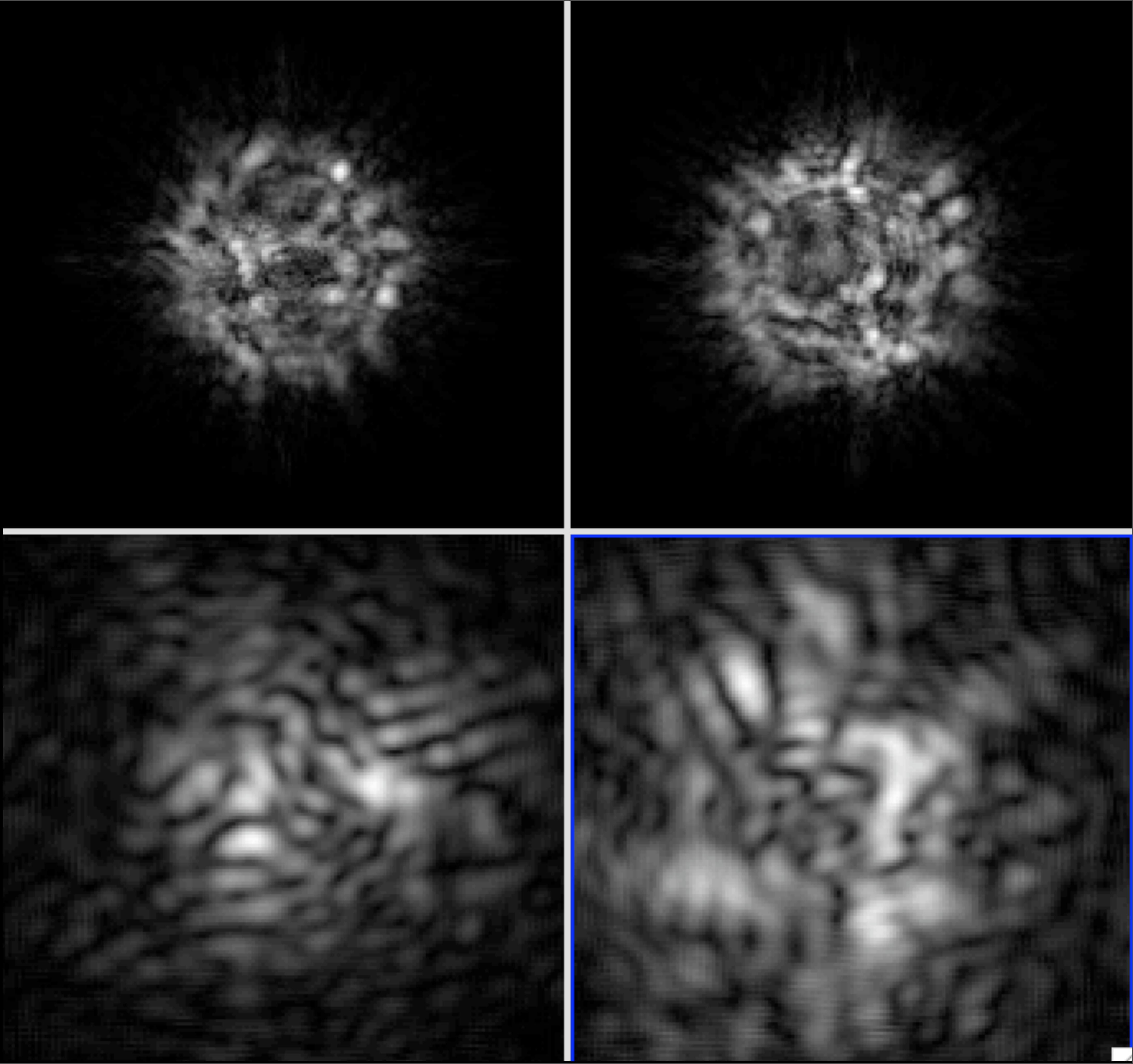


dl/l = 0.5

Nph = 2e8

After Correction :

SR = 98.6
RMS = 12nm



SH / nlCWFS comparison

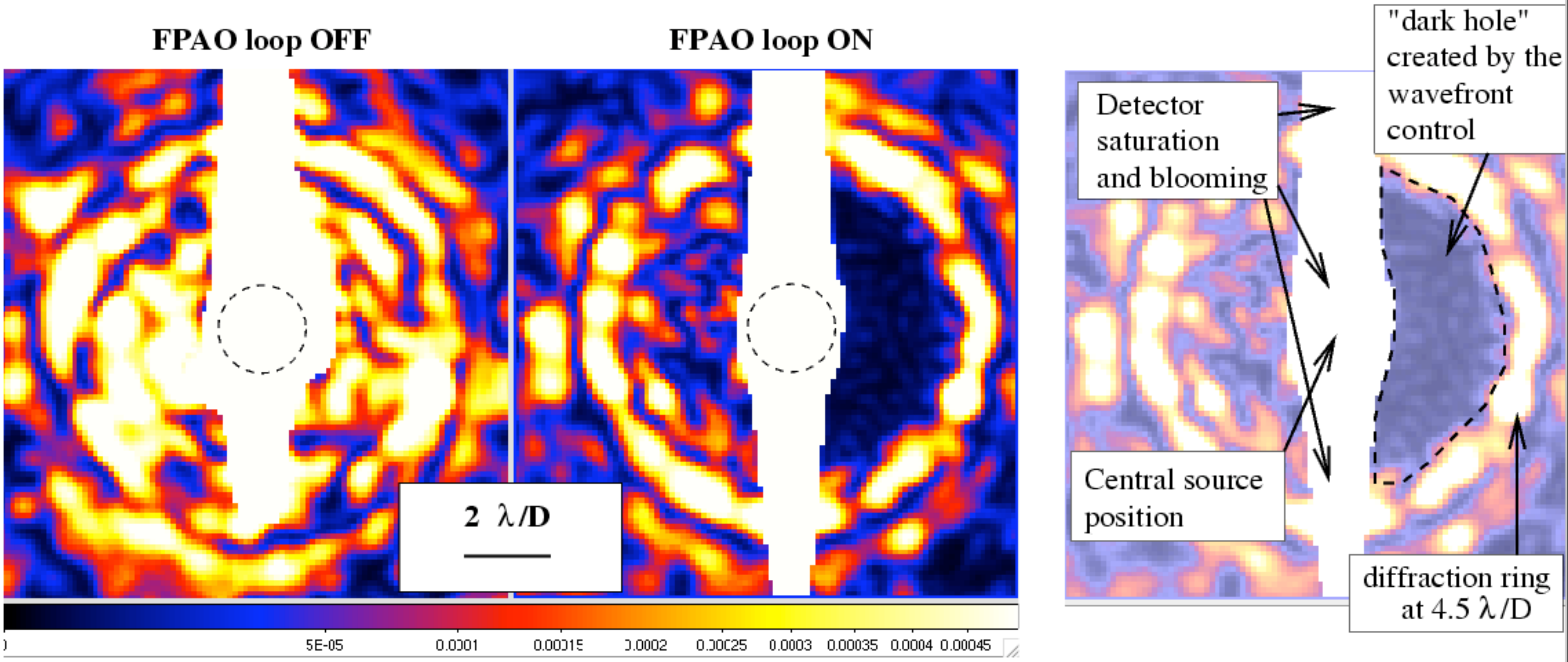
PERFORMANCE COMPARISON BETWEEN SH AND NON-LINEAR CWFS

	$\beta(SH)$	Flux gain	Contrast gain
8m telescope, tip/tilt sensing	40.0	1600 (8.0 magn)	-
8m telescope, 2 l/d (41 mas)	19.0	180 (5.6 magn)	31.8 (3.8 magn)
8m telescope, 5 l/d (103 mas)	7.6	29 (3.6 magn)	9.4 (2.4 magn)
30m telescope, tip/tilt sensing	150.0	22500 (10.9 magn)	-
30m telescope, 2 l/d (11 mas)	71.1	2525 (8.5 magn)	185.4 (5.7 magn)
30m telescope, 5 l/d (28 mas)	28.4	404 (6.5 magn)	54.7 (4.3 magn)
30m telescope, 10 l/d (55 mas)	14.2	101 (5.0 magn)	21.7 (3.3 magn)

Larger telescope / smaller separation ->bigger gain.

BUT: **small gain for extended source (LGS)** – speckled LGS from large laser launching telescope would greatly help (full telescope aperture ? Upstream AO ?)

Lab results with PIAA coronagraph + FPAO with 32x32 MEMs DM



See also results obtained at JPL HCIT & Princeton
So far, these results are obtained at <1 Hz: making FPAO run at ~kHz is challenging (detector, algorithms)

Instruments/Facilities/Projects

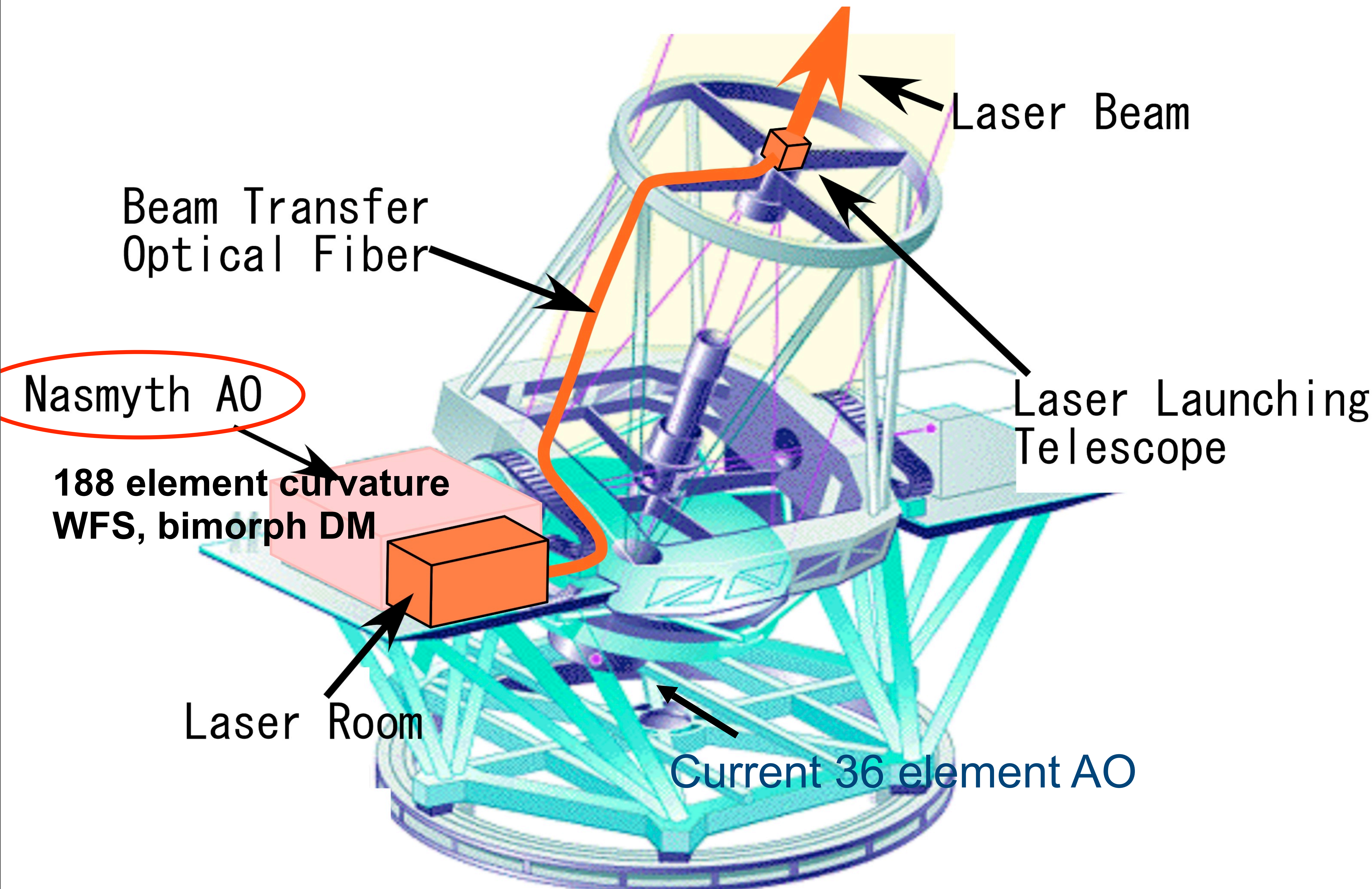
Ground:

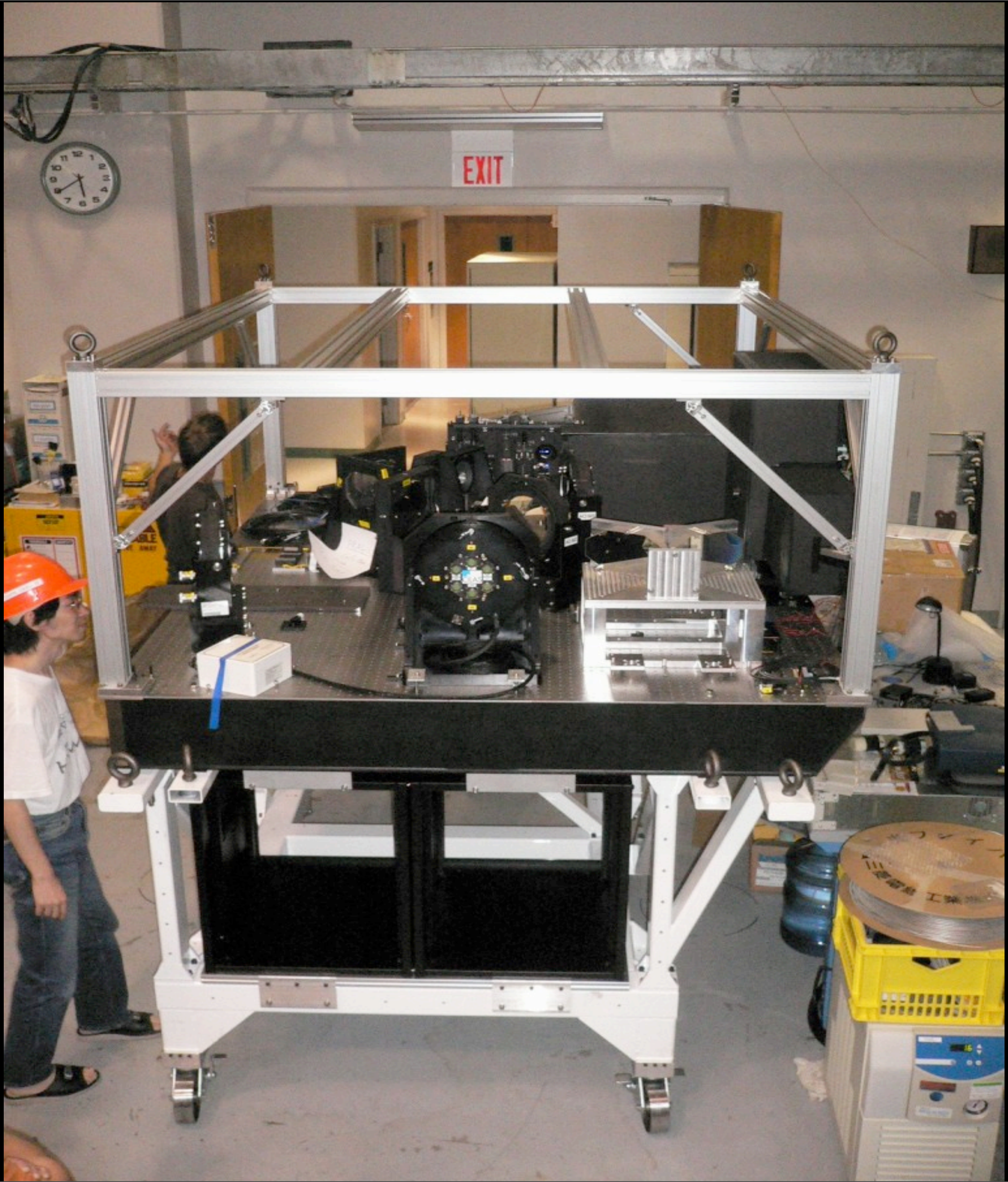
- AO188 system & HiCIAO
- Subaru Coronagraphic Extreme-AO upgrade to HiCIAO

Space:

- TOPS (1.2 m visible telescope with PIAAC)
- PECO (1.4 m TOPS)

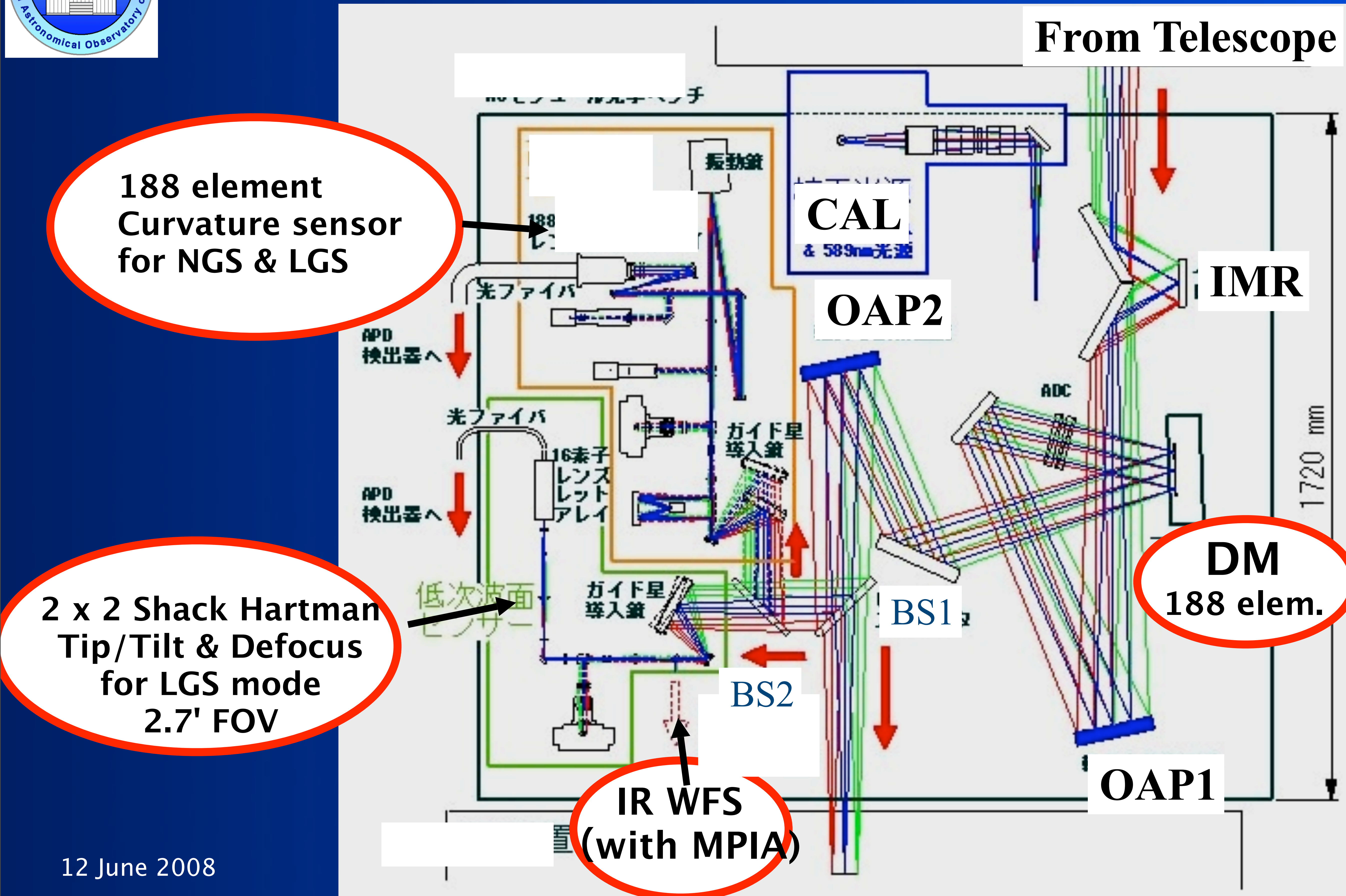
Nasmyth LGS AO



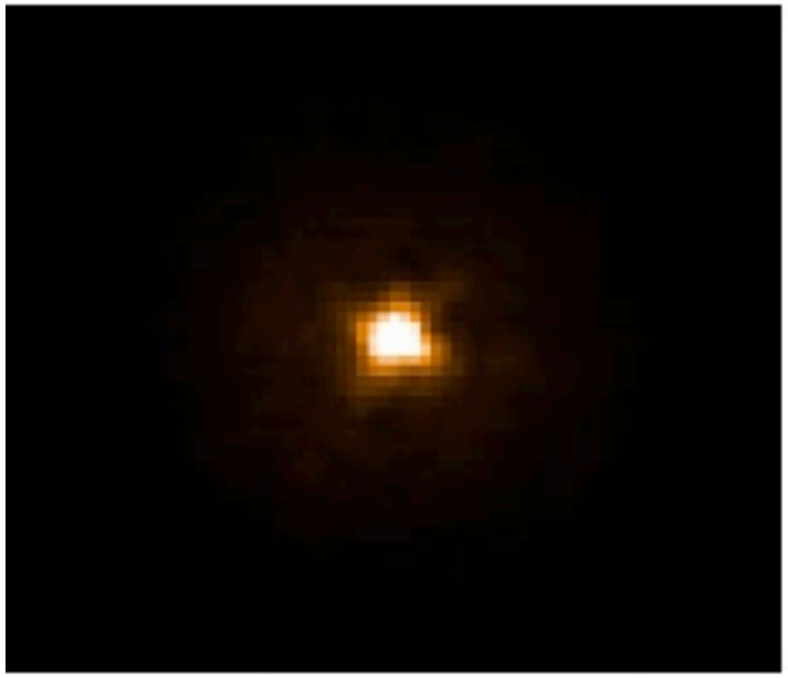

EXIT

AO188 system at the Nasmyth focus (installed in 2006/9)

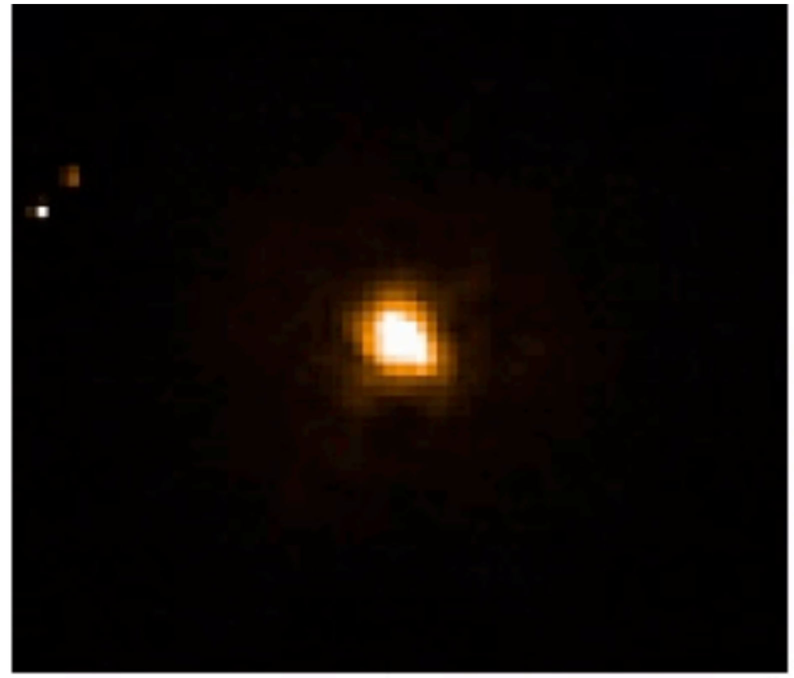
AO188 Module Layout



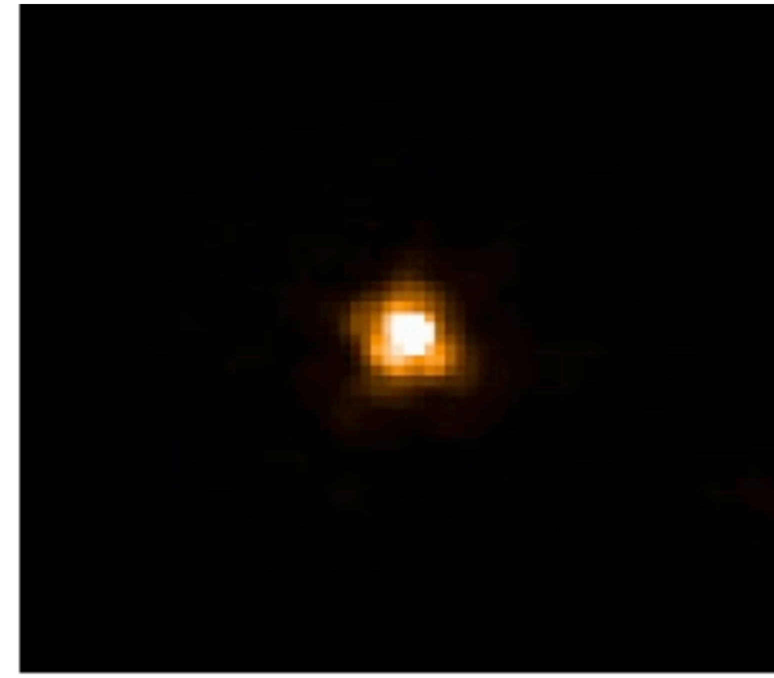
First Light Images of AO188 (2006/10)



z(1.03 μm)
FWHM 0.064″

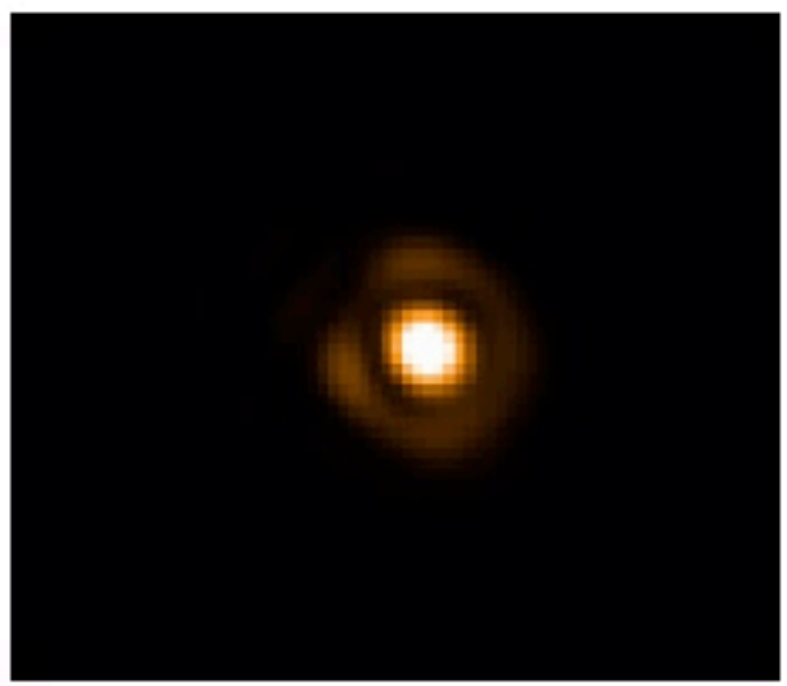


J(1.25 μm)
0.052″

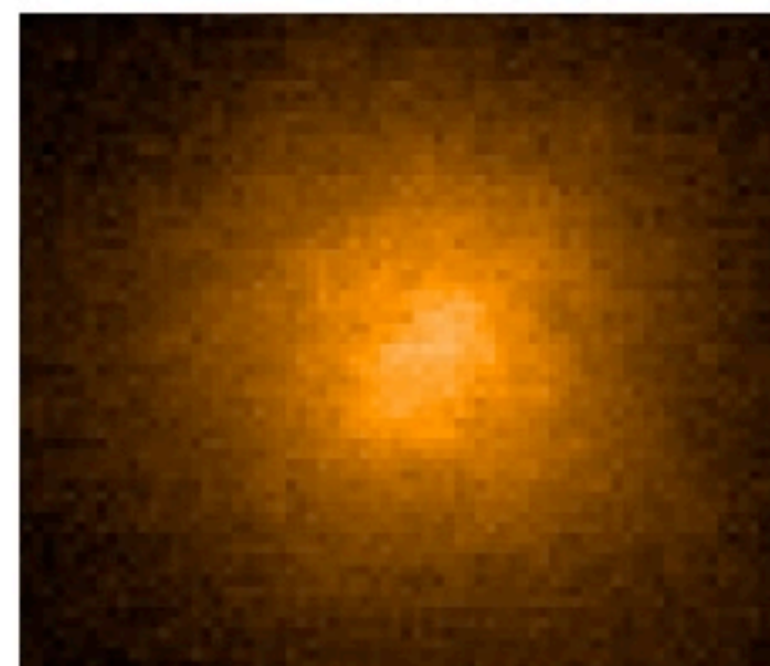


H(1.63 μm)
0.062″

K(2.20 μm)
0.061″

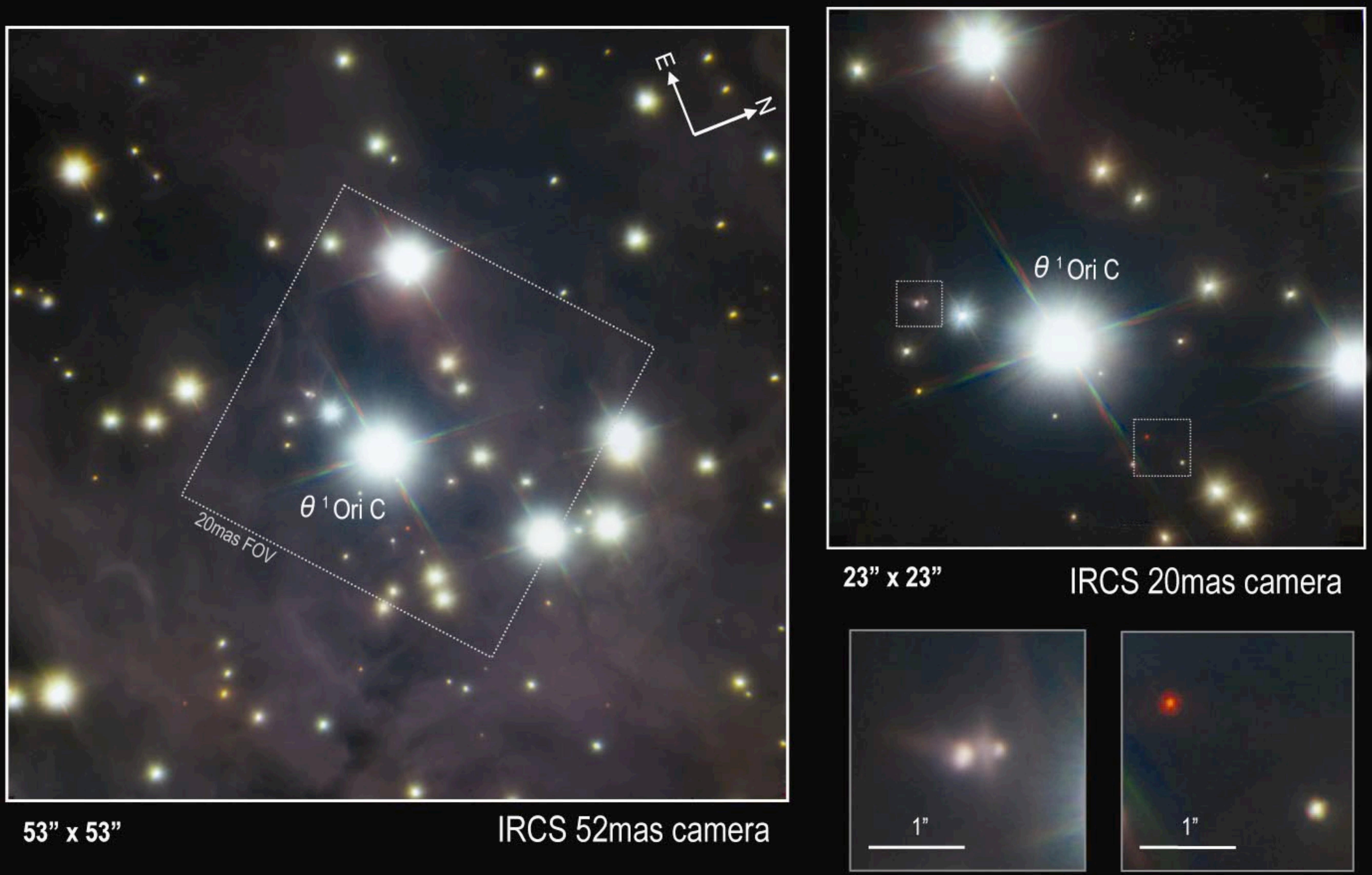


L'(3.77 μm)
0.10″



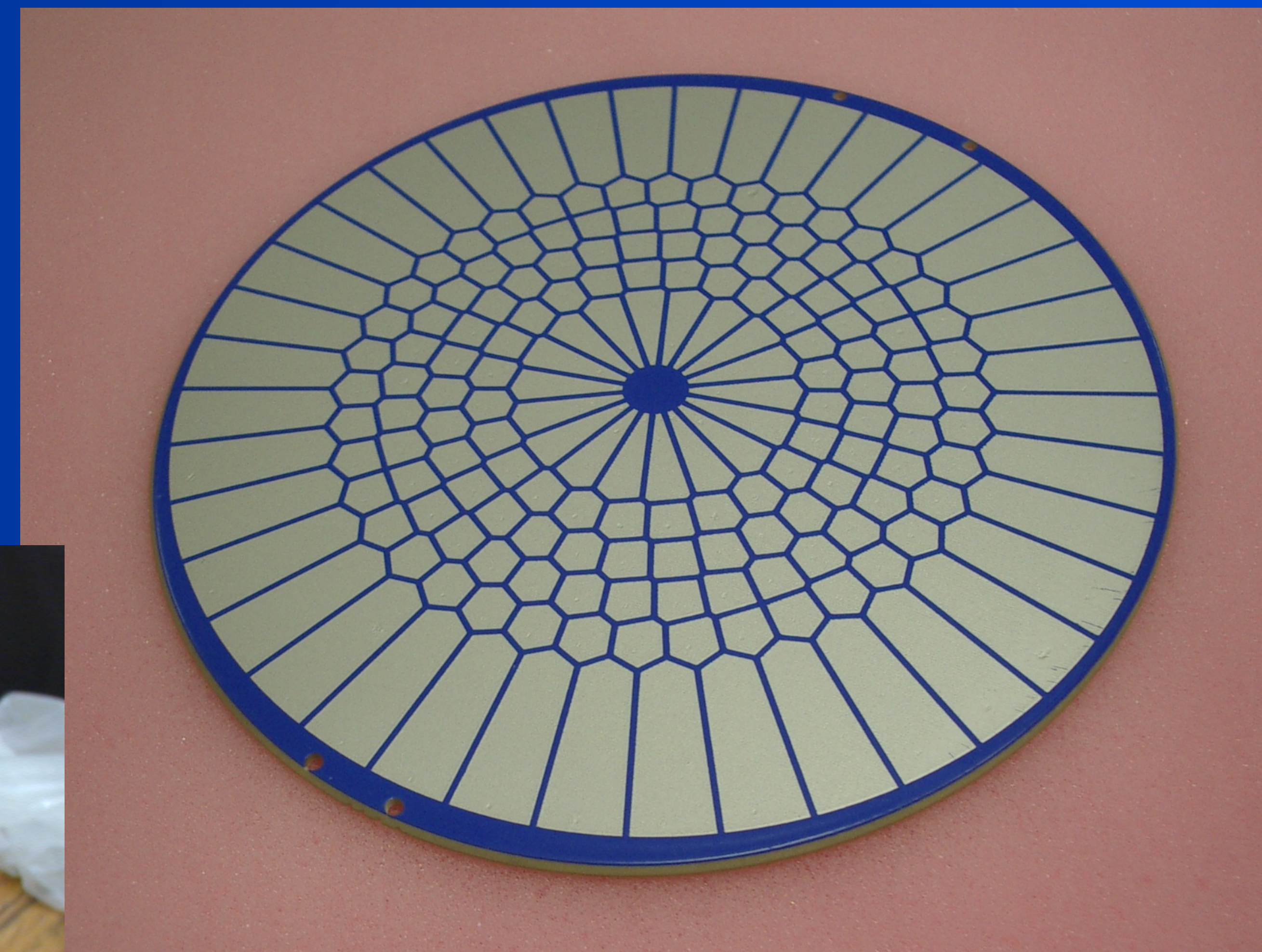
AO OFF
K 0.6″

Orion Trapezium AO188 Image (J,H,K-band)



188 element Bimorph Mirror

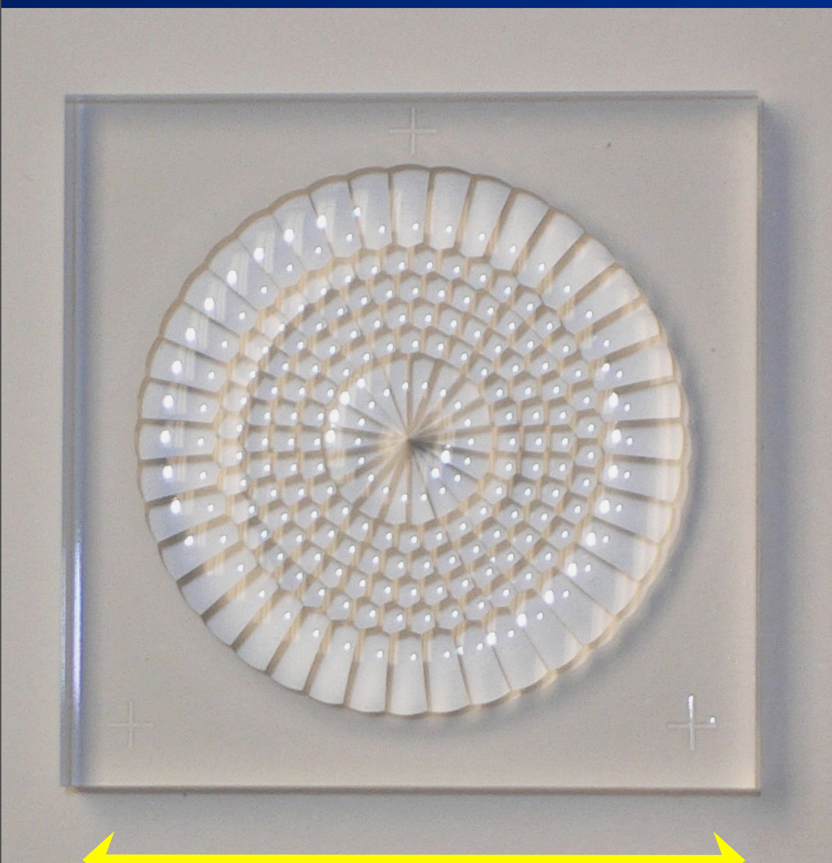
Number:	188
Effective:	90 mm
Blank Size:	130 mm
Thickness:	2 mm
Manufacture:	CILAS



Curvature radius ~10m
=> sufficient

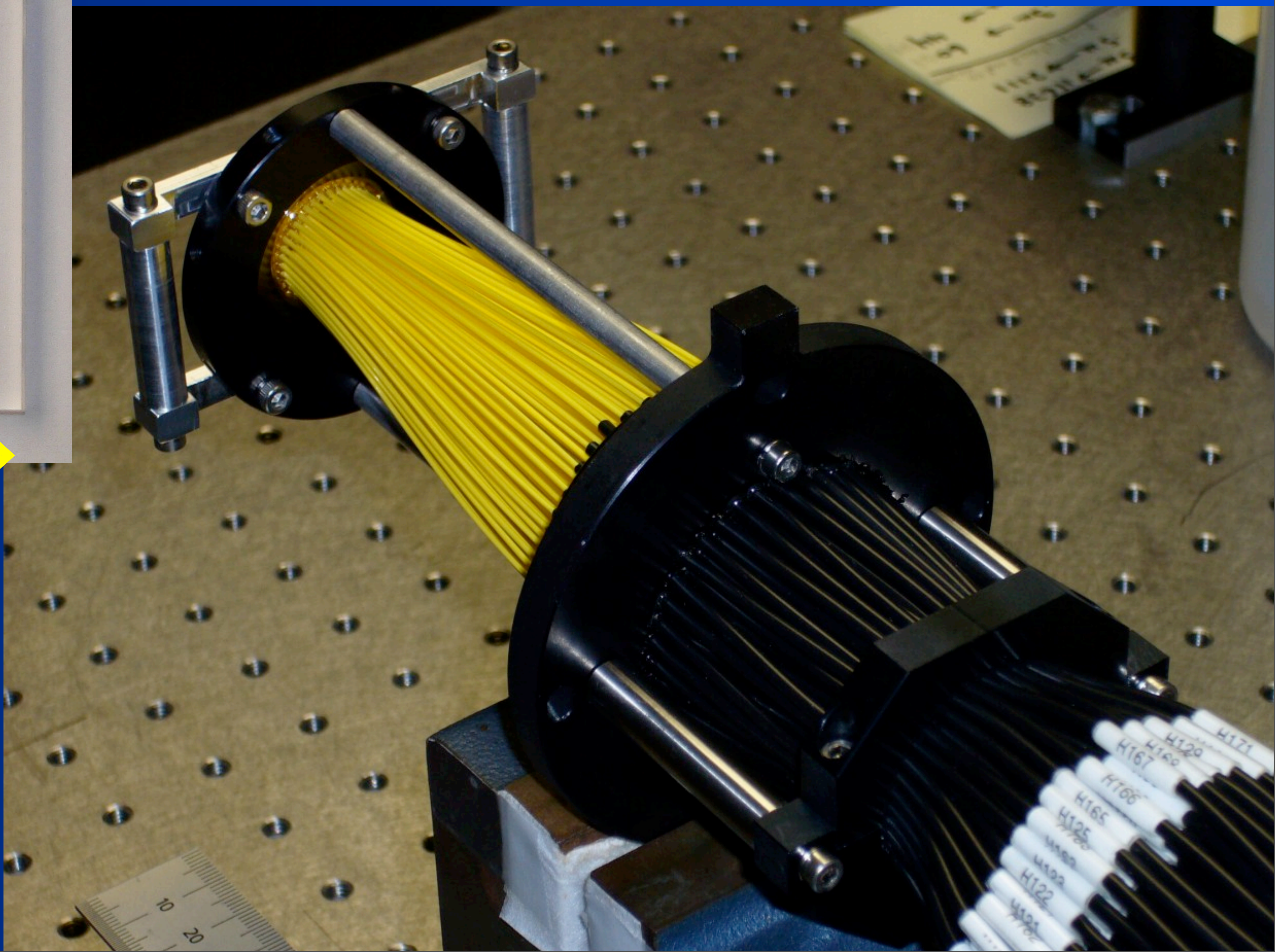
Resonance is issue

WFS Lenslet Array & Optical

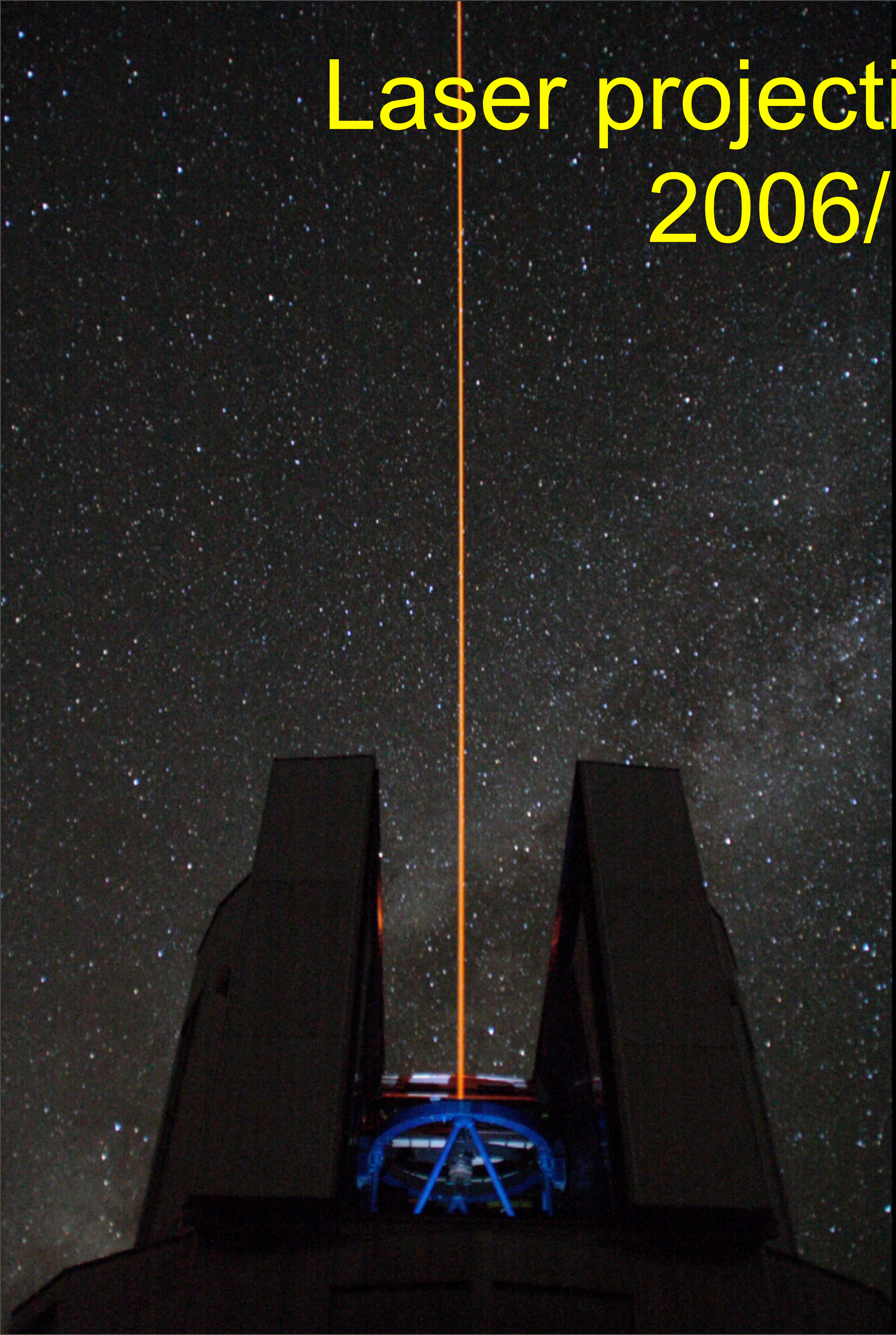


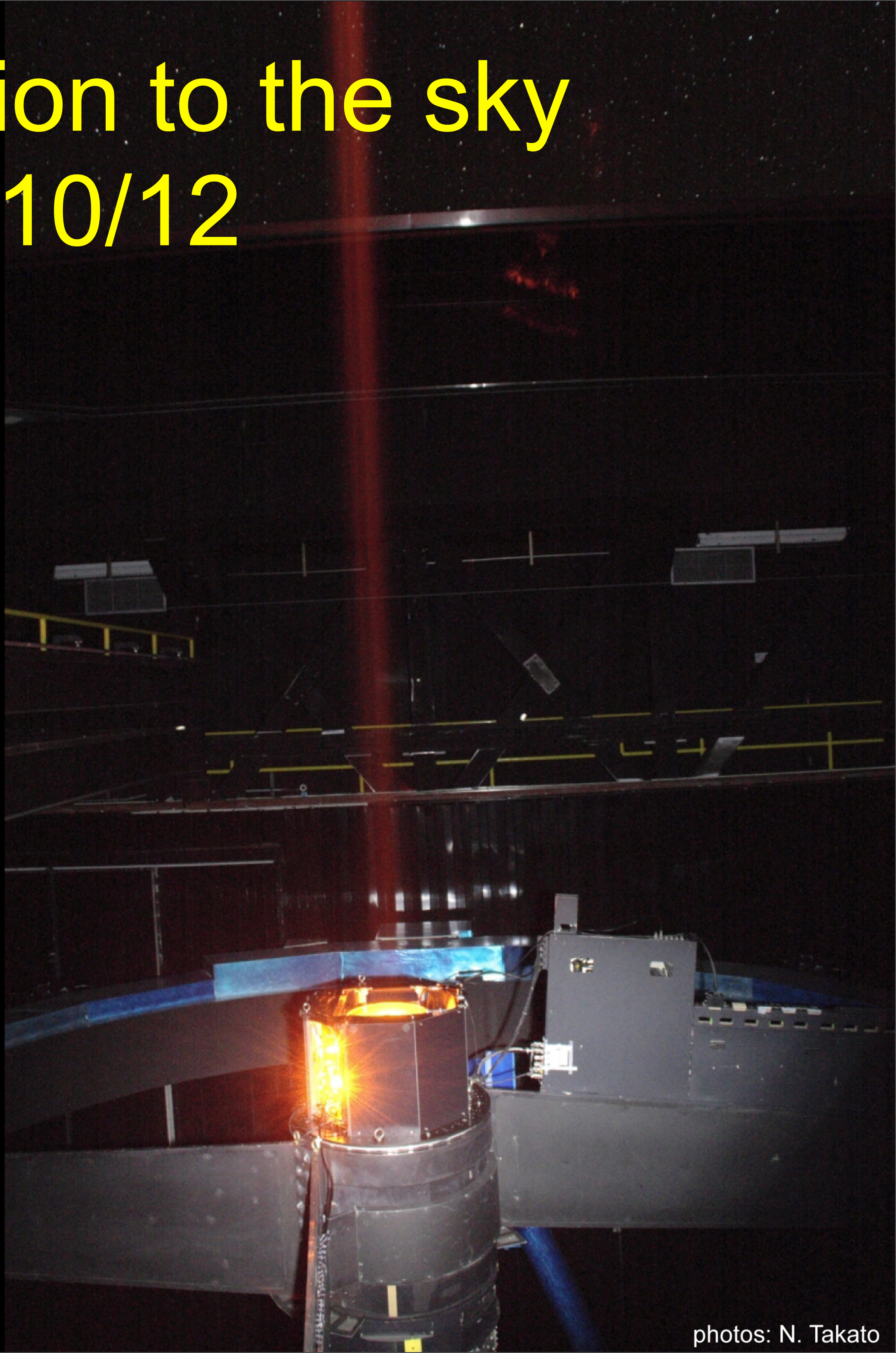
32 mm

Diamond machined plastic mold lens
(Nalux, Co.)



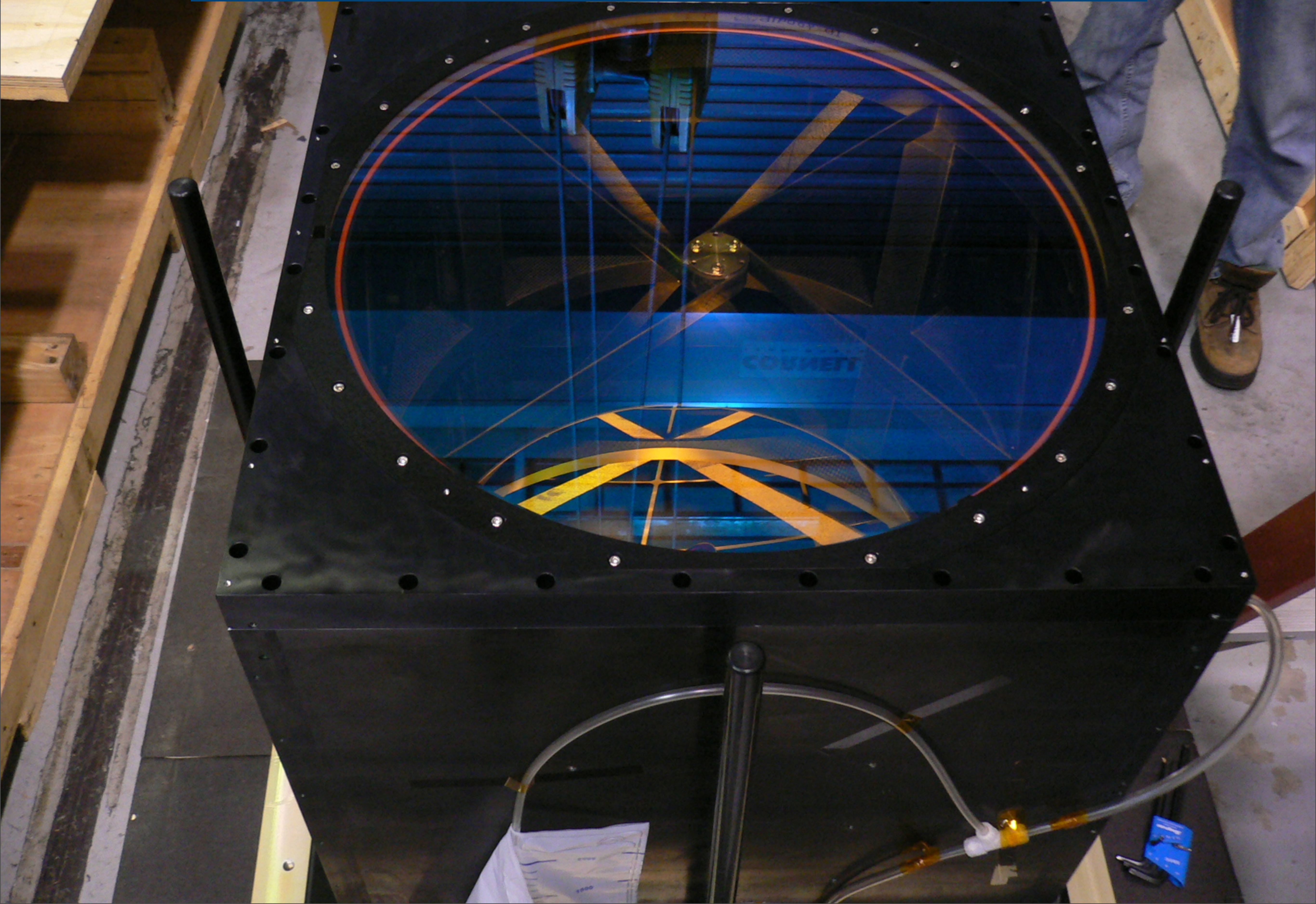
Laser projection to the sky
2006/10/12



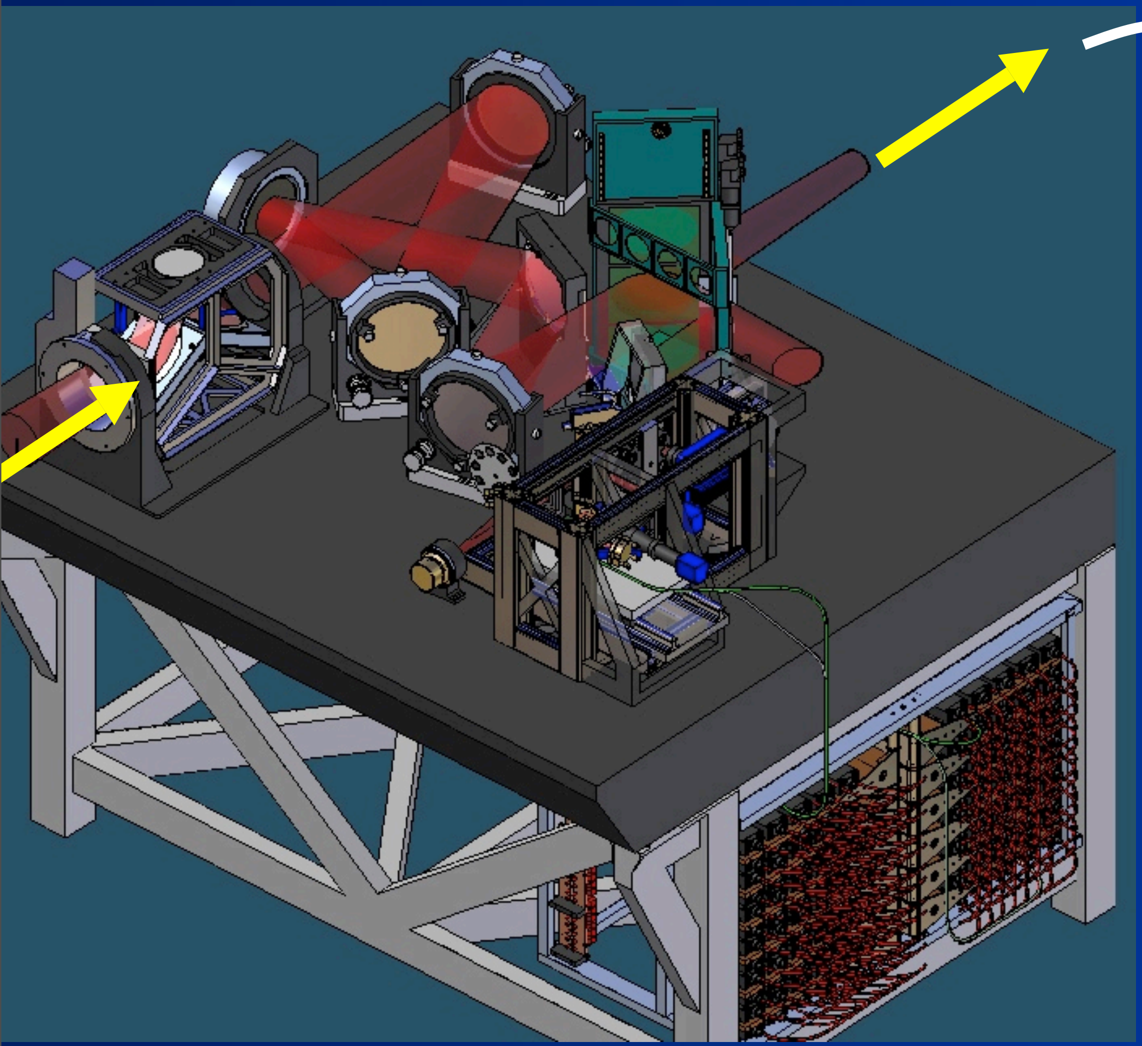


photos: N. Takato

Laser Launching Telescope（50cm）

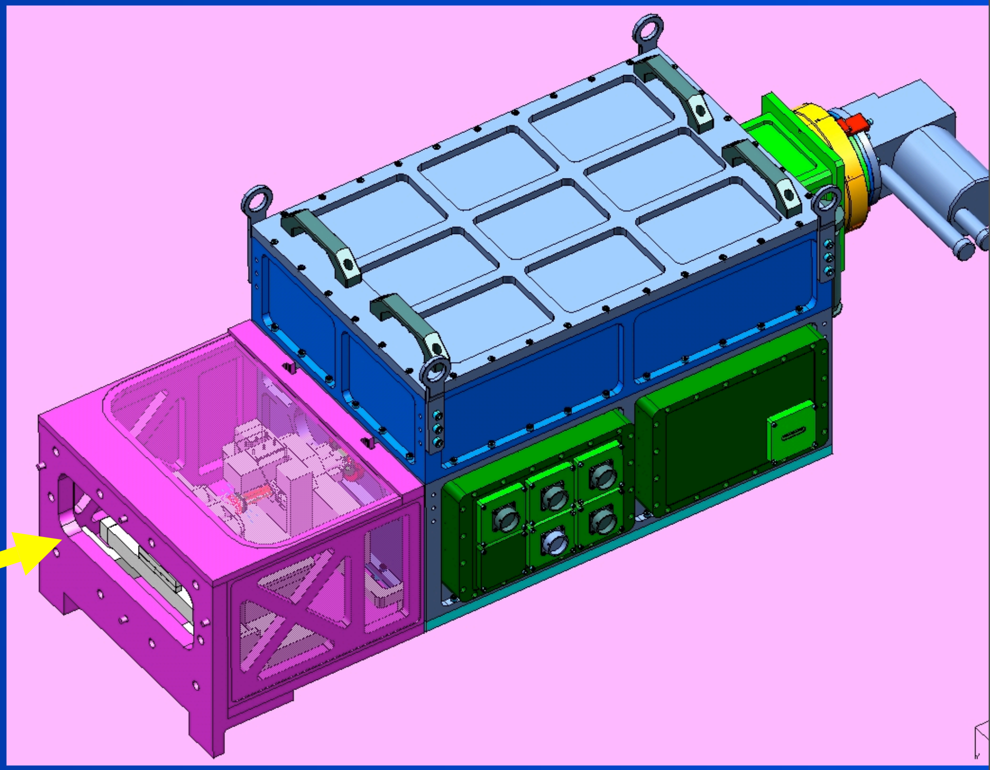


LGSAO+HiCIAO (2008~)
Exoplanet search



LGSAO188 （2006 FL）

Differential polarization/spectral imaging modes

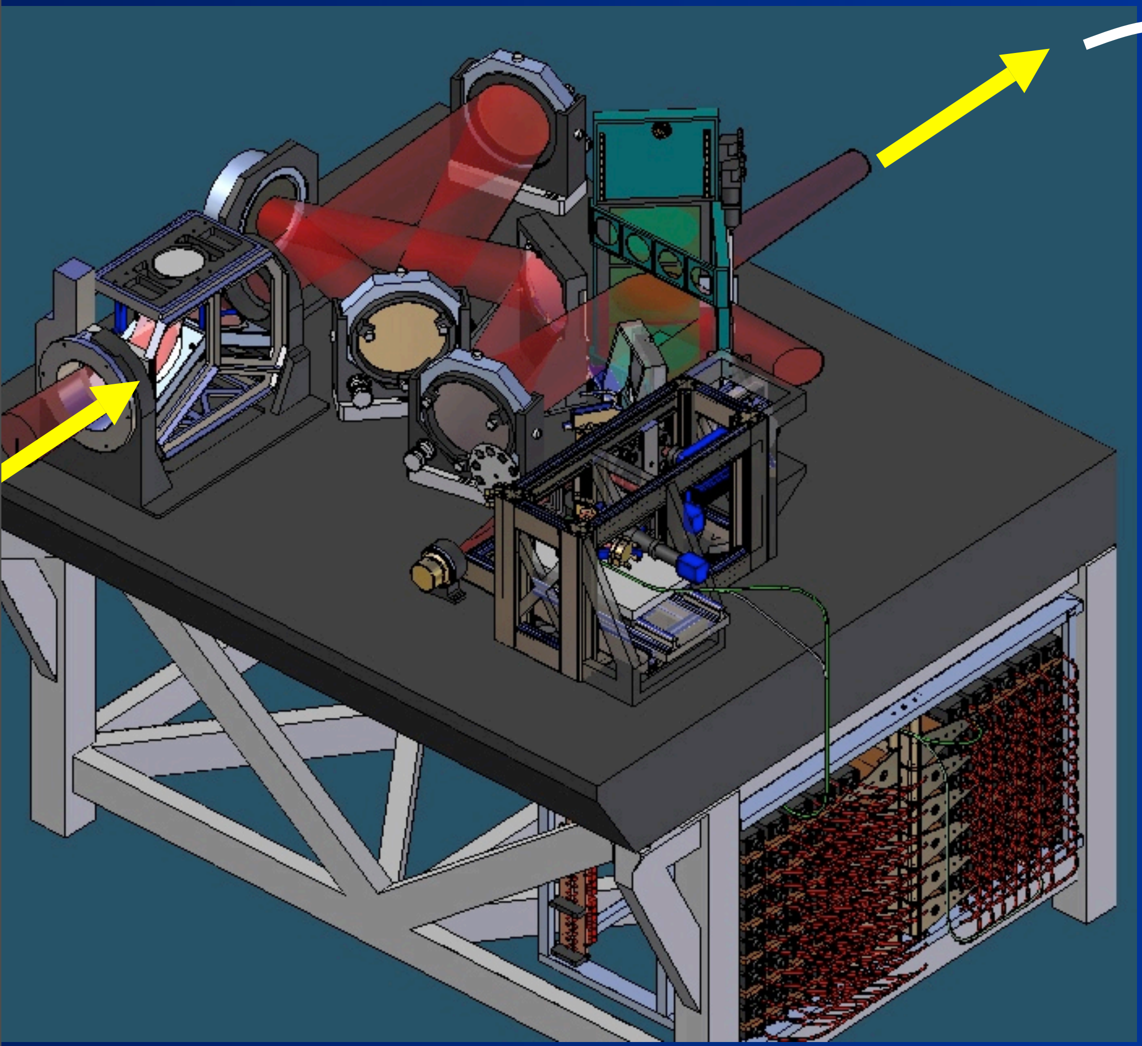


HiCIAO （2007 FL）

2048x2048 Hawaii array

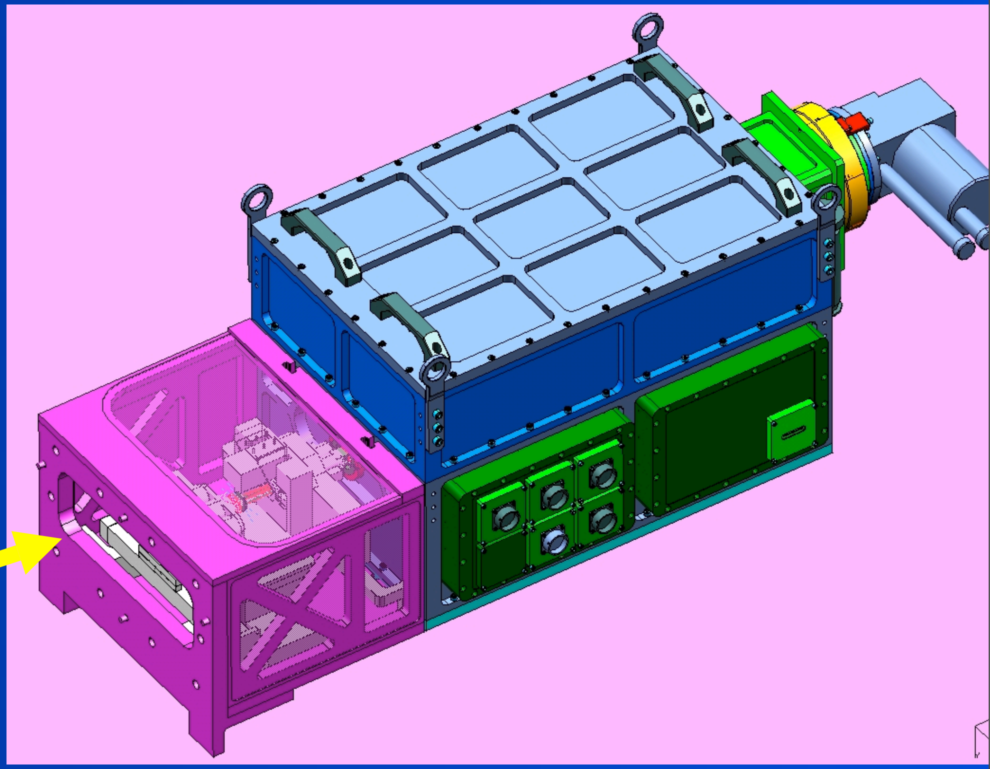
Warm optics, SDI mode, Coronagraph, Easy upgrade

LGSAO+HiCIAO (2008~)
Exoplanet search



PIAA
Coronagraph
+
MEMS 32^2
focal plane
WFS

2009



HiCIAO　（2007 FL）

LGSAO188　（2006 FL）

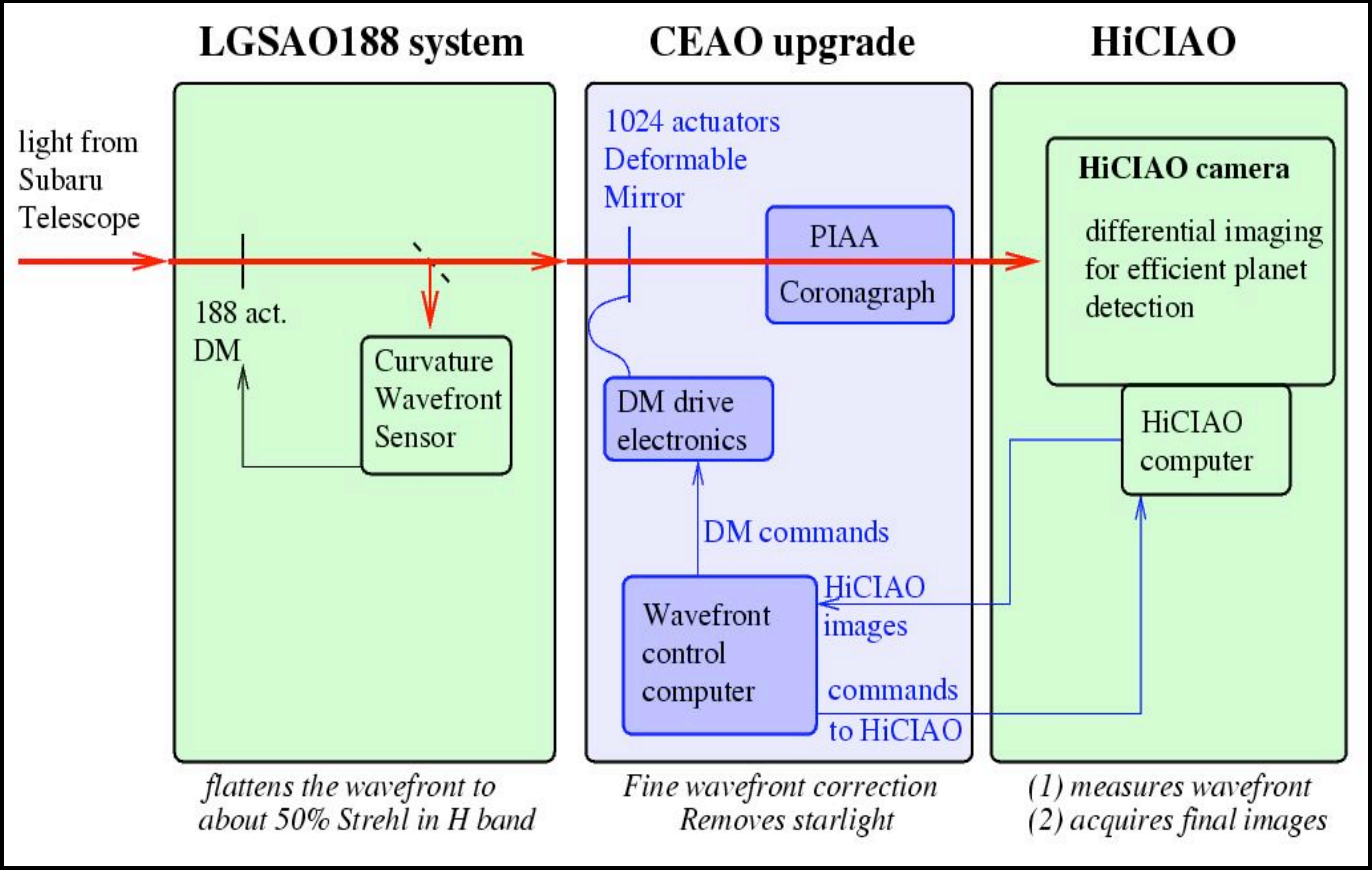
Differential polarization/spectral imaging modes

2048x2048　Hawaii array

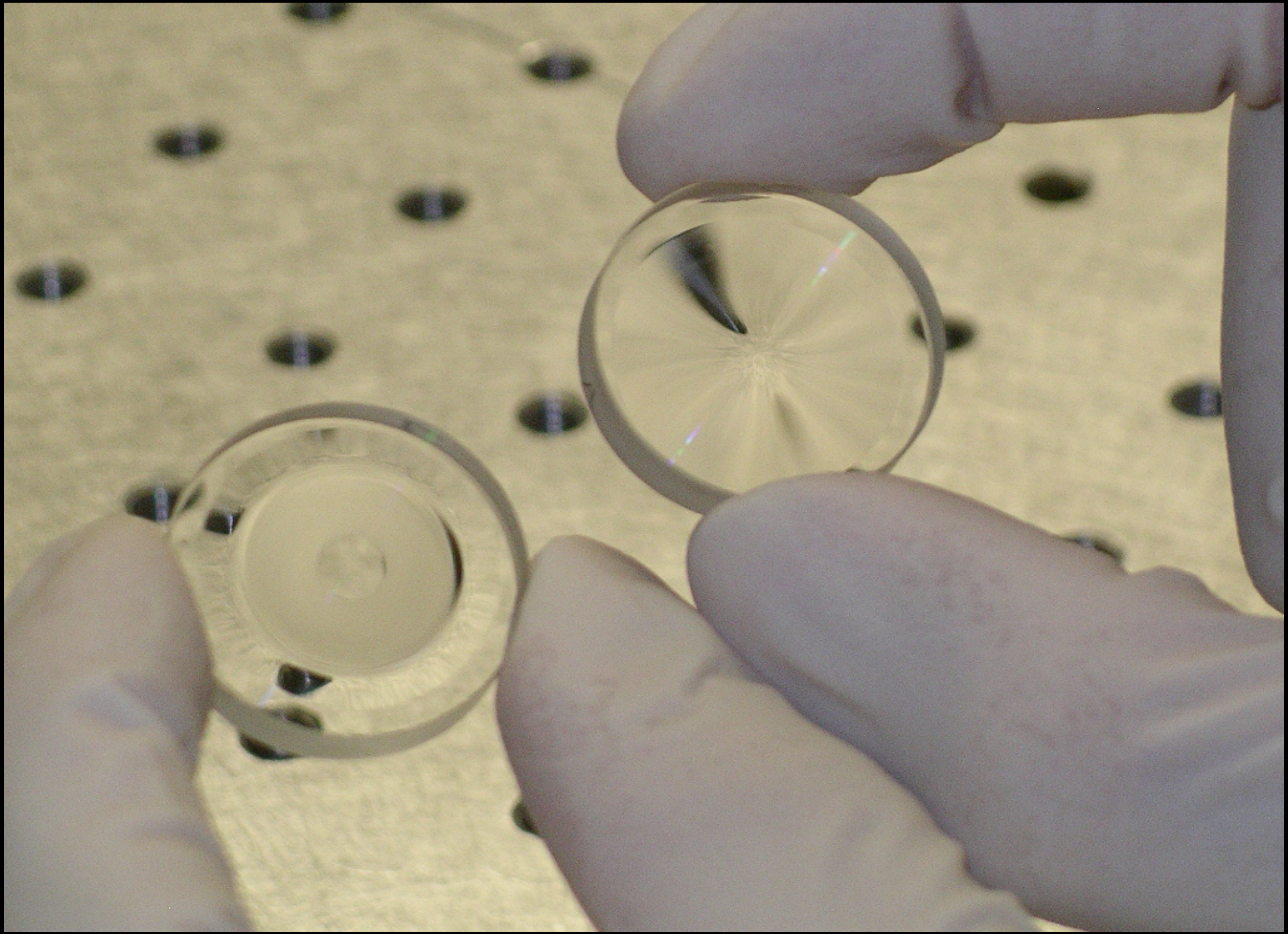
Warm optics, SDI mode, Coronagraph, Easy upgrade

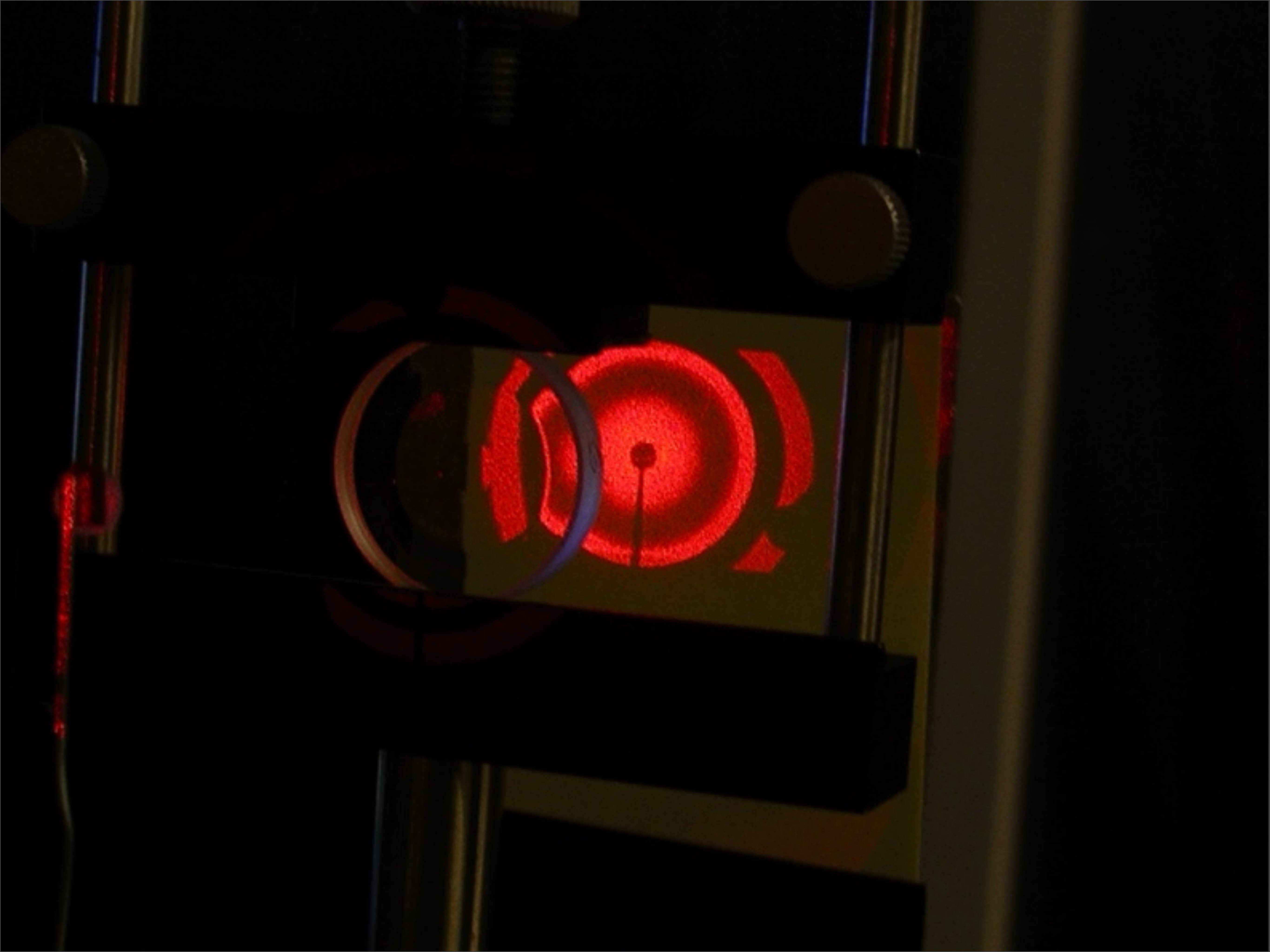
HiCIAO first light (2007)

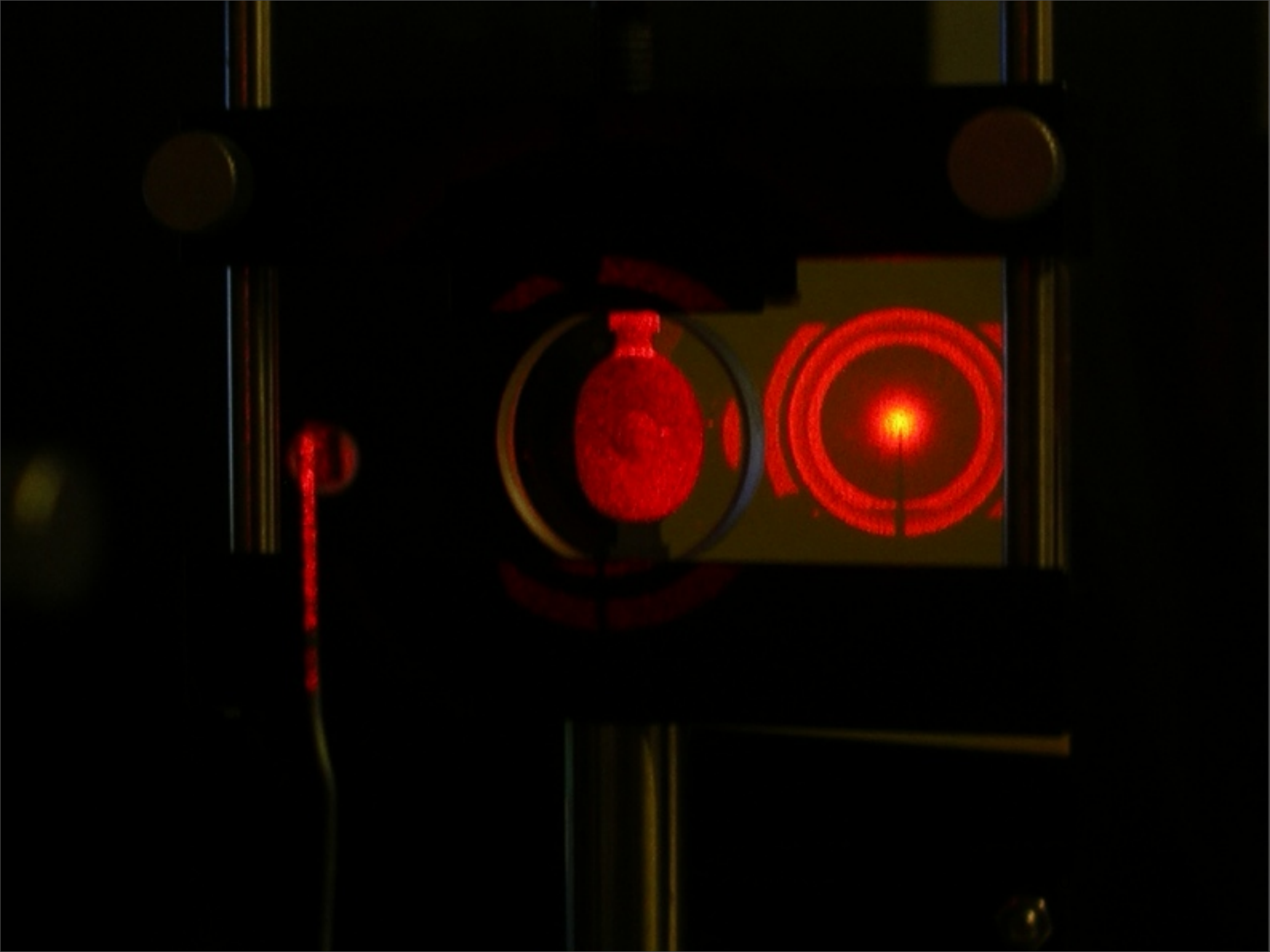
Subaru Telescope
Coronagraphic ExAO system architecture



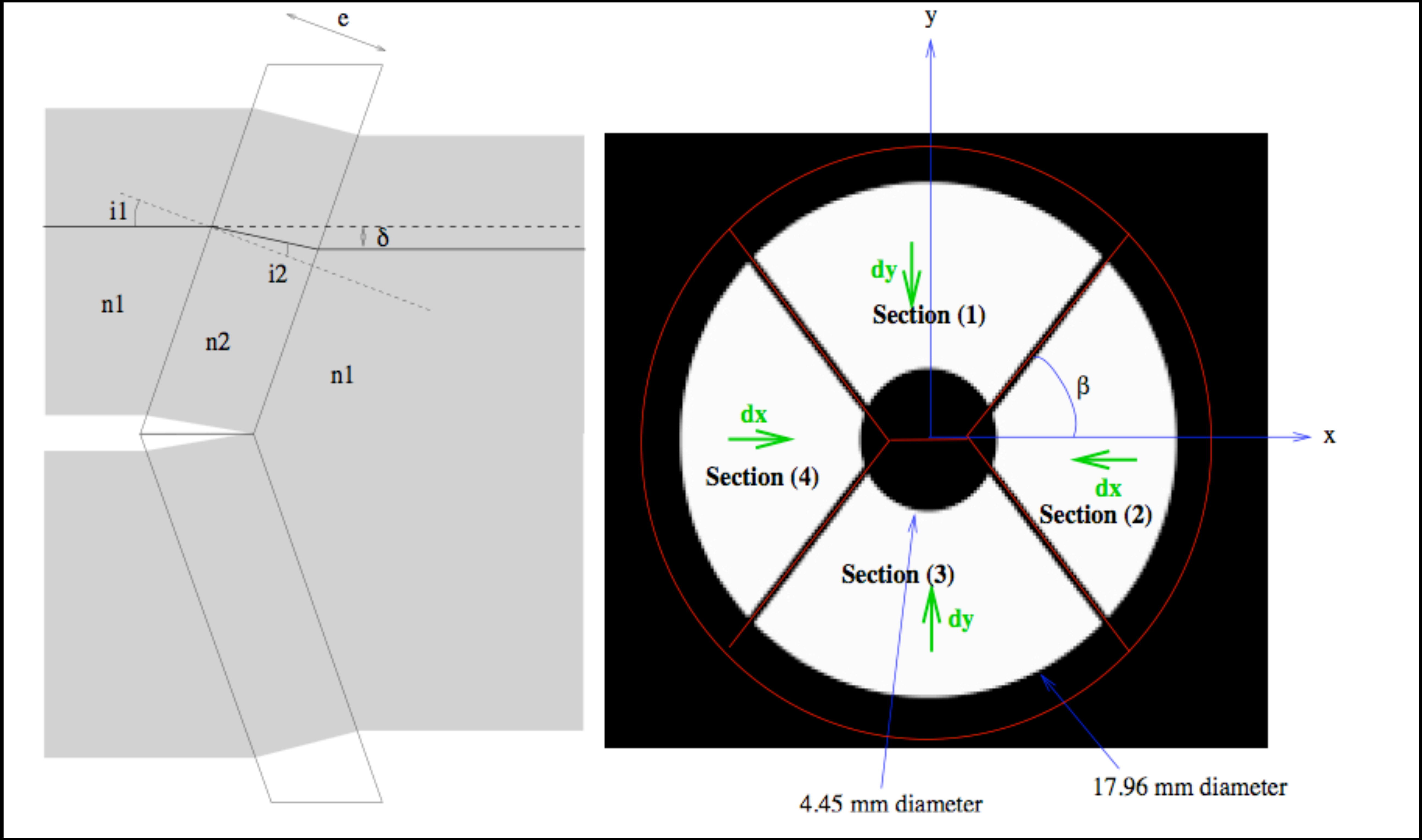
Subaru PIAA optics



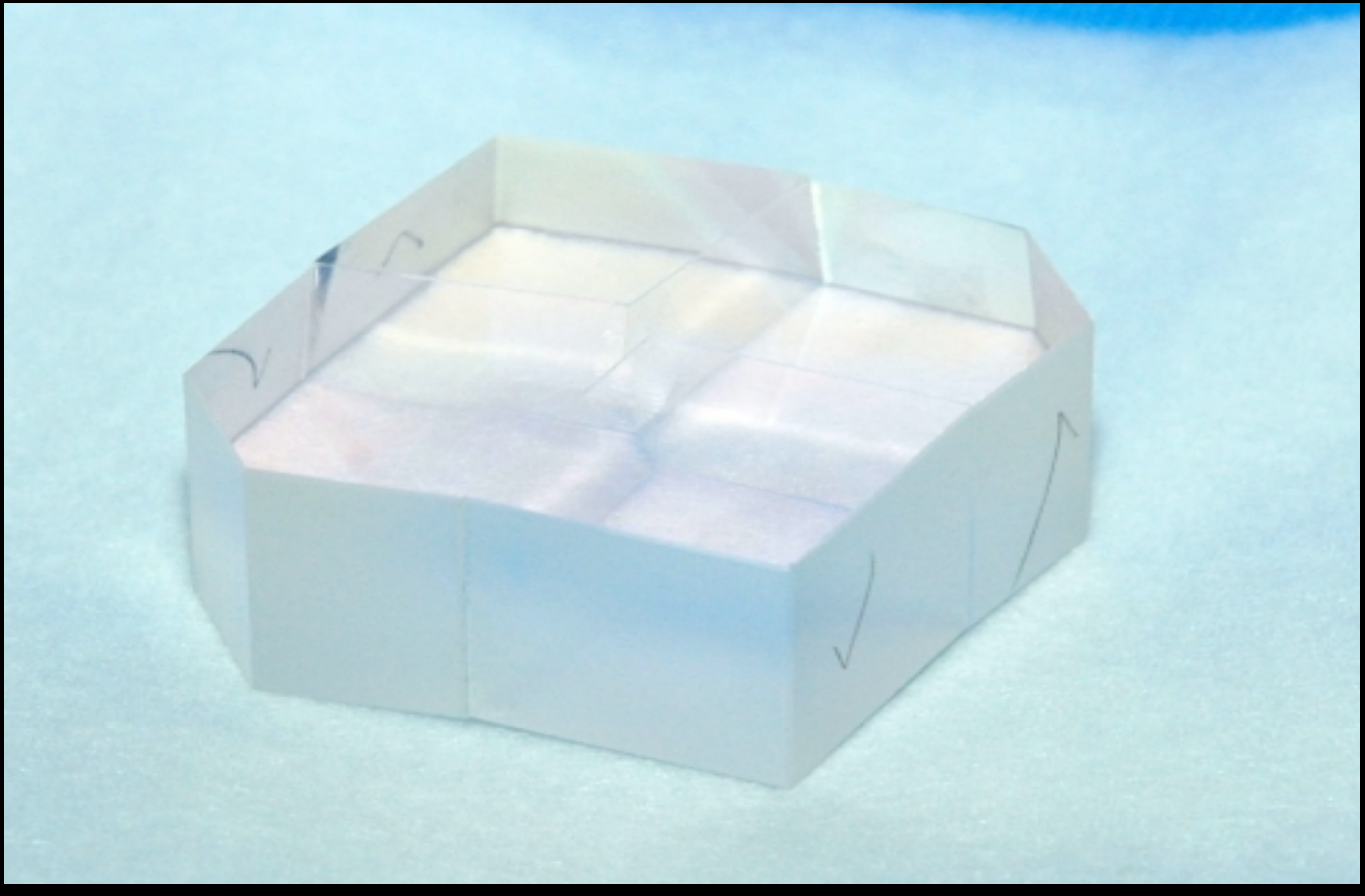




Spider Removal Plate



Spider Removal Plate (SRP)



Subaru Coronagraphic Extreme-AO system

2008 (NOW):

- Curvature system, 188 actuators, 2kHz, ~50% SR in H on bright stars
- Lyot type coronagraph, ~2.5 l/D IWA
- Differential imaging camera, 4 channels, Hawaii 2RG, ASIC, spectral/polarimatric differential imaging

2009 - HiCIAO upgrade / step 1 (Funded, under construction)

Move HiCIAO back, insert optical table with upgrade components, high flexibility

+ PIAA coronagraph (1 l/D IWA)
+ Spider Removal Plate
+ 1024 actuators MEMs DM for slow focal plane AO
(+ Low order WFS)

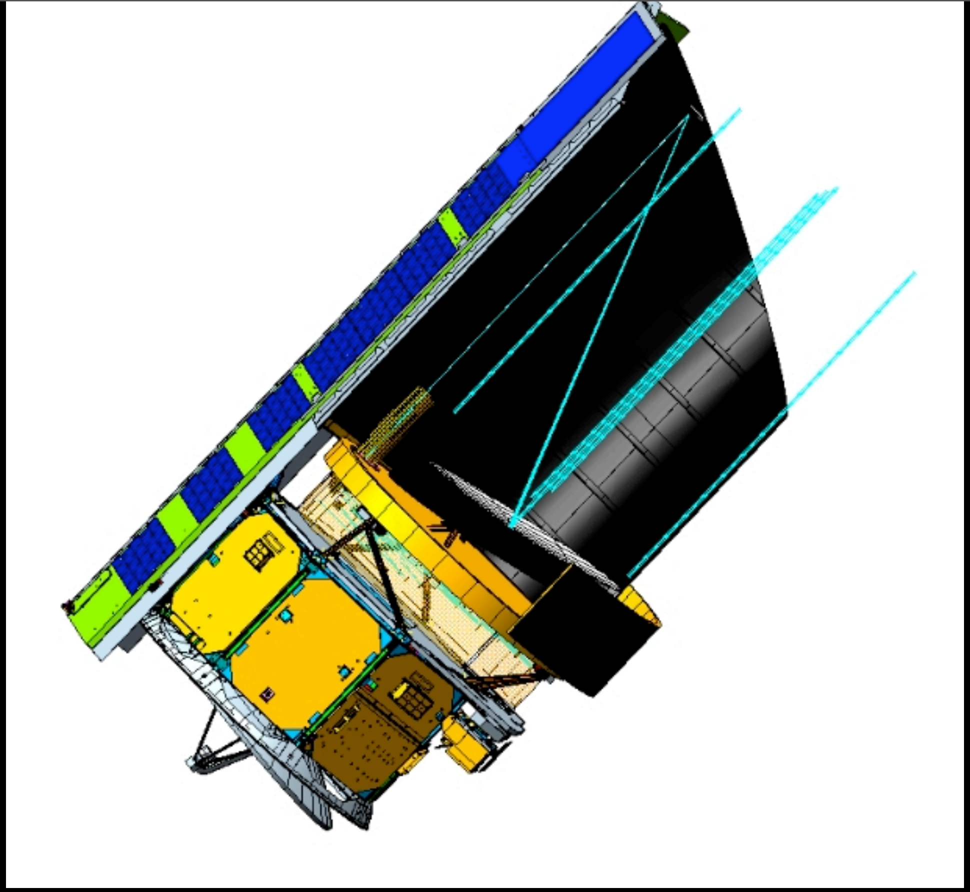
Future upgrades (not funded yet)

+ faster focal plane WFS
+ visible (~0.8 micron) high performance non-linear WFS
+ upgrade to 64x64 DM
+ IFU (Princeton University)
+ visible (Ex)AO system

Imaging exoplanets from space

TOPS overview

High contrast coronagraphic imaging of the immediate environment of nearby stars

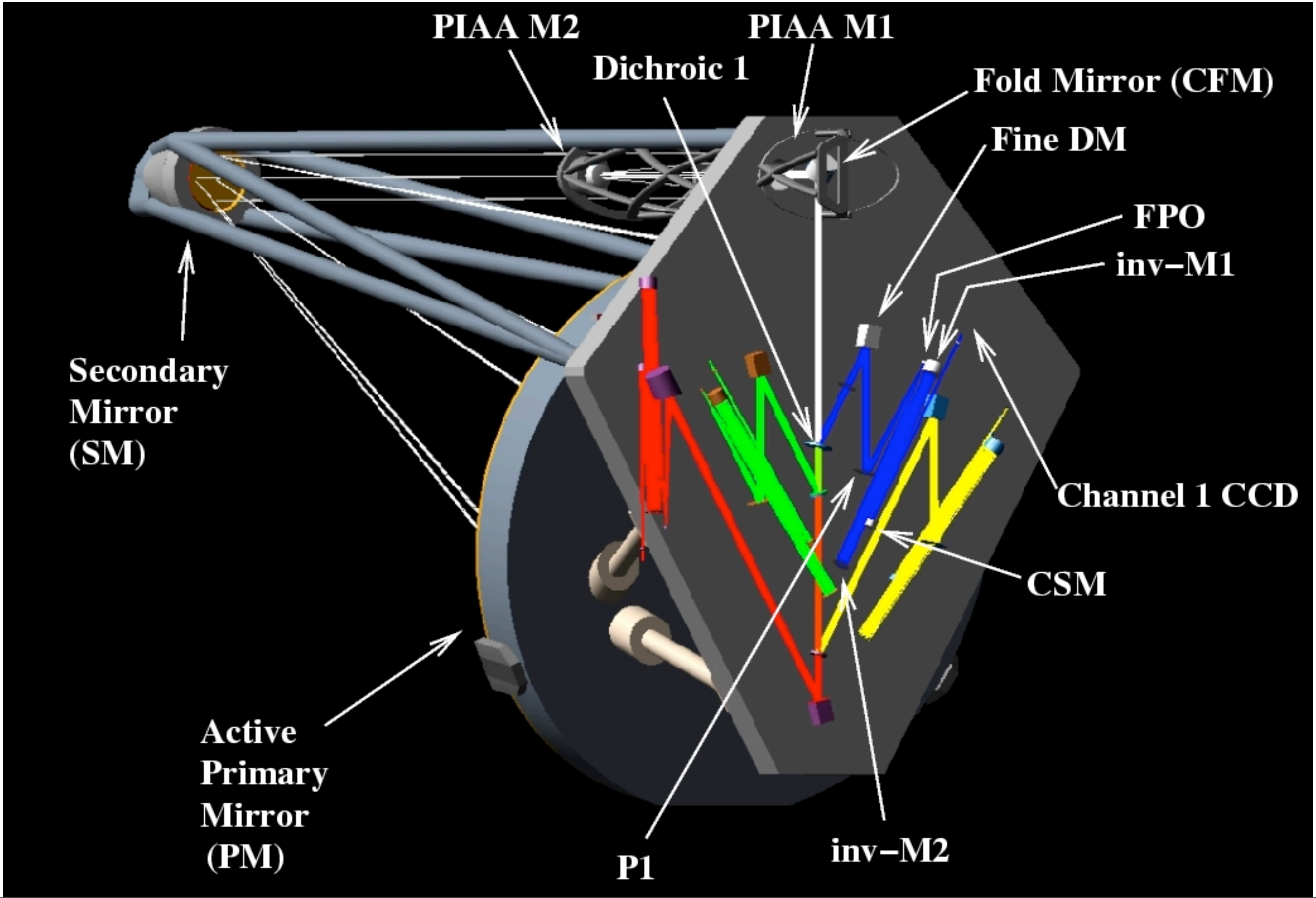


Originally proposed as a DISCOVERY-class mission:

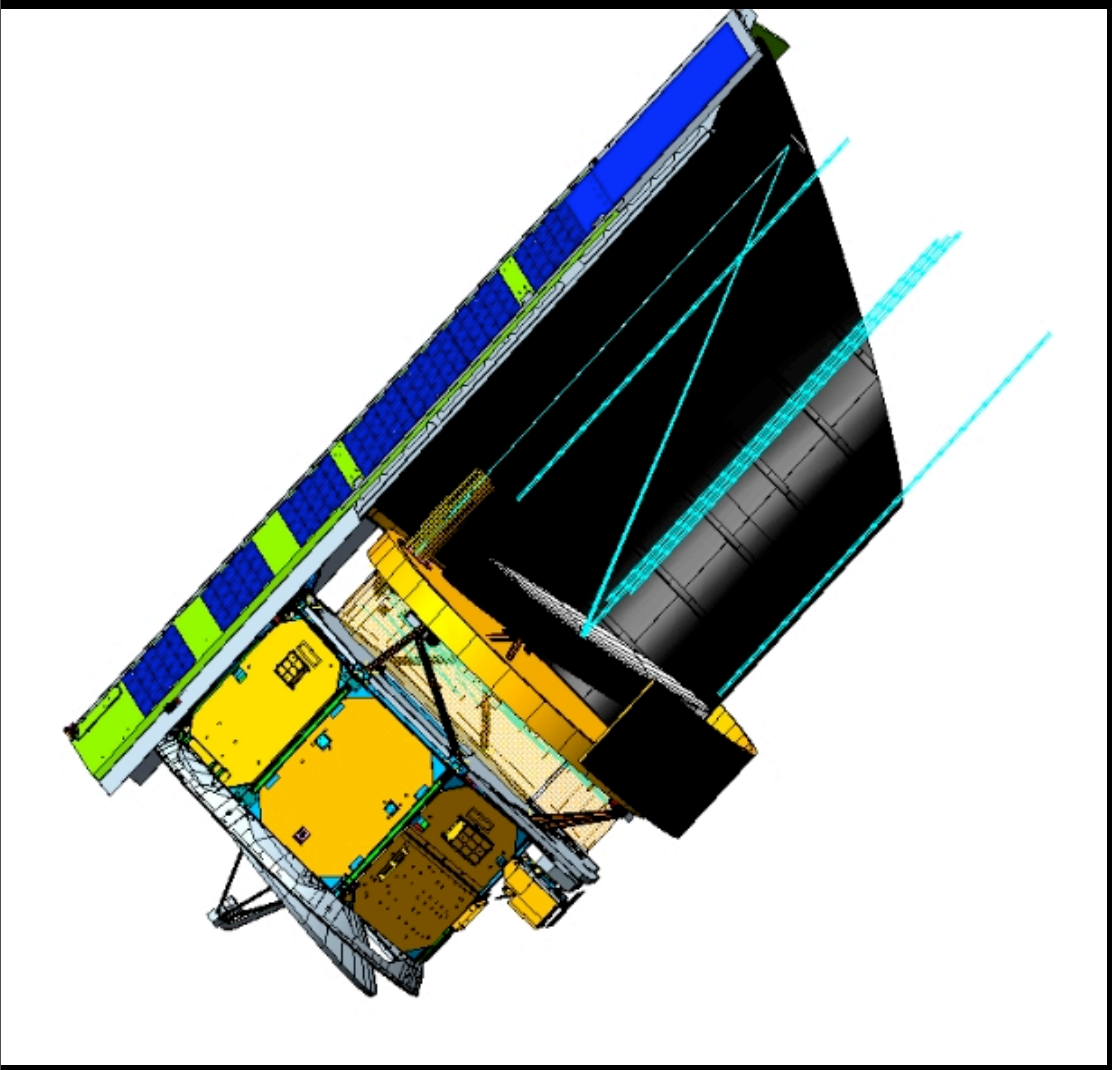
- 1.2m diameter off-axis telescope -> **If sized at ~2m, can detect & characterize Exo-Earths**
- 0.4 - 0.9 micron spectral coverage / R~20
- High contrast coronagraphic imaging of a narrow field of view with **efficient PIAA coronagraph**
- Active primary mirror -> thermal actuation
- Efficient wavefront control scheme
- Extremely stable Optical Telescope Assembly (OTA)

Ongoing technology development

TOPS Optical Telescope Assembly



Providing a stable environment for high contrast imaging



Earth-trailing orbit (Spitzer-like)
receding at ~0.11 AU per year
3-year mission baseline
(5-year would be possible)

Disturbance-free payload
OTA "floats" within the spacecraft with no mechanical contact. Electromagnets control OTA position & pointing within spacecraft

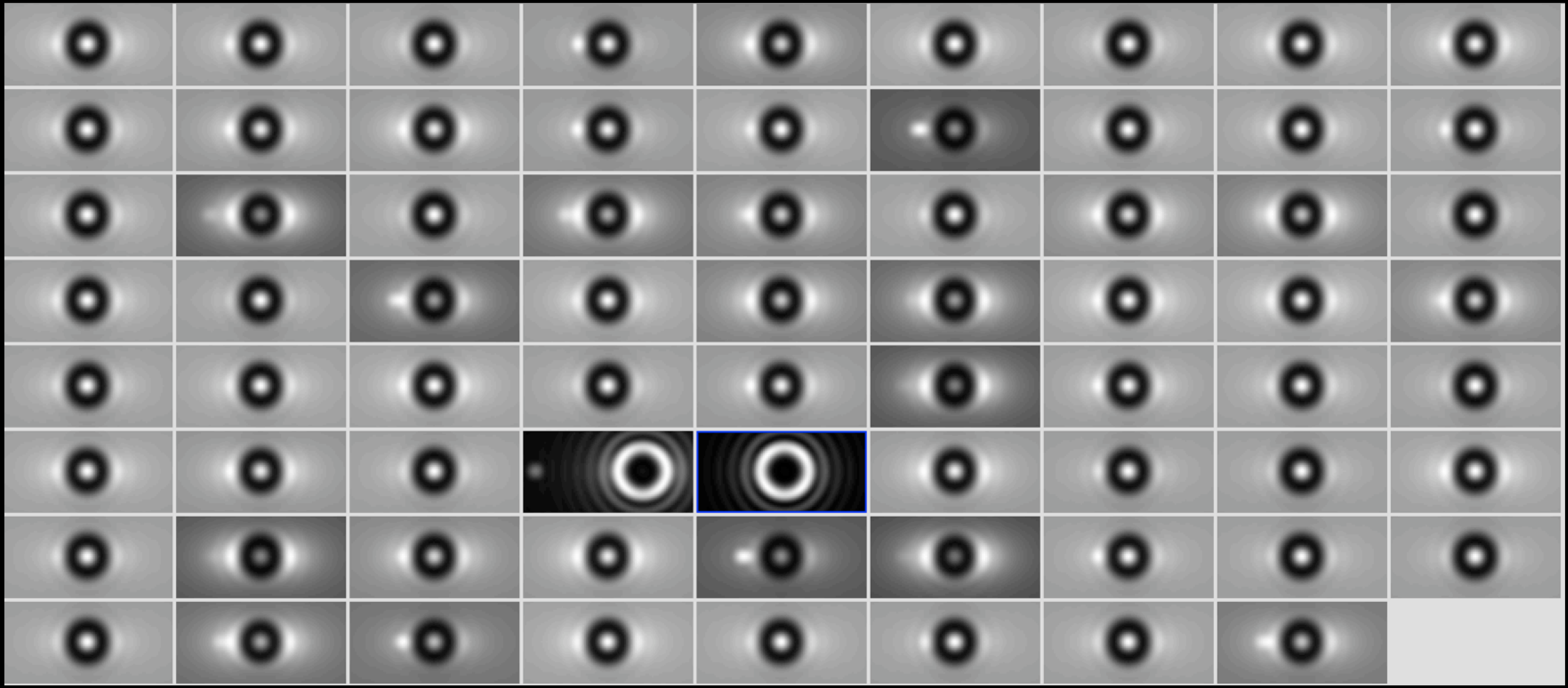
Effective exposure times in 0.5-0.6 micron band

	TOPS (1.2-m)	***PIAA (1.5-m)***	***TOPS2 (2-m)***	***PIAA (3-m)***	***PIAA (4-m)***
#Exo-Earths within 2 l/D	10	23	**67**	212	476
... within 4 l/D	2	2	**6**	23	67
#Exo-Earths, t=1hr	2 / 3	3 / 5	**7 / 16**	24 / 49	51 / 118
#Exo-Earths, t=10hr	3 / 7	7 / 17	**22 / 40**	65 / 147	172 / 299
Approximate cost	~$1B		~$2B	~$??B	

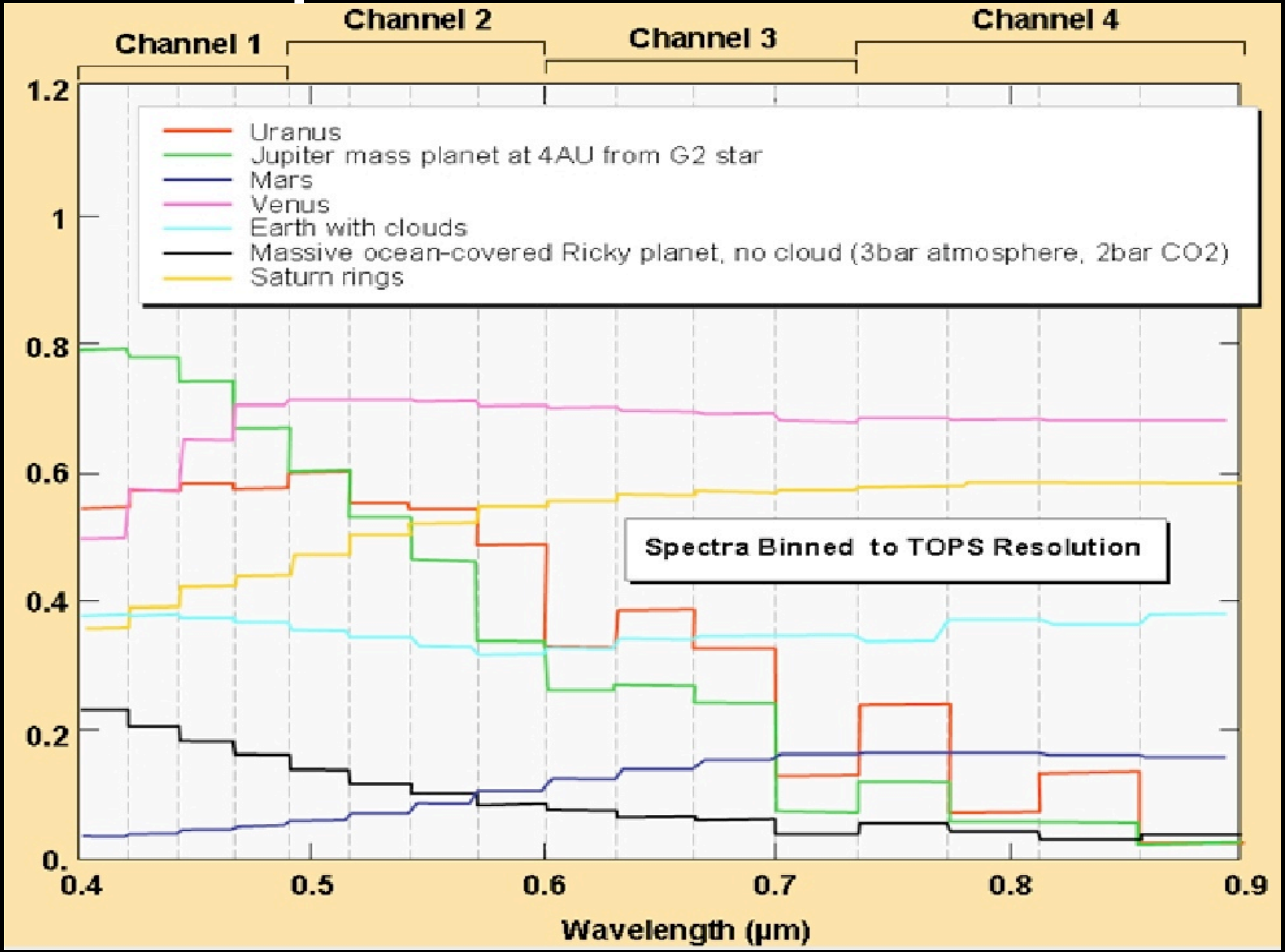
Notes: Rows 3 and 4 list the number of Exo-Earths which would be detected at SNR=7 with respectively 1hr and 10 hr effective exposure times. Two numbers are given: the small number requires a 50% detection probability for a single observation; for the larger number, a 20% detection probability per observation is required. Alpha Cent A and B are included in this table, but may not be suitable targets due to their duplicity and the fact that Exo-Earths might lie beyond the Outer Working Angle of the instrument. If they are to be excluded, each number in this table should be reduced by two.
Costs estimates given in the table do not include the completion and operation of our 1-m PIAA telescope test-bed, required to bring up the TRL of key technologies.

50 % WFC overhead
50 % mission overhead
20 % Quantum Efficiency
x 6 observations

2 yr mission time
-> 260 hr effective time available
40 targets @ > 74% detection
or 22 targets @ > 98.5% detection

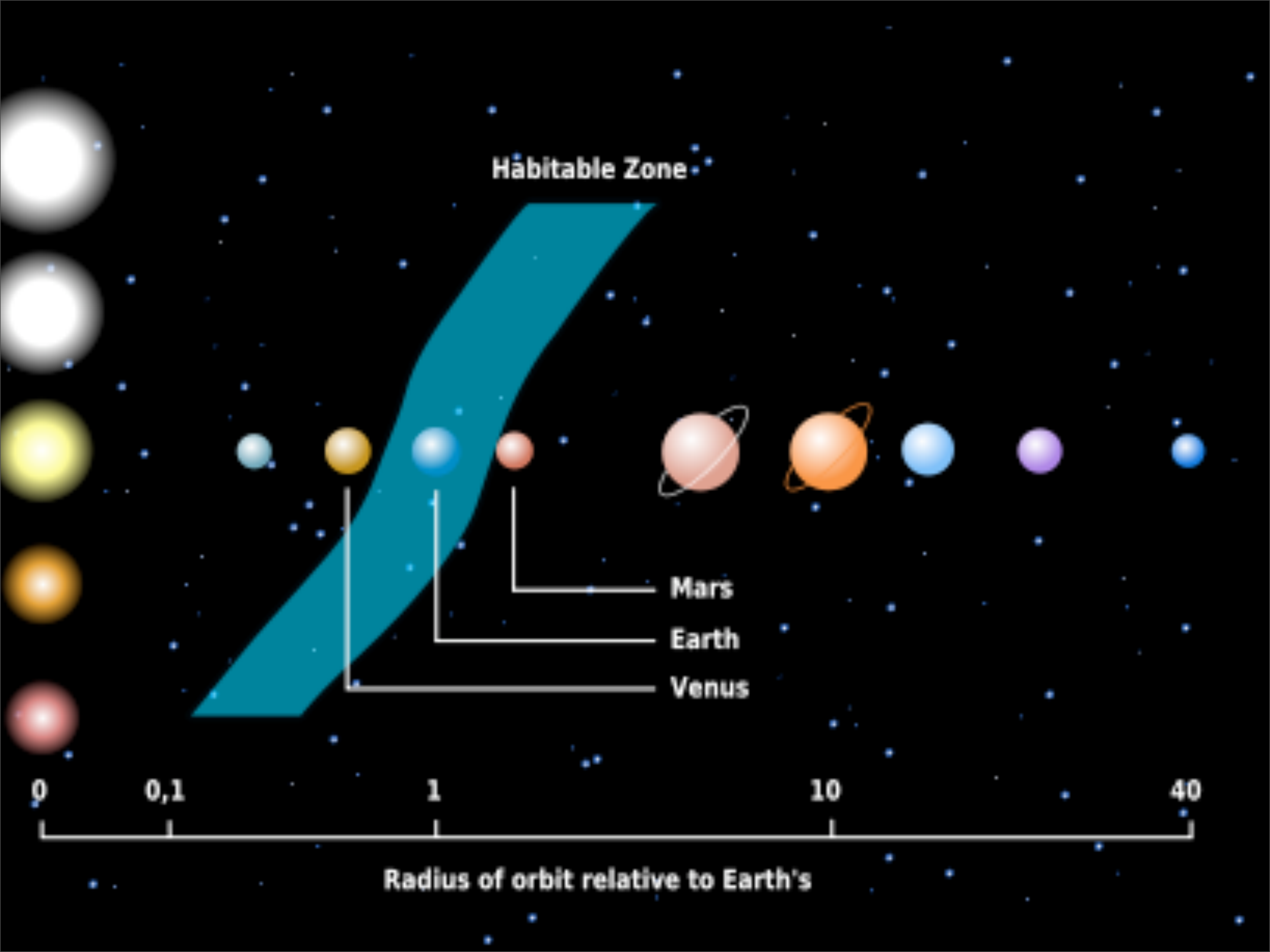


Planet characterization with TOPS 16 spectral channels

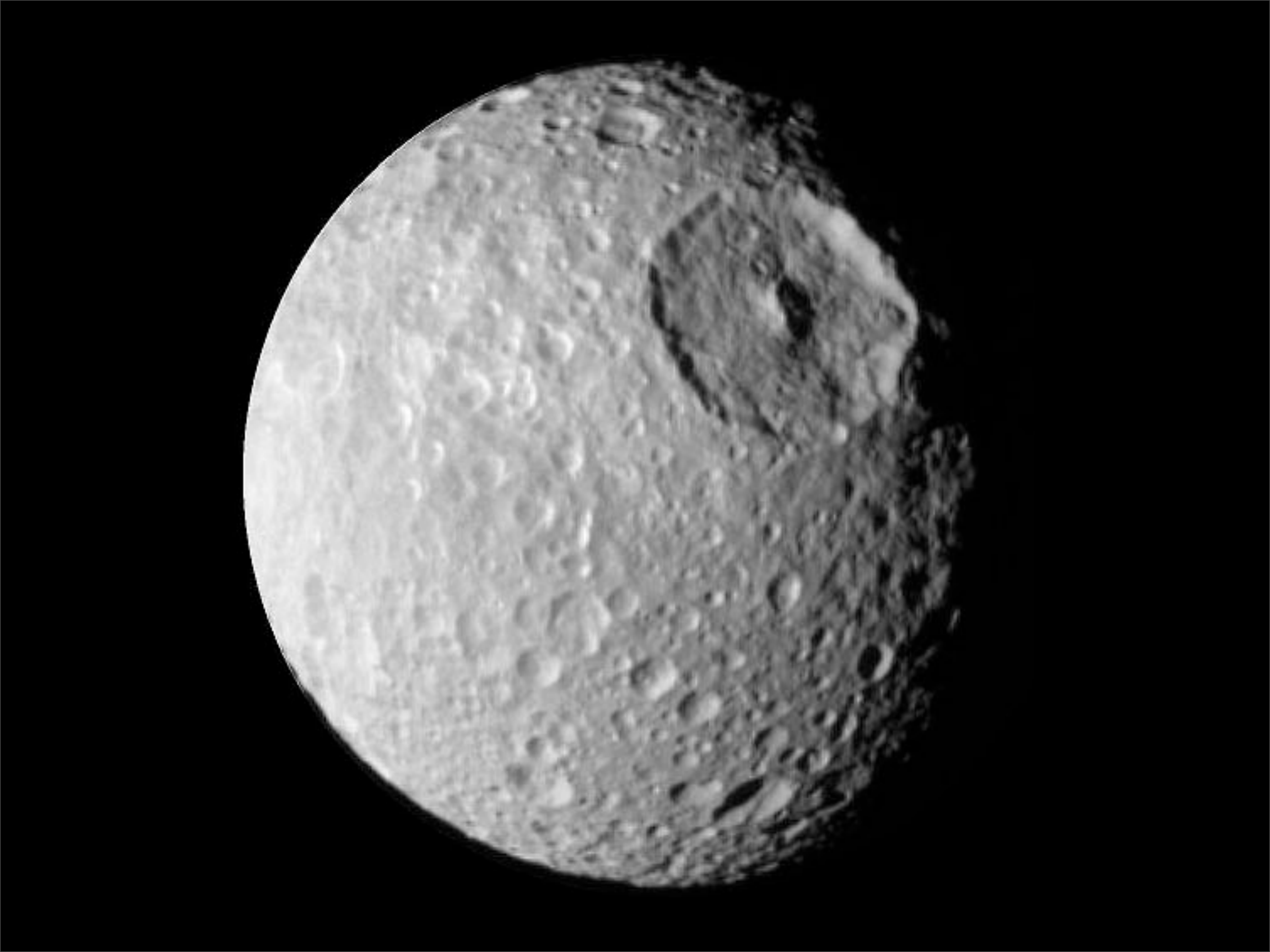


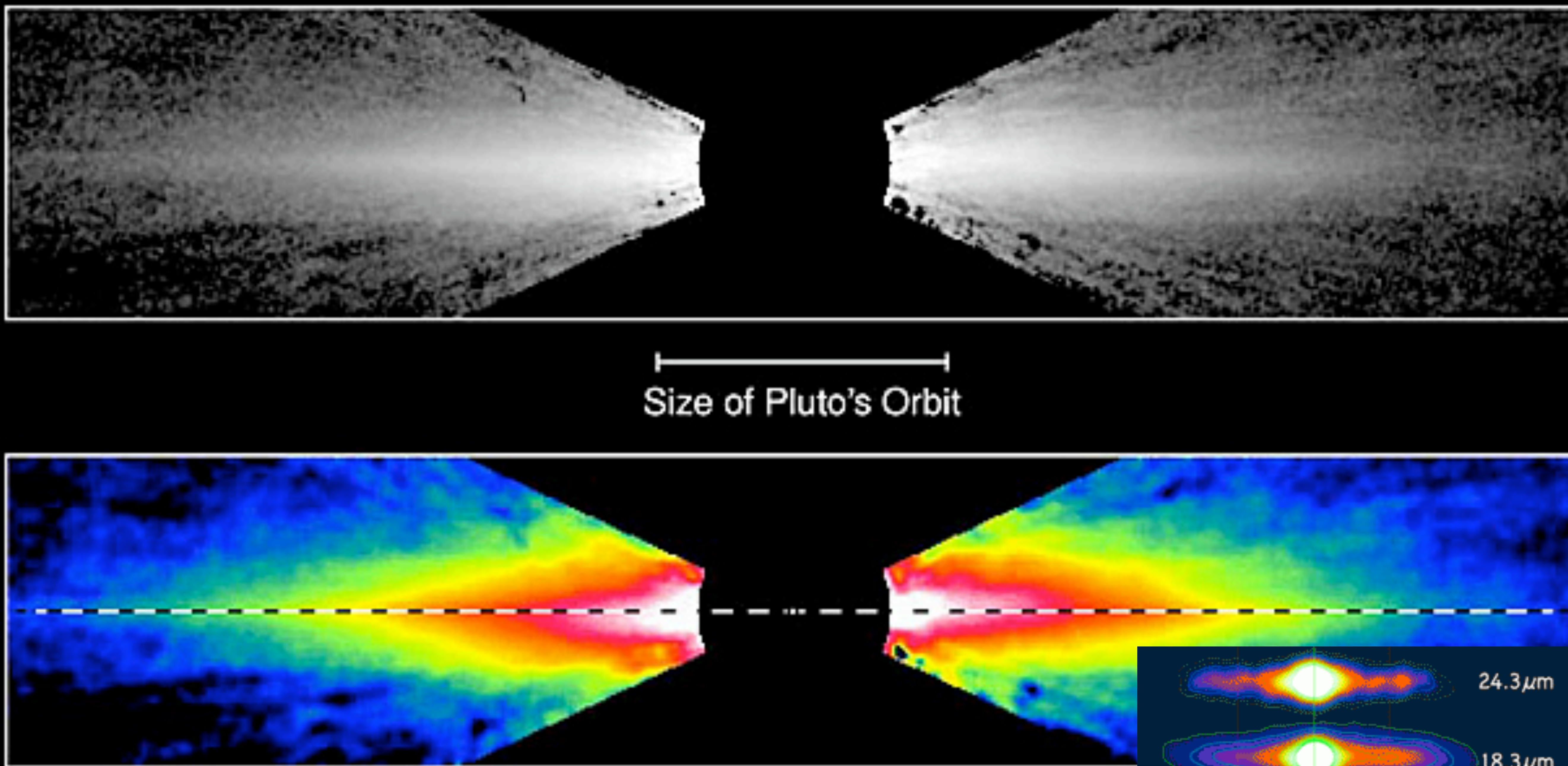
Backup slides

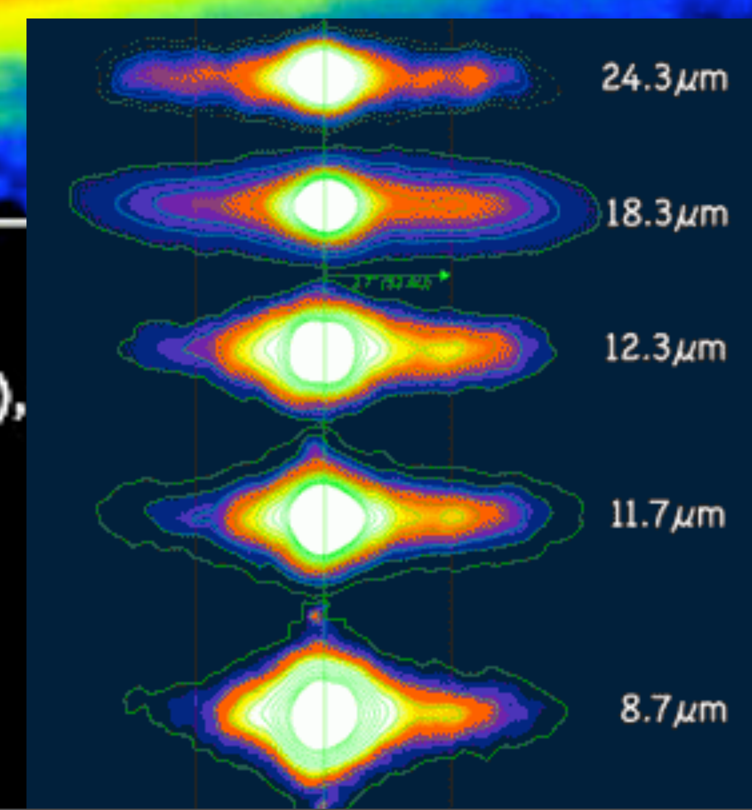
Life on other planets ?



Habitable Zone
Mars
Earth
Venus
0
0,1
1
10
40
Radius of orbit relative to Earth's







Warped Disk · Beta Pictoris

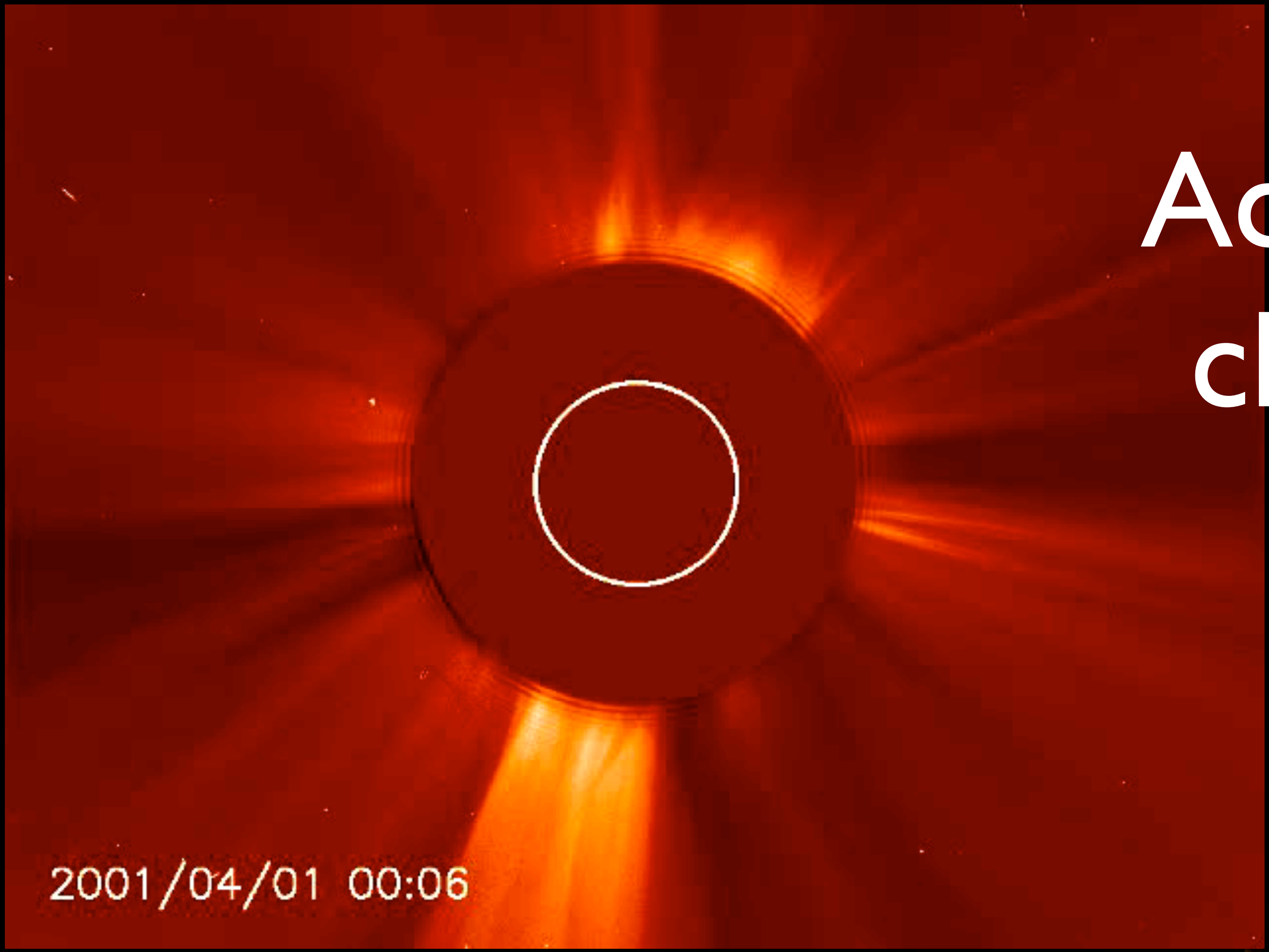
PRC96-02 · ST ScI OPO · January 17, 1995 · C. Burrows and J. Krist (ST ScI),

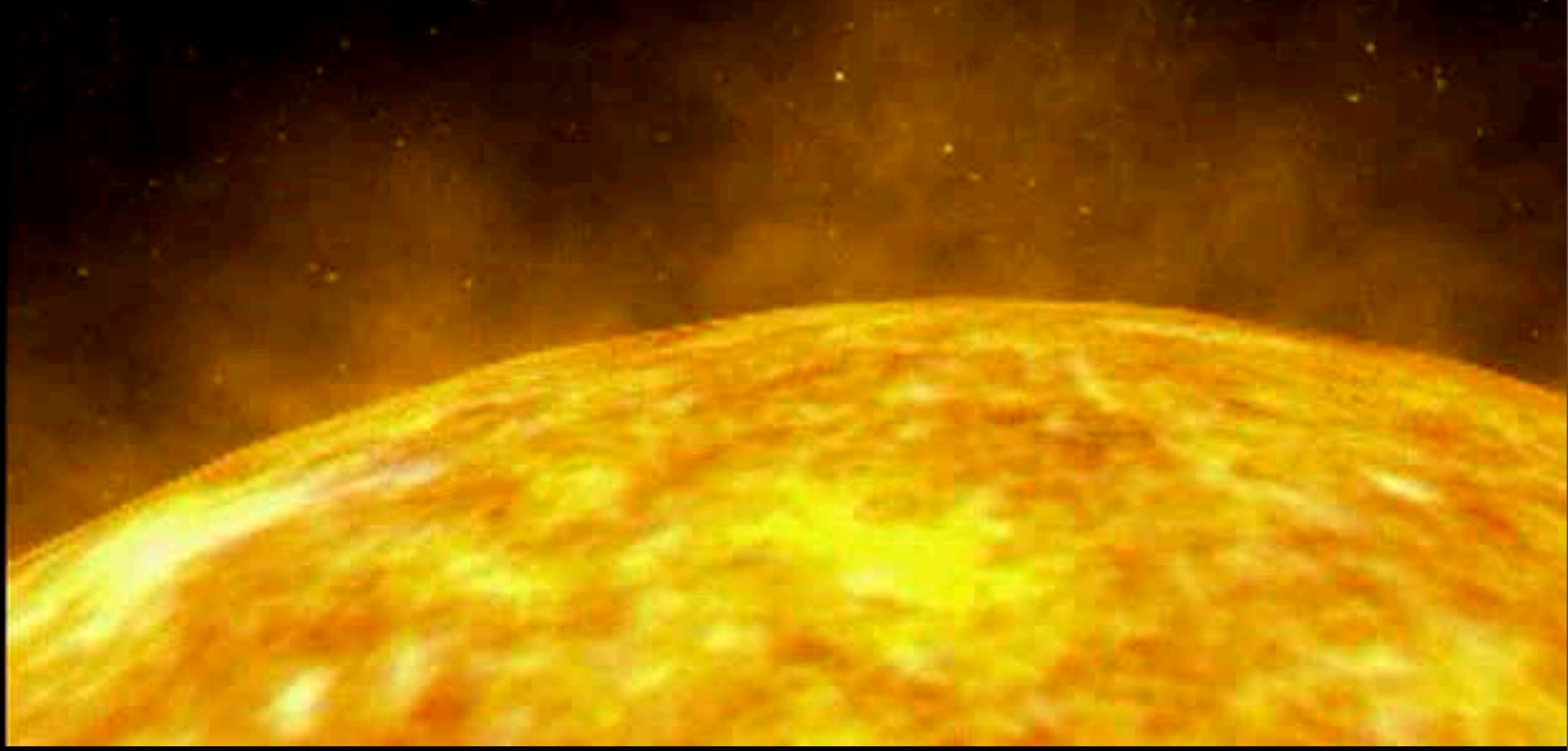

Image by Tony or Daphne Hallas

Star/planet interactions

Active stars are a challenge for life

Active stars are a challenge for life



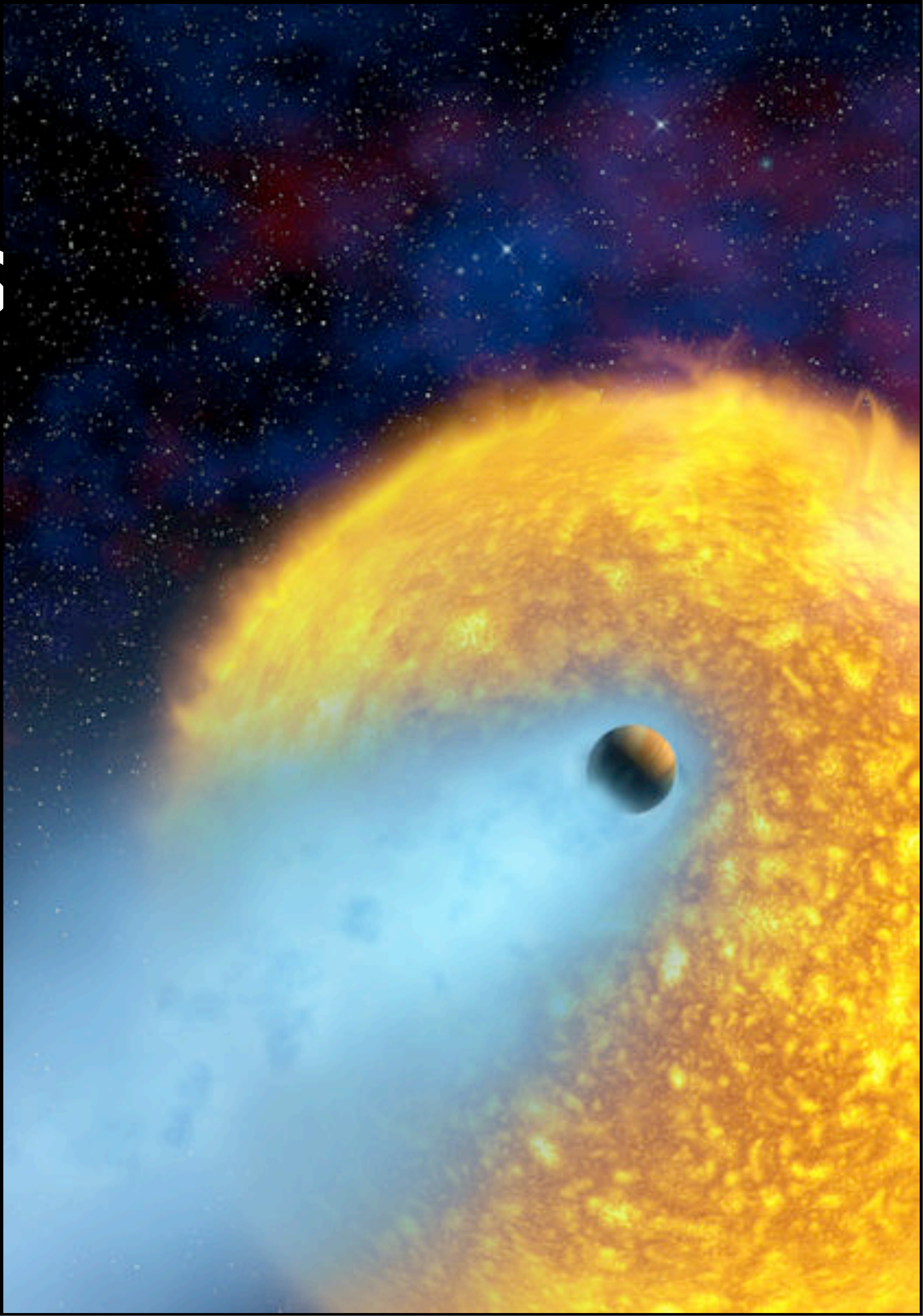


Planetary atmospheres blown away

HD209458b ---------->

Planet magnetic field

offers protection



<u>When</u> is a planet habitable ?

- Too many collisions in the first few 100 Myr
- Stellar activity decreases with time -> challenge for life around young stars
- Stars get brighter with time -> HZ moves out !

  We have ~400 Myr left before CO_2 cycle fails to regulate Earth's temperature

- Magnetic field is a good thing, but WILL "freeze away" with time

Water...

Mars & Venus lost their oceans

H2O -> Hydrogen + Oxygen

Oxygen oxydizes rocks (Mars is red), Hydrogen escapes in space

Why not Earth ??? Right size, right spot.

~2 billion years ago Oxygen concentration went up (bacteria) -> recaptures Hydrogen, stops H2O loss.

Carbon cycle regulates temperature on Earth

- Production:

  Volcanos & direct emission from Earth's crust (~0.5 Gt/yr)

  Humans burning fossil fuels (~6 Gt/yr)

- Removal (depletion in 10 000 yrs for atmosphere, 500 000 yrs for atm+oceans):

  Silicate wheathering

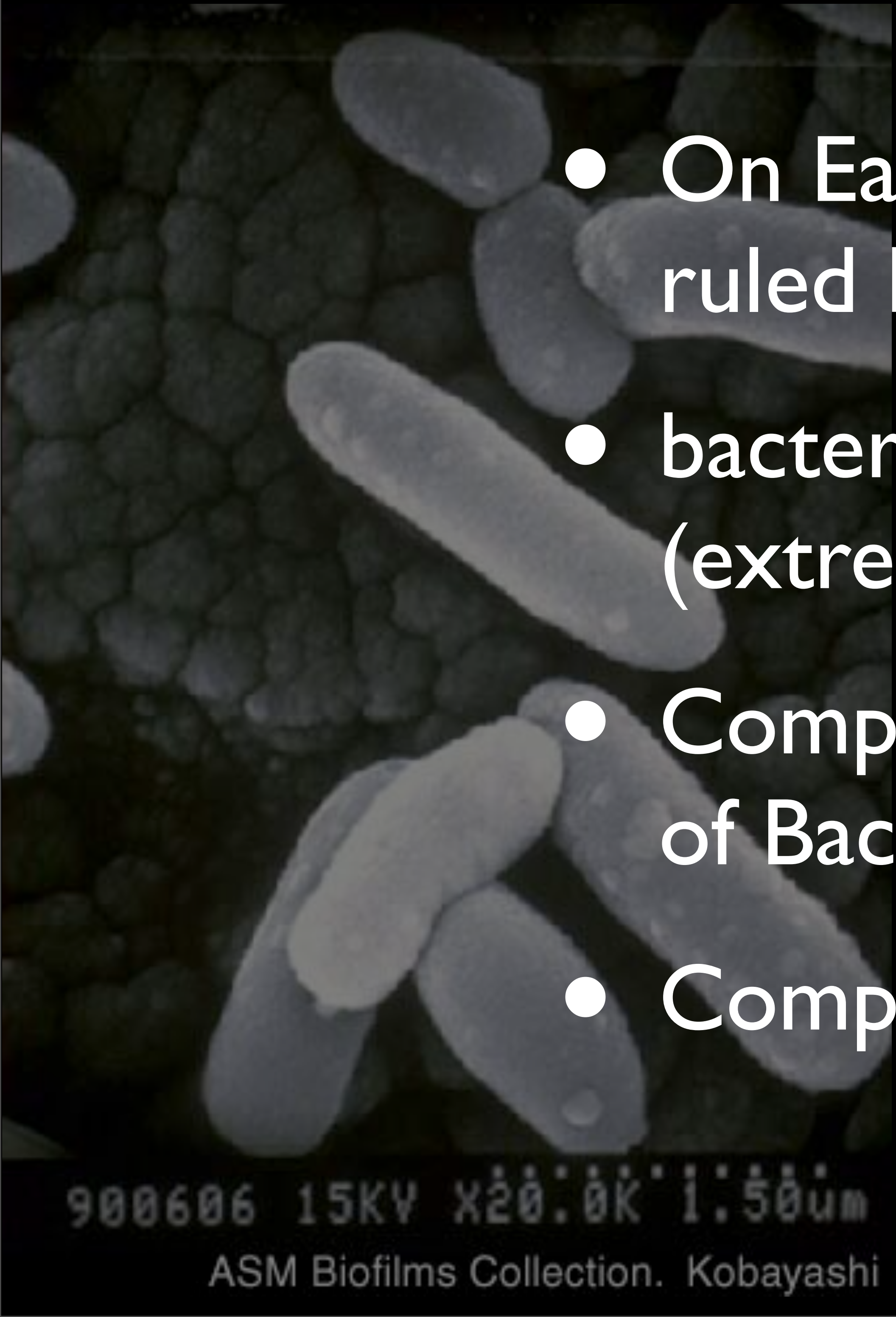
  Carbonate deposition

  Burial of organic matter

Are planets geared towards life?

- Lab experiments have produced, “from scratch”:
  - All 20 amino acids found in living organisms
  - Complex sugars
  - Lipids
  - All five bases of DNA and RNA (A,T,G,C,U)
- Comets and meteorites also contain amino acids.
- So the basic ingredients were rapidly available in Earth’s early soil and oceans and are probably present wherever water, soil and energy are present.

What kind of life ?



- On Earth, bacteria got an early start and ruled Earth for the first 2 billion yrs
- bacteria live in many environments (extremophiles)
- Complex life started with unlikely merging of Bacteria + Archaea -> Eukaryote
- Complex life may be rare event ...

How much time needed to have complex life ?

Life on Earth does not evolve at a constant pace

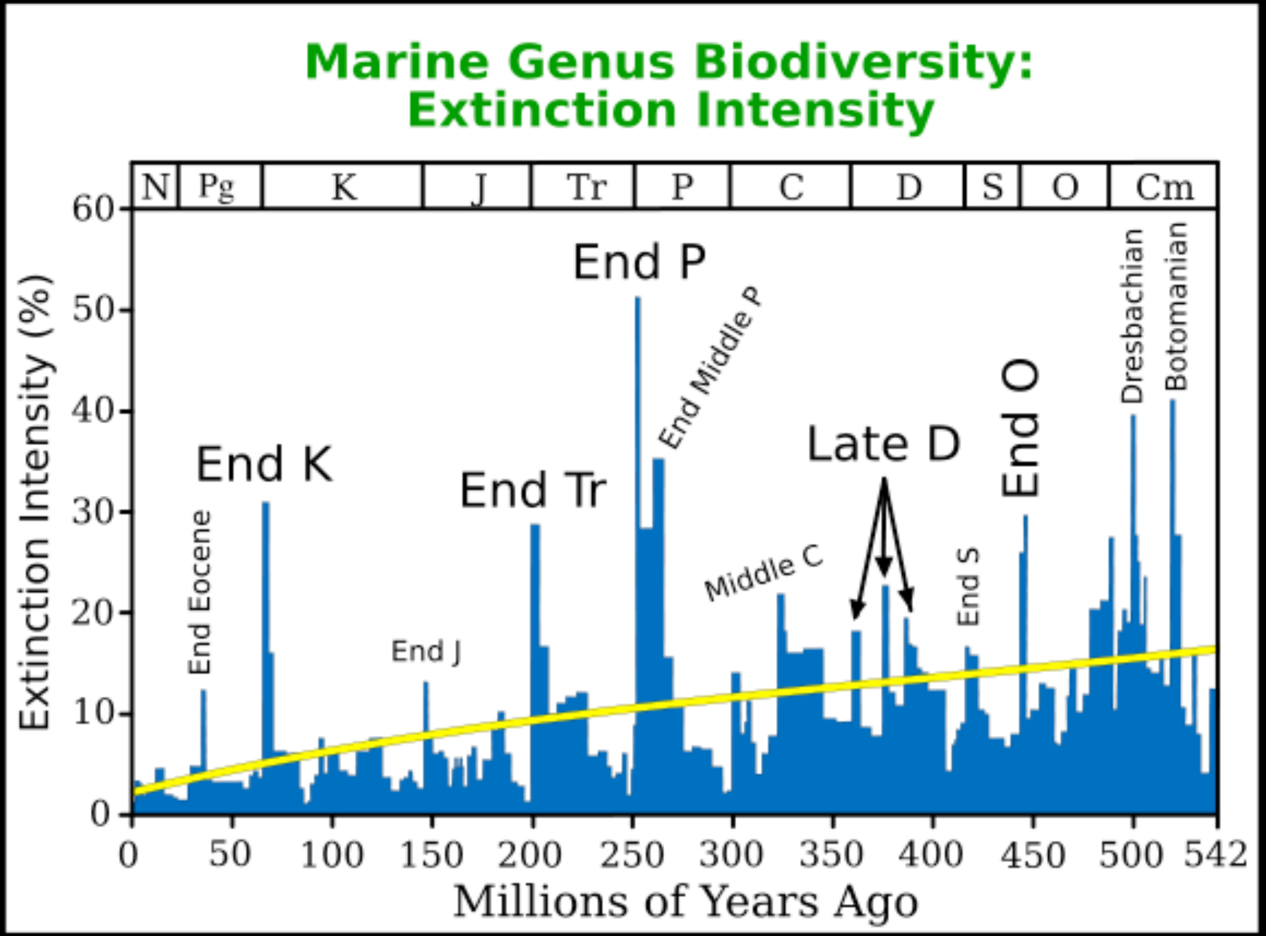
BIG jumps forward :

~2 Gy ago: Eukaryotes appear

560 Myr ago: Cambrian explosion

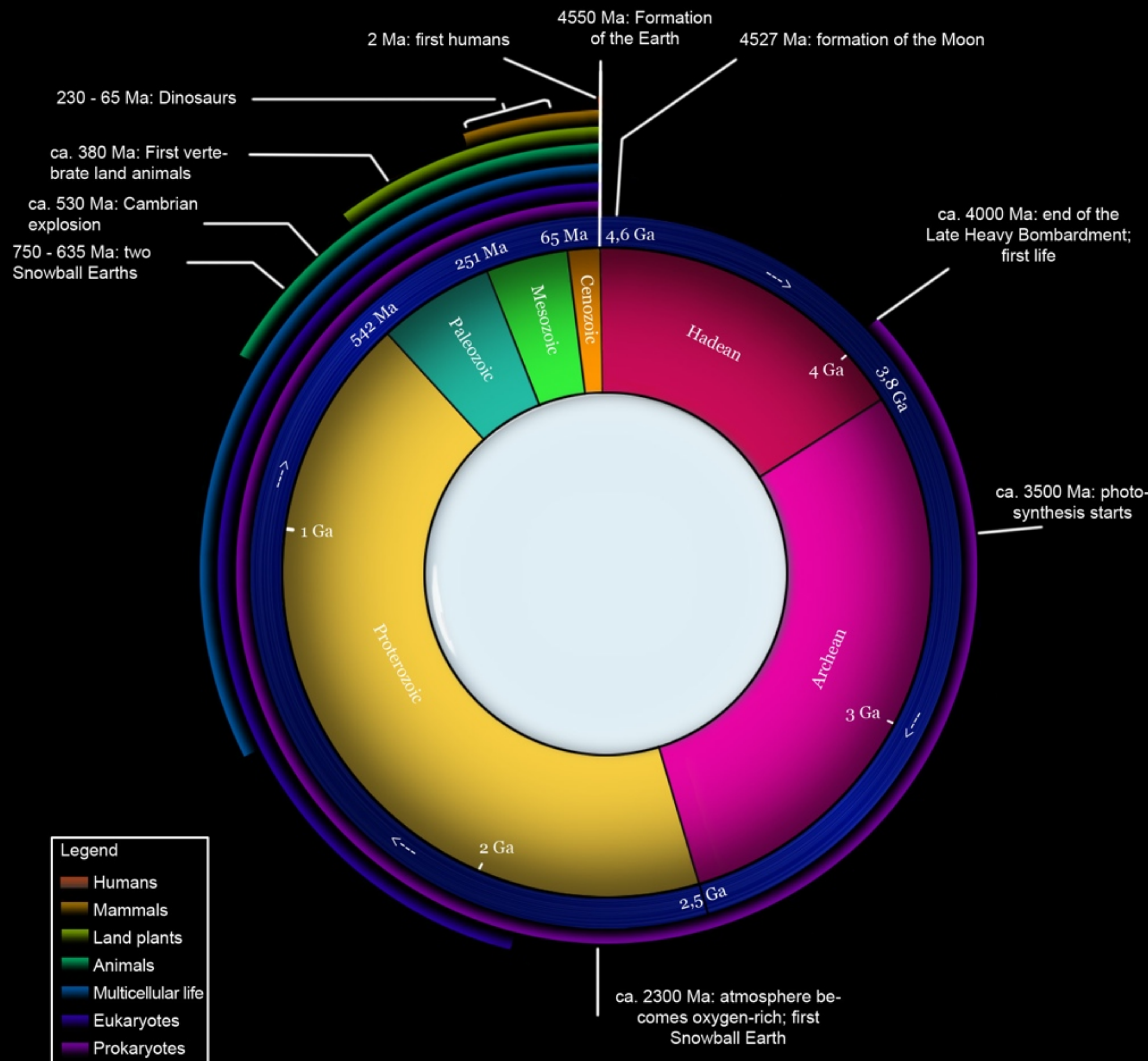
But also...

“Snowball Earth” episodes 2.3 Myr and 790 to 630 Myr ago



Several mass extinctions since Cambrian explosion

(large impact, massive



4550 Ma: Formation of the Earth
2 Ma: first humans
4527 Ma: formation of the Moon
230 - 65 Ma: Dinosaurs
ca. 380 Ma: First vertebrate land animals
ca. 530 Ma: Cambrian explosion
750 - 635 Ma: two Snowball Earths
ca. 4000 Ma: end of the Late Heavy Bombardment; first life
ca. 3500 Ma: photosynthesis starts
ca. 2300 Ma: atmosphere becomes oxygen-rich; first Snowball Earth
65 Ma
4,6 Ga
251 Ma
542 Ma
Cenozoic
Mesozoic
Paleozoic
Hadean
4 Ga
3,8 Ga
Archean
3 Ga
2,5 Ga
2 Ga
Proterozoic
1 Ga
Legend
Humans
Mammals
Land plants
Animals
Multicellular life
Eukaryotes
Prokaryotes

Conclusions

COMPLEX life, AS WE KNOW IT requires special conditions on planet

- simple life forms (bacteria / Archaea) might be much more common

BUT many many "suitable" planets in our galaxy, and many many galaxies... (Drake equation)

Within next decades, we will finally be able to probe for life on exoplanets not too different from Earth