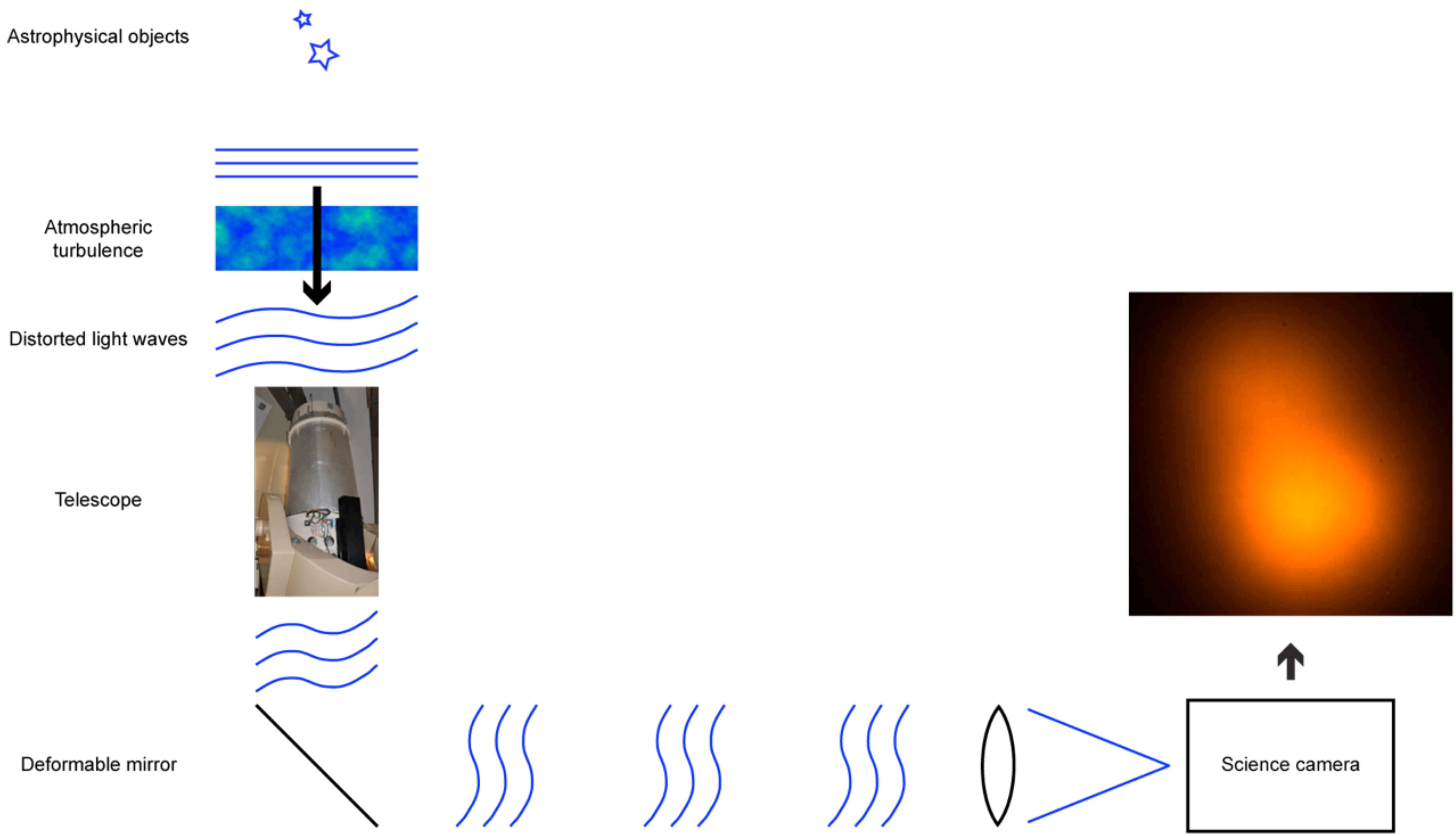
Robotic, Extreme and Beyond:

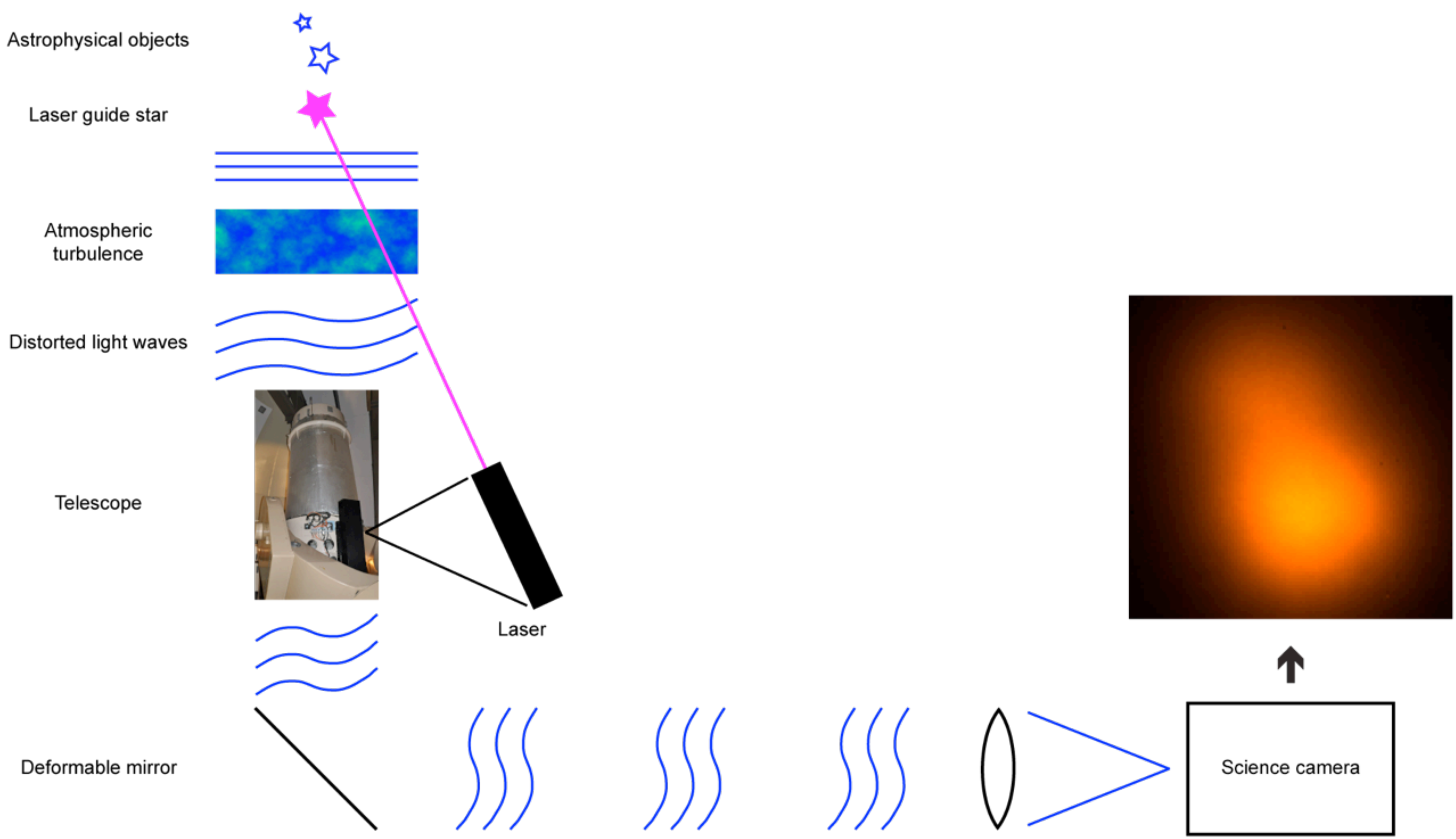
Rayleigh Laser Guide Stars Pioneering the Next Decade of Astronomical Adaptive Optics

Christoph Baranec
Caltech

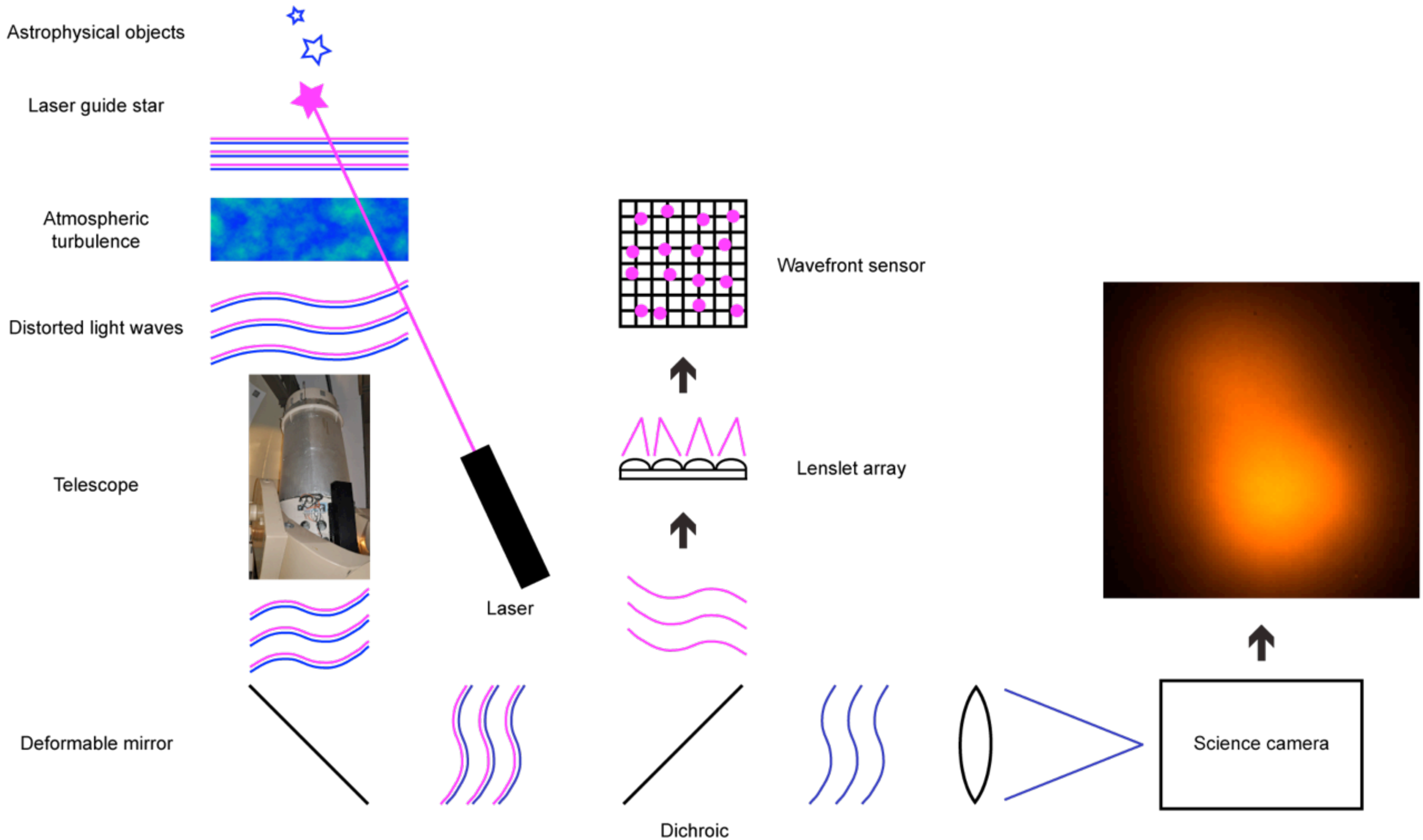
- How does an adaptive optics system work?
- What are laser guide stars?
- Innovative laser adaptive optics architectures:
  - –Robotic: Robo-AO, clones
  - –Extreme: PULSE upgrade to PALM-3000
  - –Beyond (i.e. wide field): MMT, LBT/VLT, ‘Imaka

Adaptive optics refresher

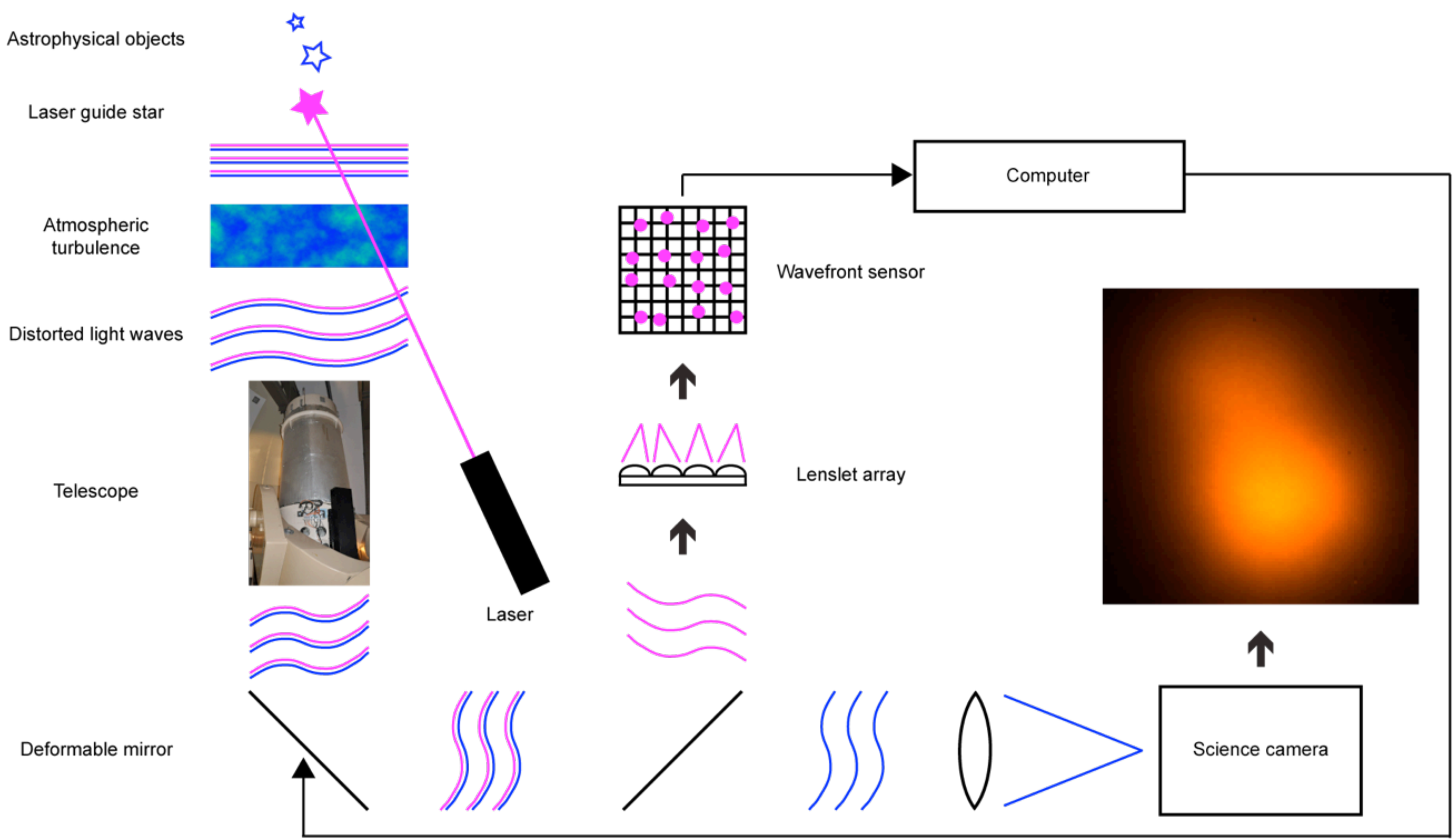

Astrophysical objects
Atmospheric turbulence
Distorted light waves
Telescope
Deformable mirror
Science camera

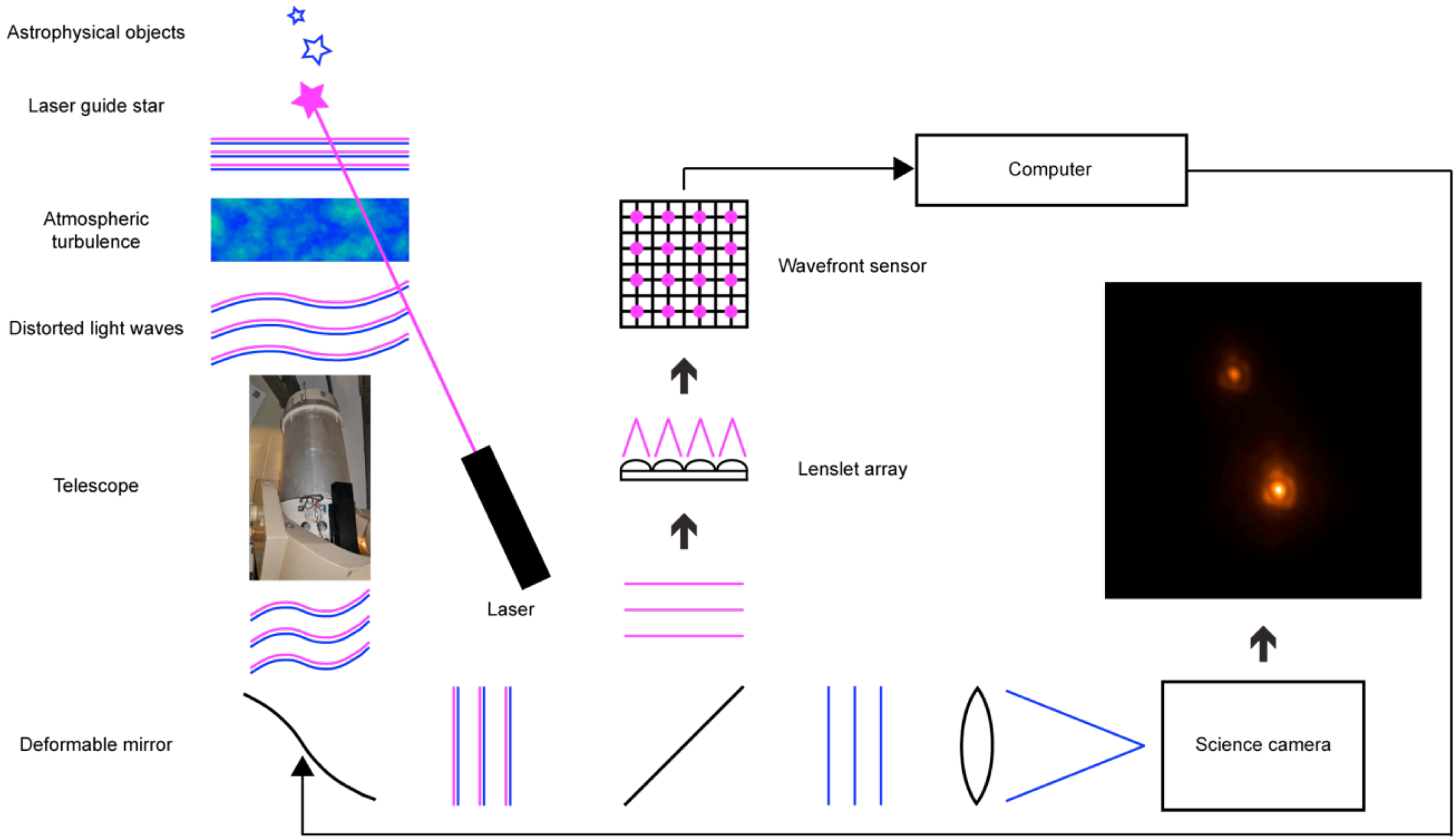


Astrophysical objects
Laser guide star
Atmospheric turbulence
Distorted light waves
Telescope
Laser
Deformable mirror
Science camera



Astrophysical objects
Laser guide star
Atmospheric turbulence
Distorted light waves
Telescope
Deformable mirror
Laser
Dichroic
Wavefront sensor
Lenslet array
Science camera


Astrophysical objects
Laser guide star
Atmospheric turbulence
Distorted light waves
Telescope
Deformable mirror
Laser
Computer
Wavefront sensor
Lenslet array
Science camera


Astrophysical objects
Laser guide star
Atmospheric turbulence
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Telescope
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Wavefront sensor
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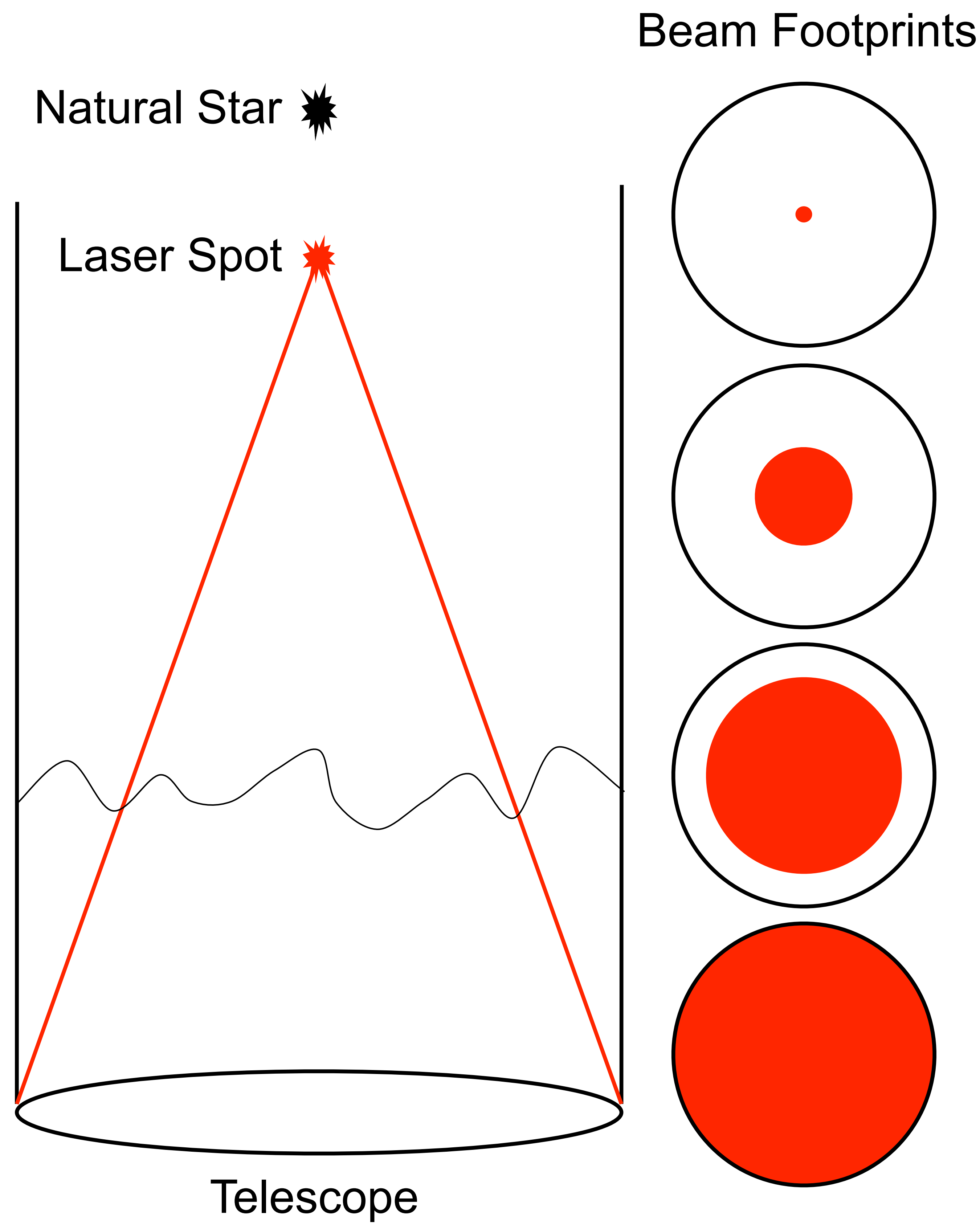
Science camera

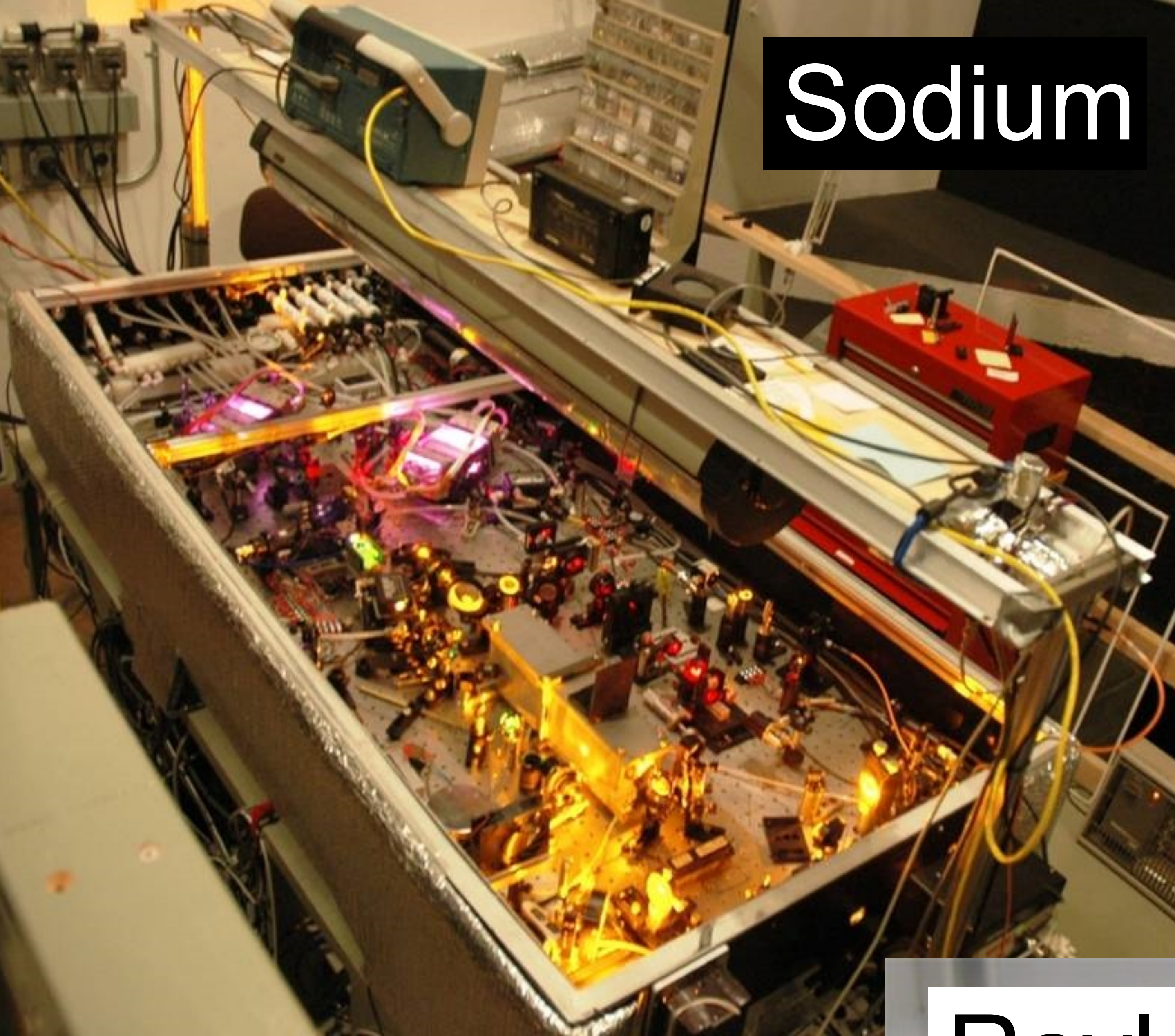
Lack of enough bright natural guide stars in the sky led to the development of laser guide stars.

- **Sodium lasers** excite the D2 transition of mesospheric (~90km) Sodium ions.
- **Rayleigh lasers** backscatter off of air molecules (up to ~10km).

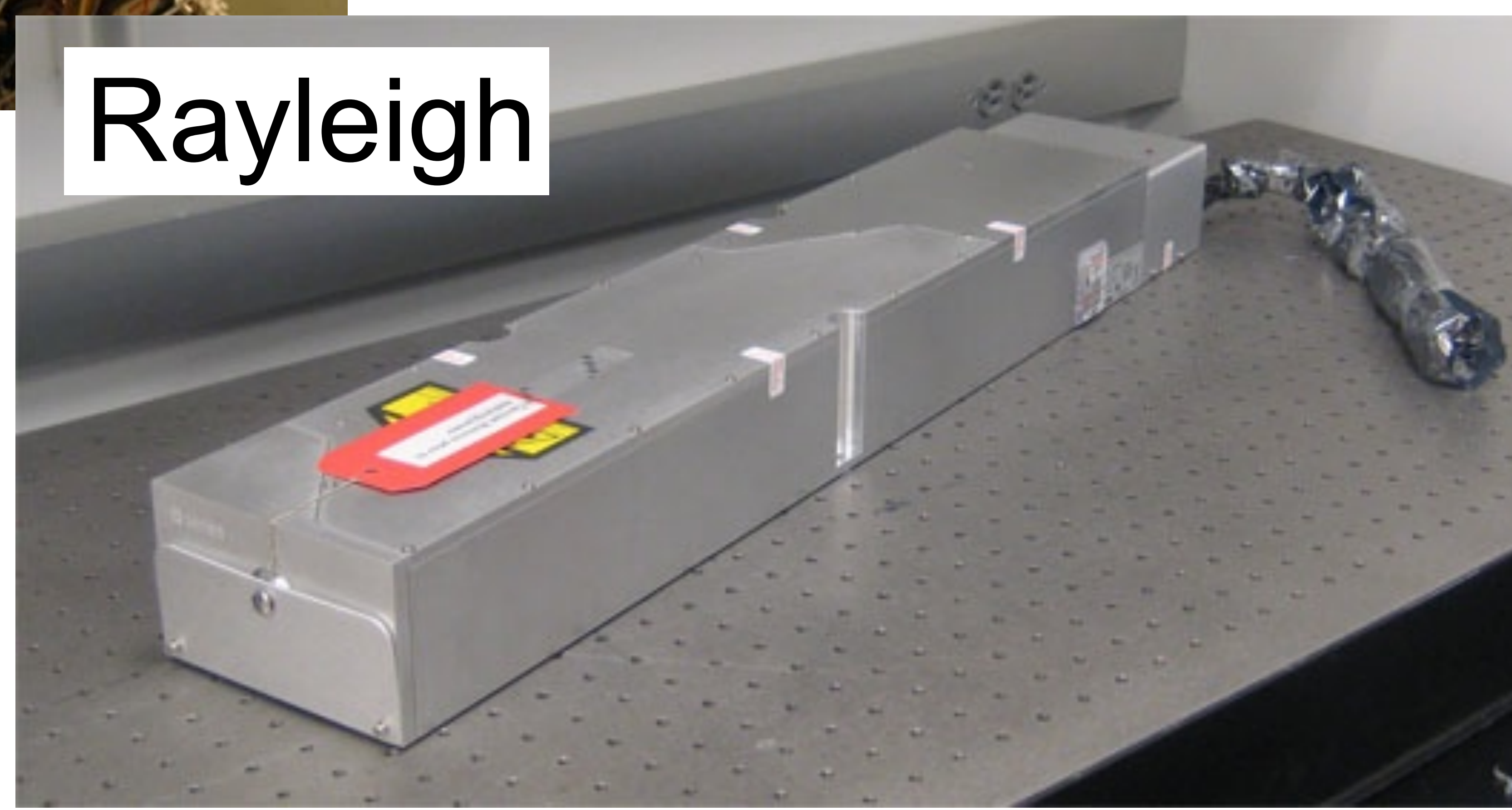
Focal Anisoplanatism

- D = 10 m
  - Sodium ~150 nm
  - Rayleigh, >1 um
- D = 1.5 m
  - Sodium ~25 nm
  - Rayleigh ~90 nm



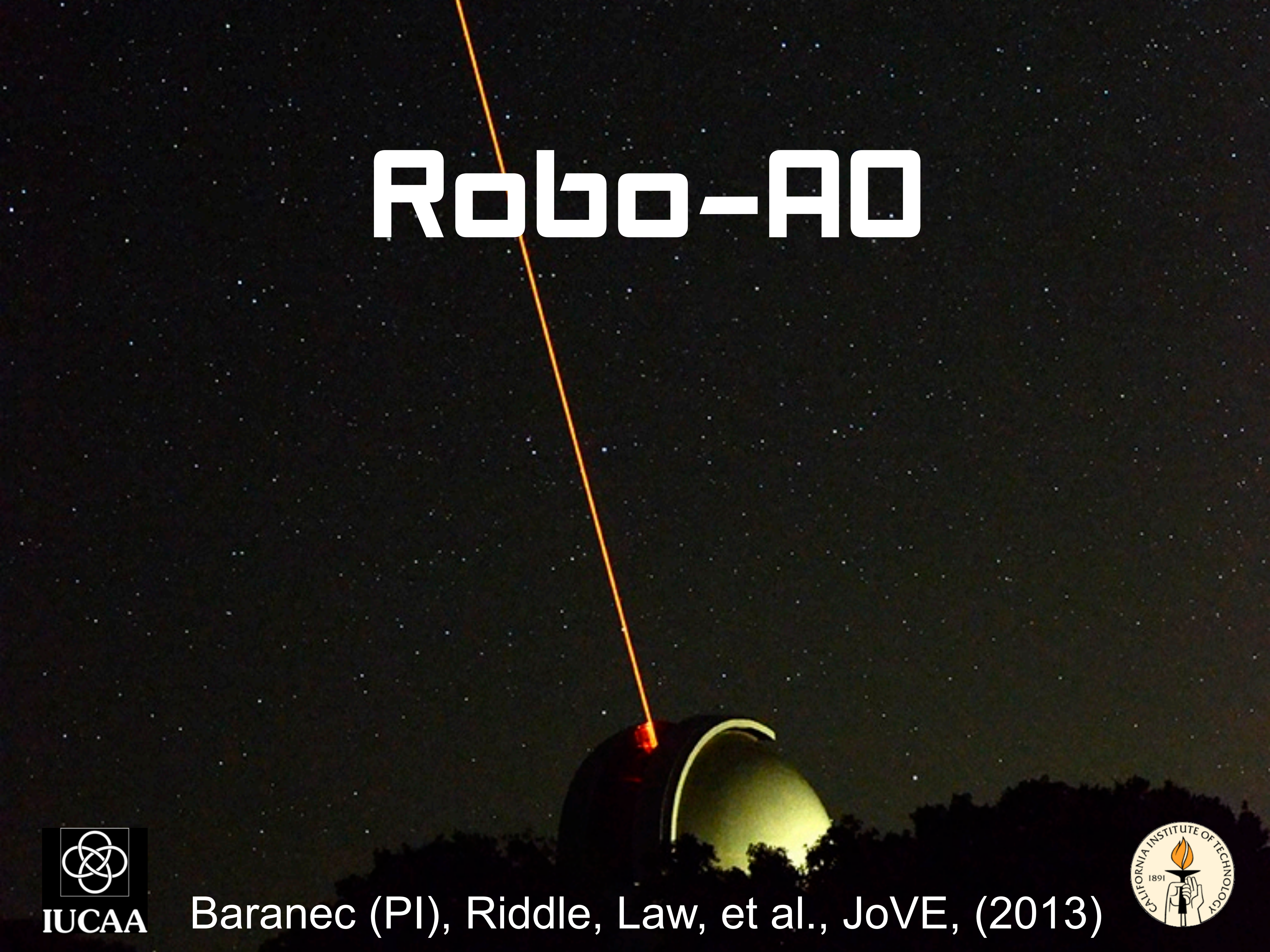


Chicago Sum Frequency Laser at 5.1-Hale Kibblewhite et al.
(10W for ~$1M+)



Commercial laser
(10W for $100K)

Robo-AO

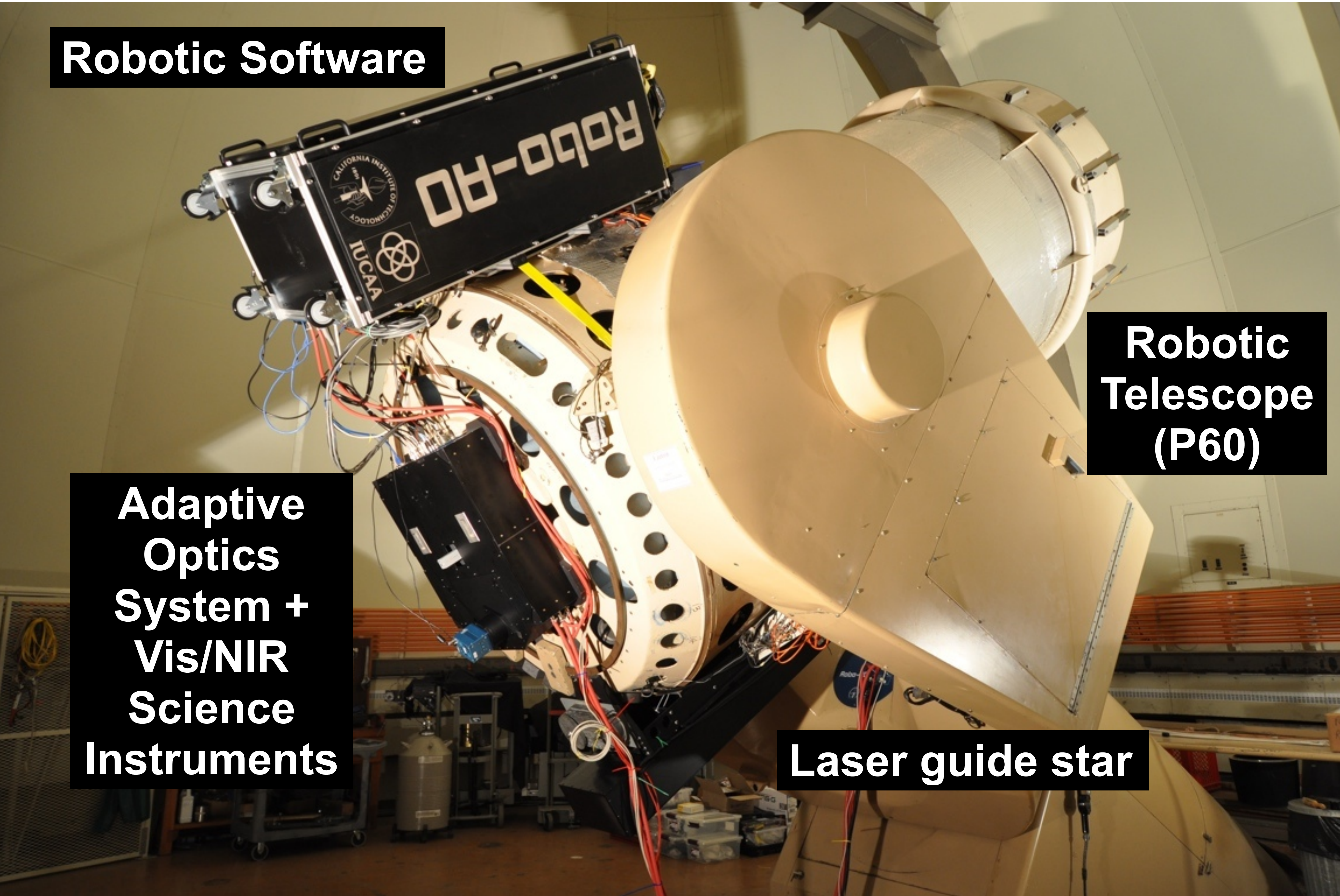


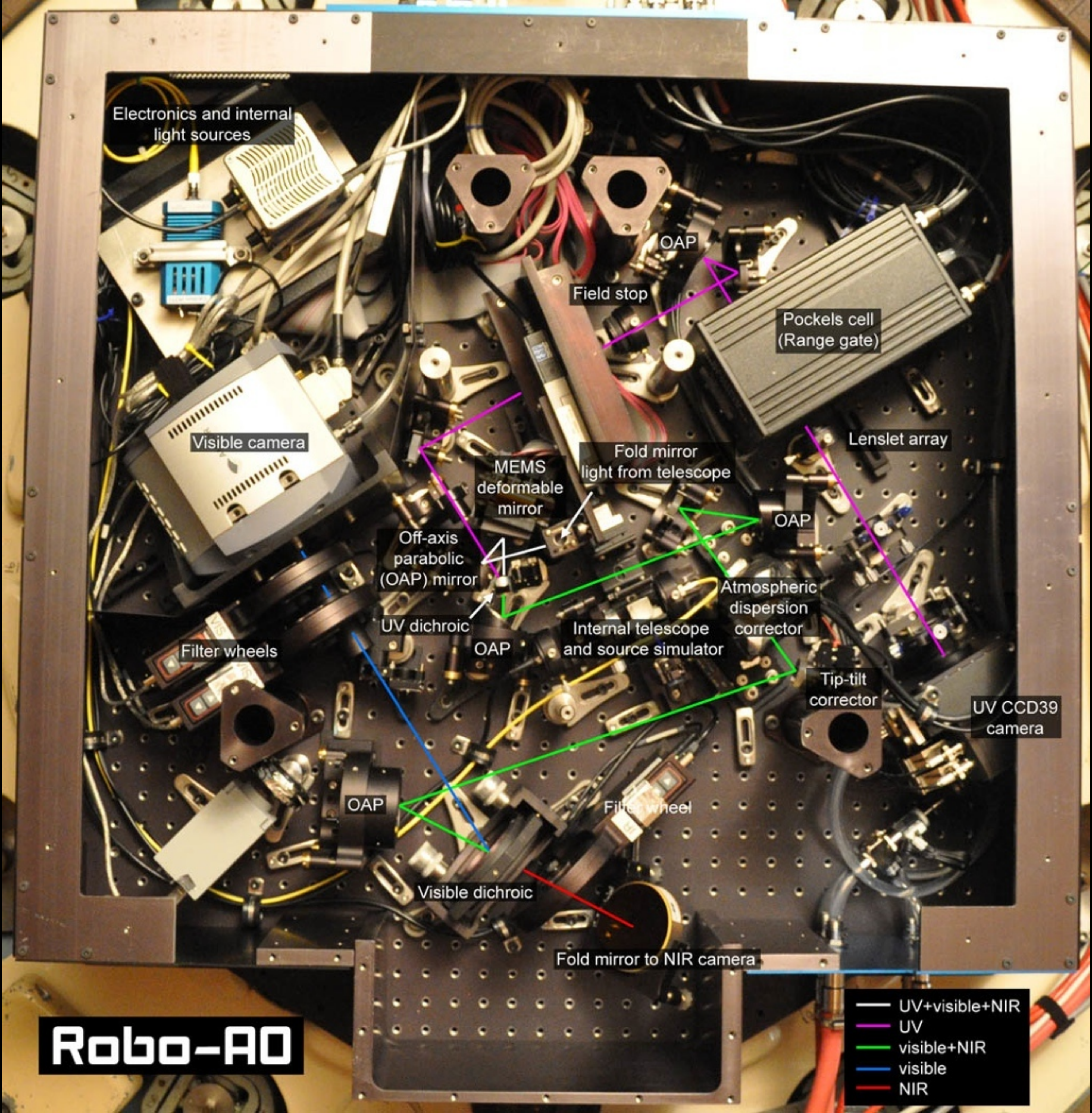
Baranec (PI), Riddle, Law, et al., JoVE, (2013)

Why is Robo-AO special?

	Traditional (Sodium Laser) Guide Star Adaptive Optics	Robo-AO Robotic Laser Guide Star AO
Telescope diameter	3-10m	1.5-3m
Observing bands	Infrared	Visible + Infrared
Lock-on time	5-35 min / target	86 s / target
Targets per night	Tens	up to ~220
Program length	Few nights	Weeks+
Targets per program	~100	Thousands+
Personnel	1+ astronomer(s), 1 T.O., 1 inst. scientist, 1 laser engineer, 4 spotters	1 astronomer (peacefully sleeping)

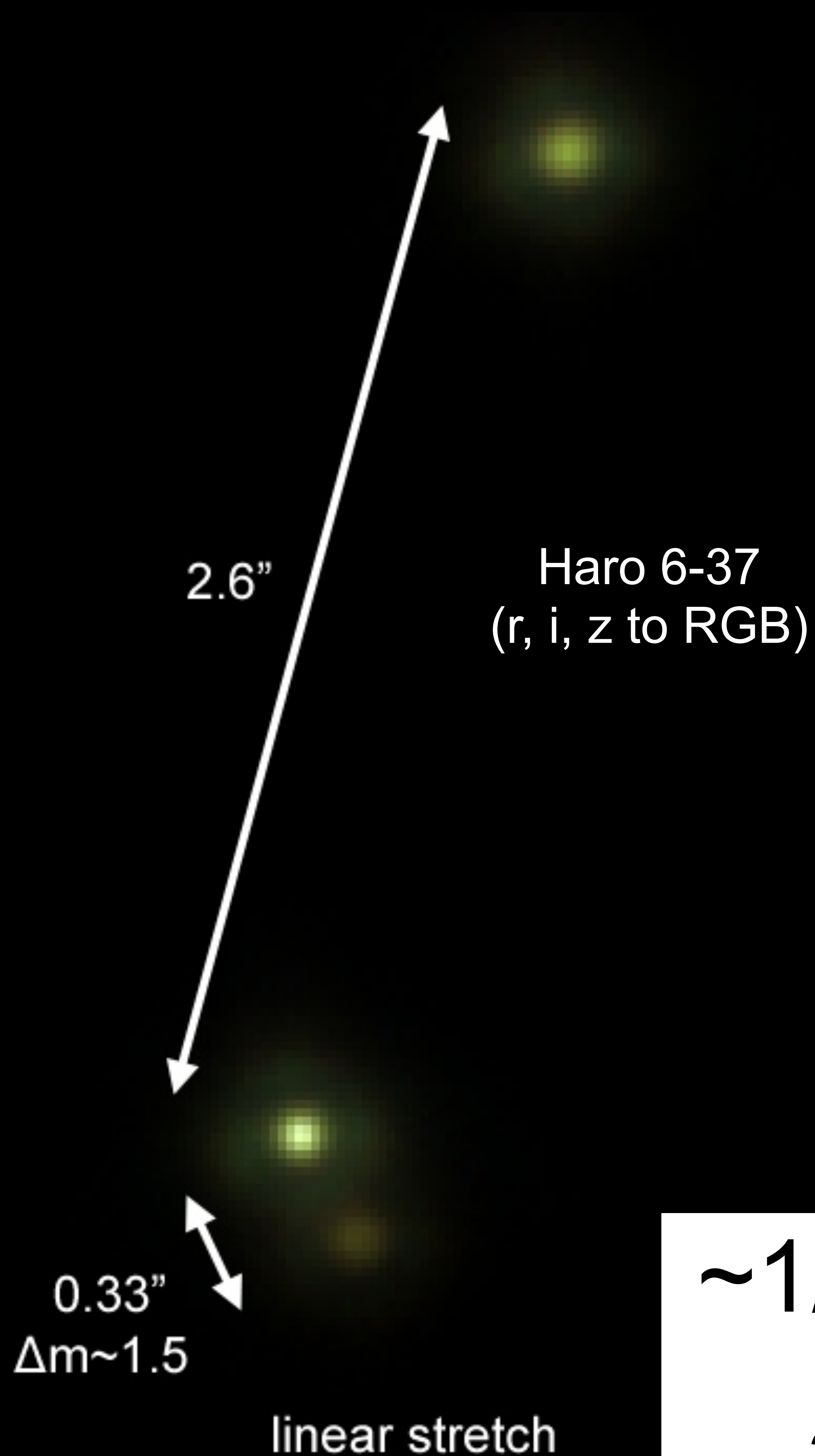
Robo-AO on the Palomar 60” telescope





Electronics and internal light sources
OAP
Field stop
Pockels cell (Range gate)
Visible camera
Lenslet array
Fold mirror light from telescope
MEMS deformable mirror
OAP
Off-axis parabolic (OAP) mirror
Atmospheric dispersion corrector
UV dichroic
OAP
Internal telescope and source simulator
Filter wheels
Tip-tilt corrector
UV CCD39 camera
OAP
Filter wheel
Visible dichroic
Fold mirror to NIR camera
Robo-AO
UV+visible+NIR
UV
visible+NIR
visible
NIR

First on-sky correction, August 14, 2011



λ (nm)	FWHM	Strehl	RMS WFE (nm)
625	0.11”	7.1%	161
765	0.12”	14.7%	168
890	0.14”	20.4%	178

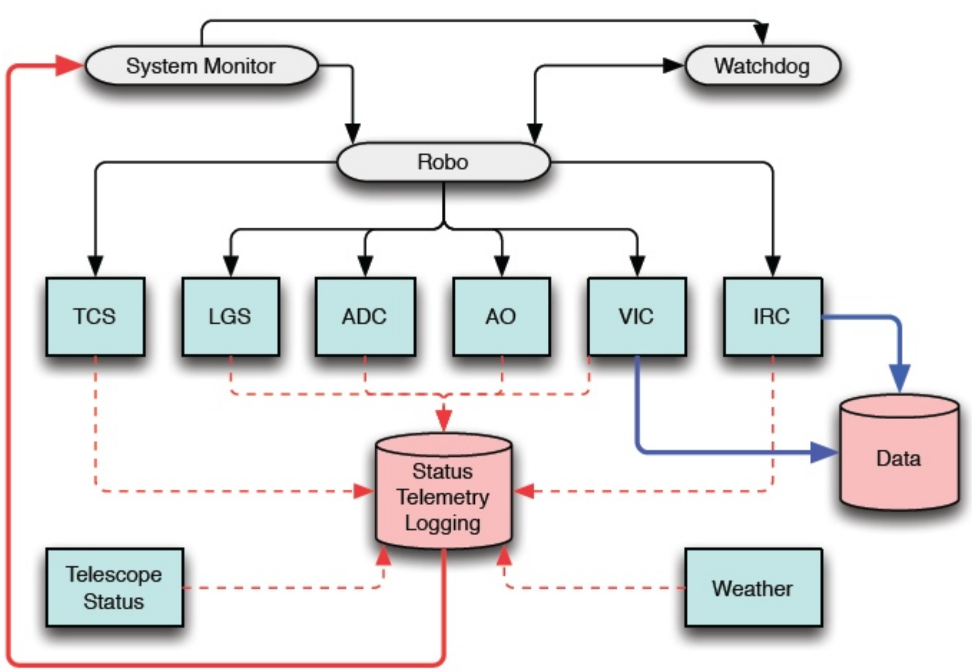
~1/2 resolving power of HST

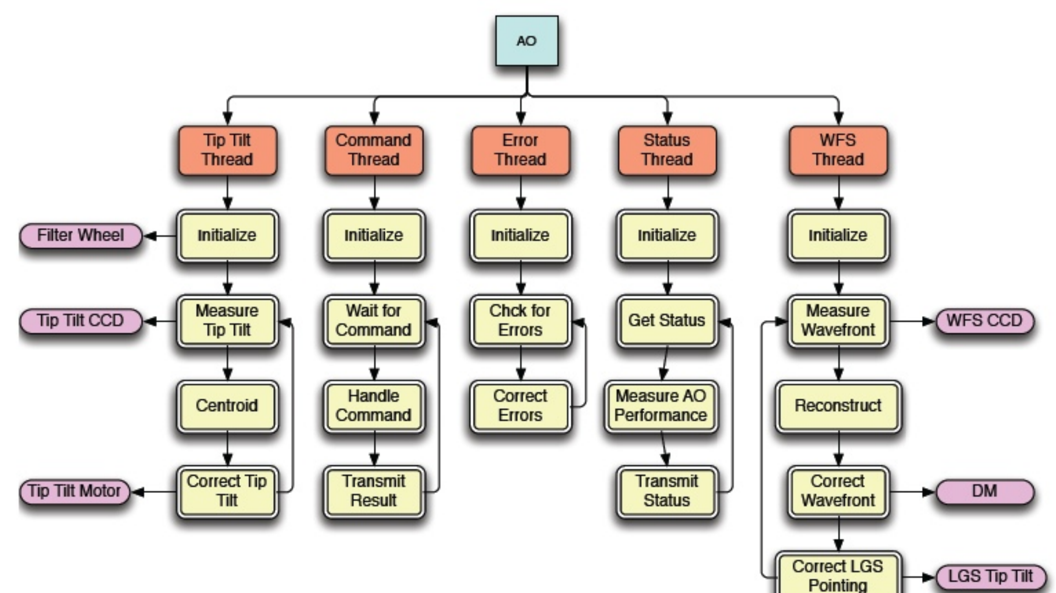
at < 1/10,000th the cost

Software + Automations

Reed Riddle (Caltech; ex-TMT)

Linux/C++ ~100,000 lines of code





AO Science…
by the thousands!

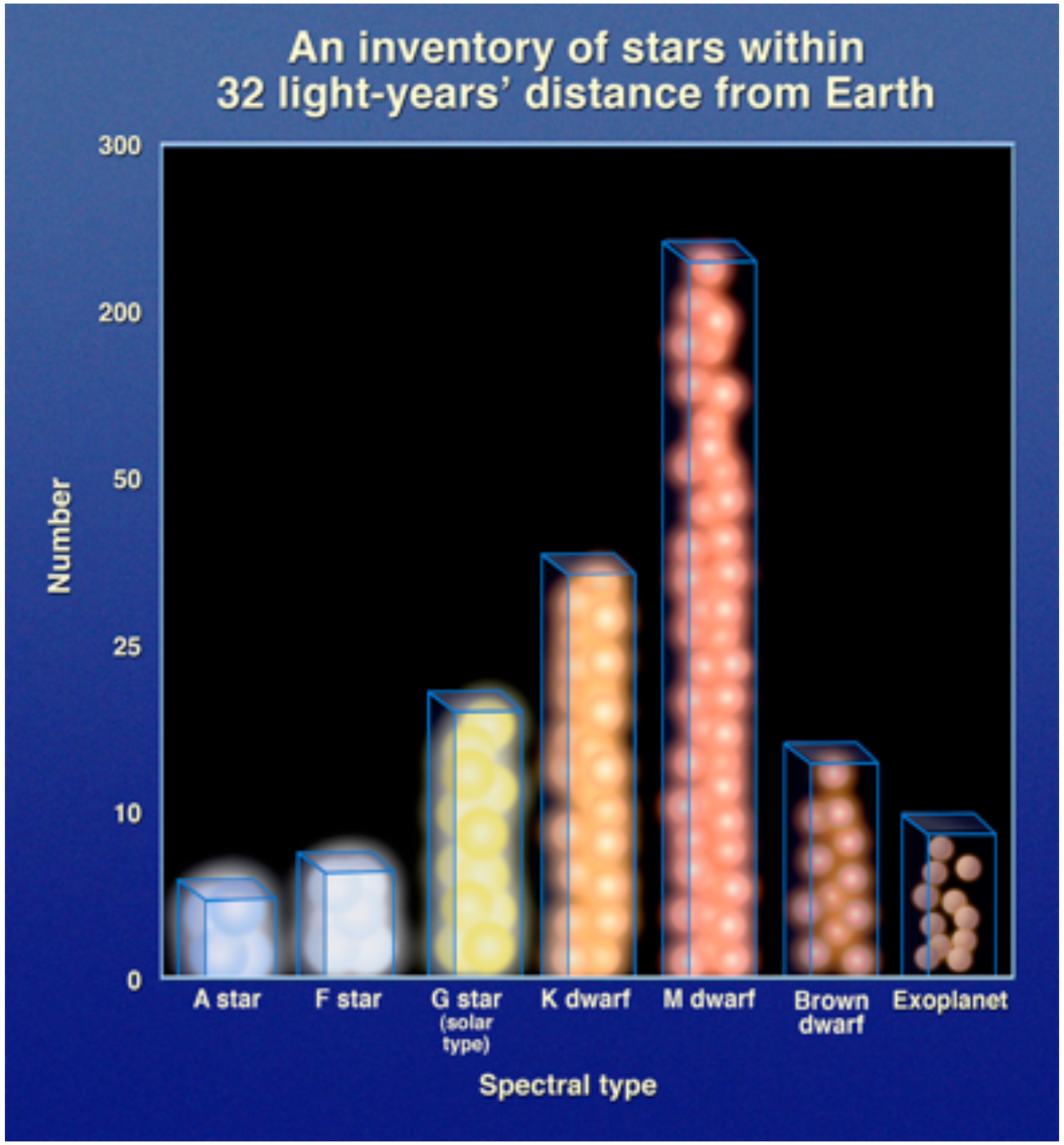
Ultimate AO Binarity Survey

Survey of ~3,000+ members in local solar neighborhood
(Based on RECONS sample, T. Henry et al.)

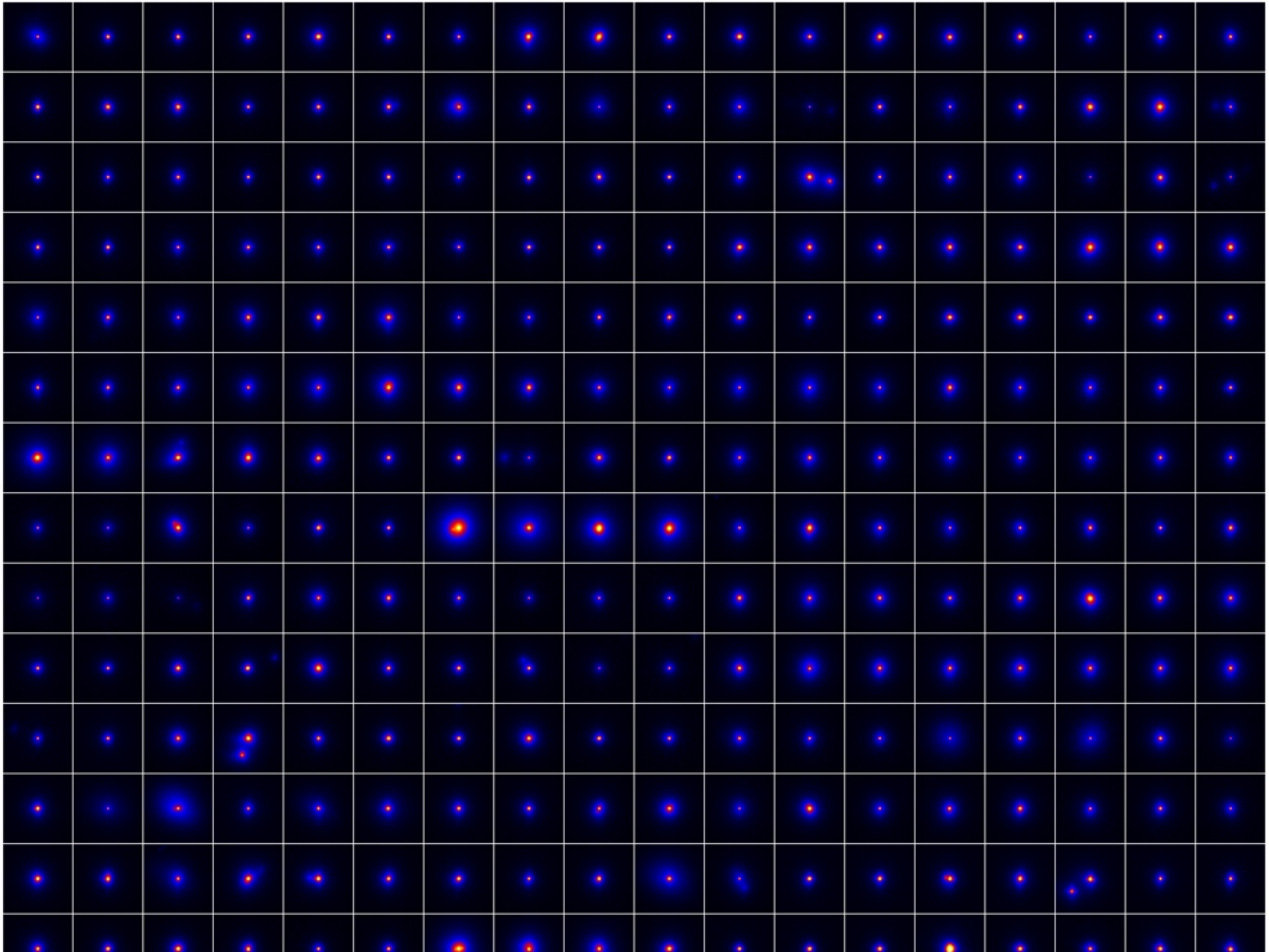
All spectral types,
companions down to
brown dwarfs for most

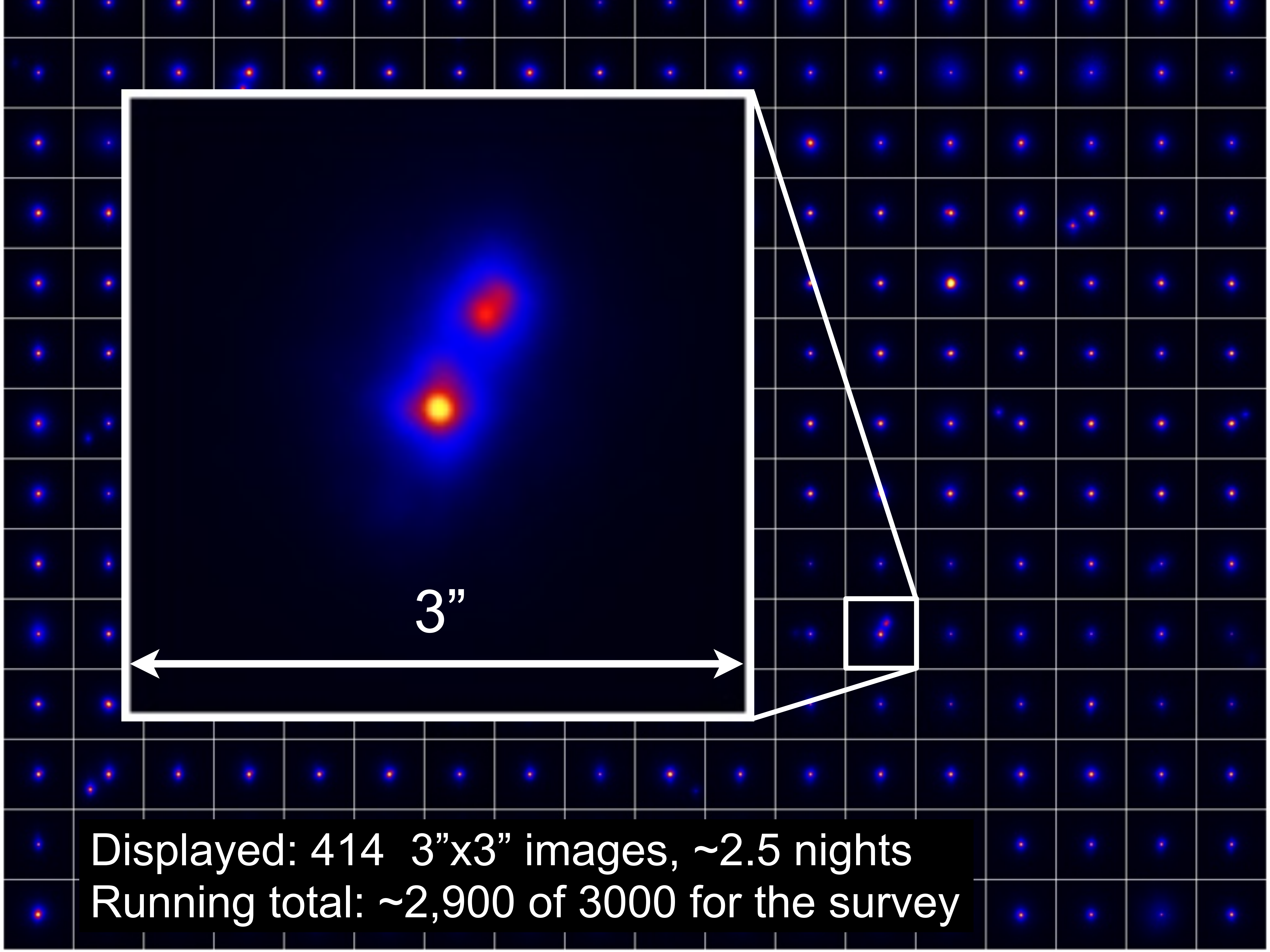
Robo-AO: 0.1” to 1.0”

1 to 100 AU range

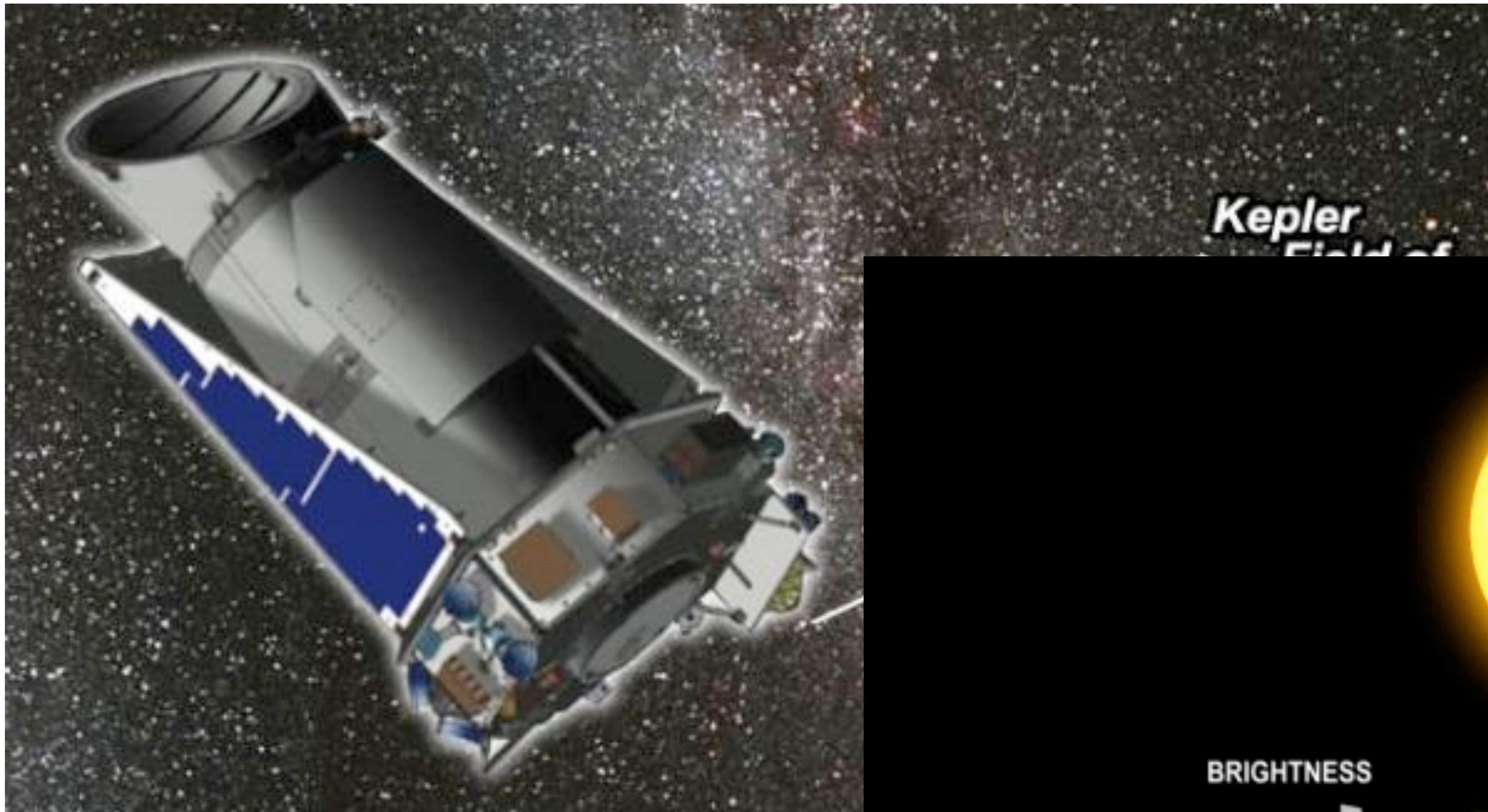


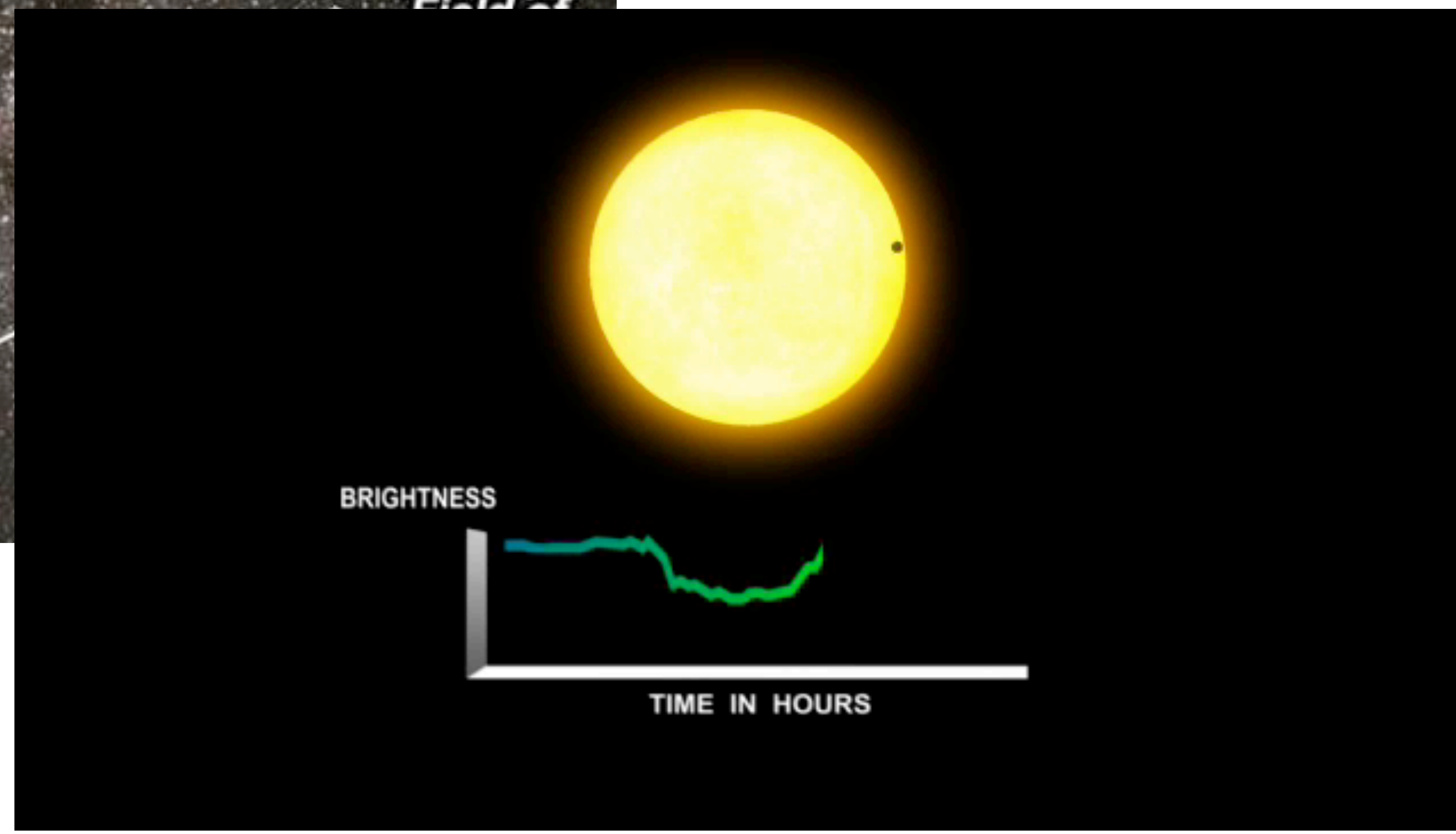
Nick Law
~~U. Toronto~~ UNC-CH
(Project Scientist)




3”
Displayed: 414 3”x3” images, ~2.5 nights
Running total: ~2,900 of 3000 for the survey

Kepler planetary candidates





Identify blended binary systems

Photometry in Kepler visible bandpass

Identification of transit host

Robo-AO has imaged ~1050 KOIs

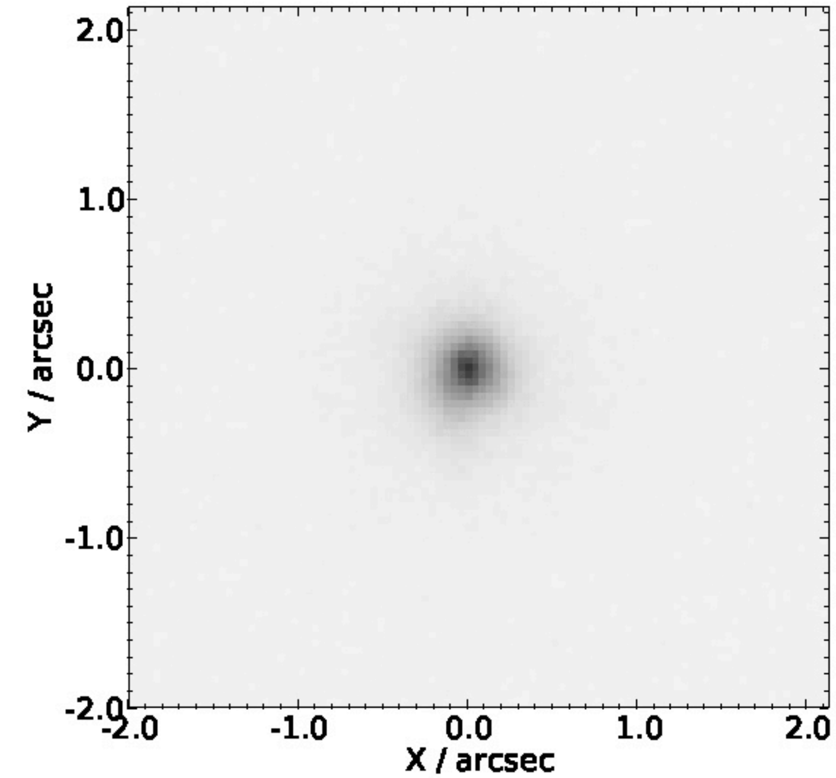
~52 total hours including overheads

We’ll finish the rest (including the new release) this summer!

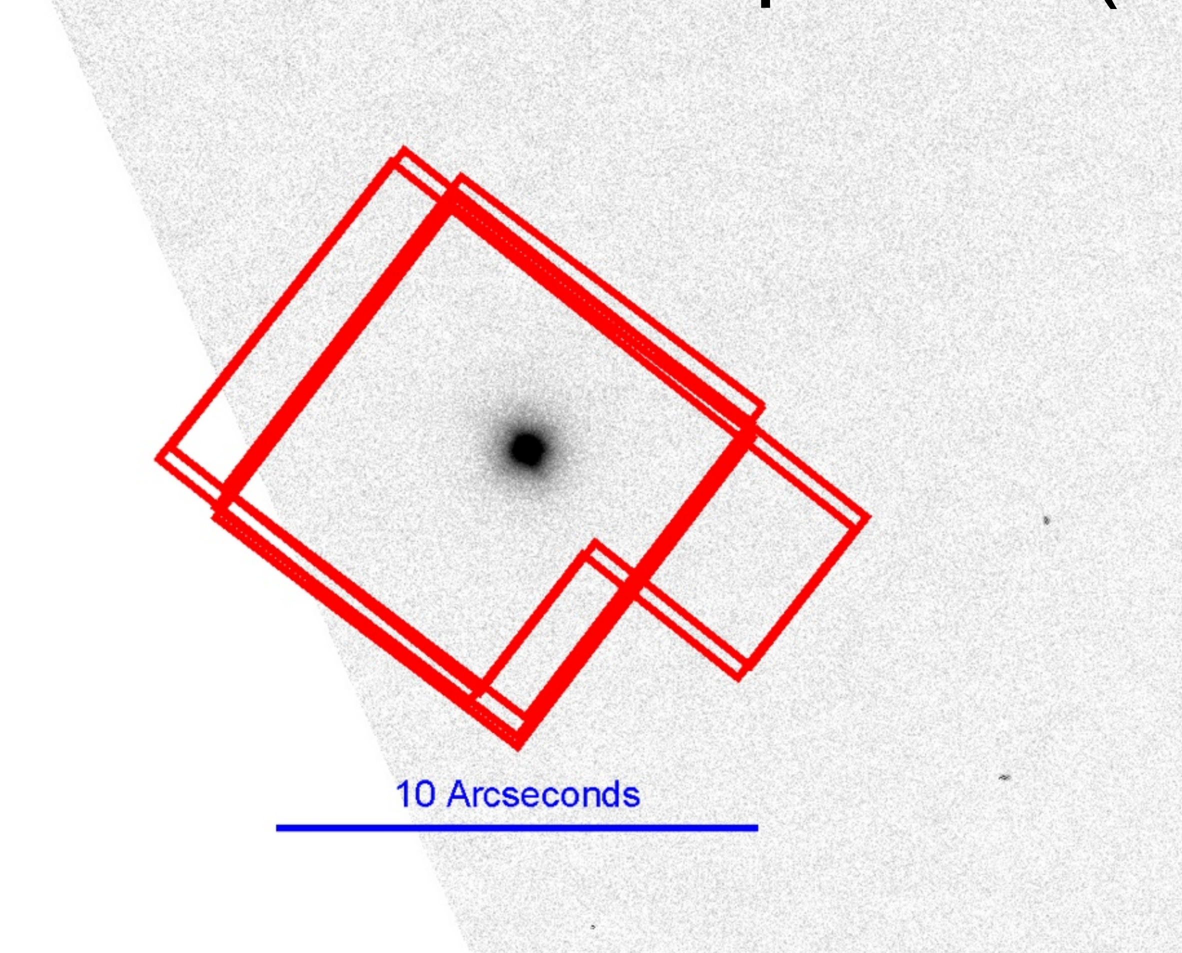
Robo-AO team in collaboration with Caltech ExoLab (J. Johnson)

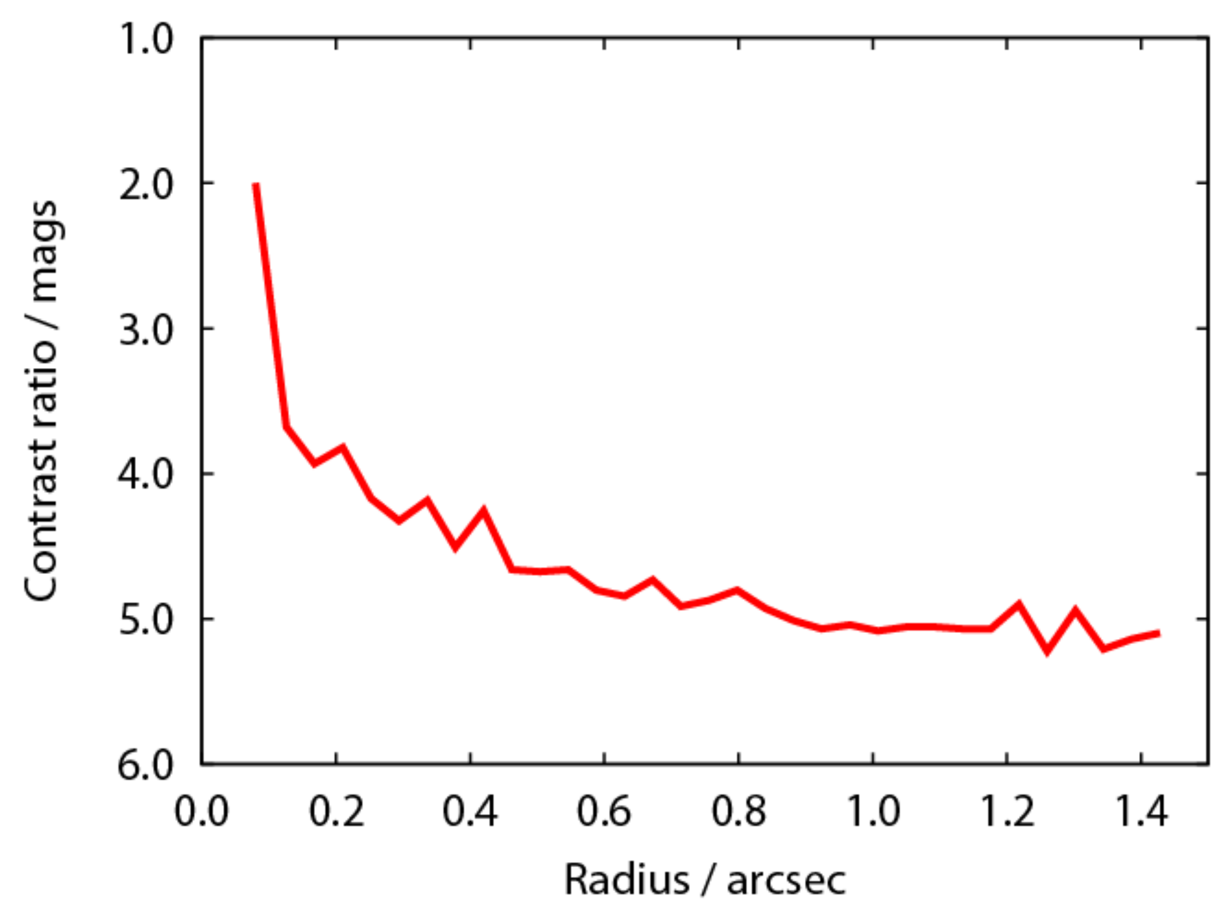
Robo-AO/Kepler publications

- **Kepler-32**
  - –Swift et al. ApJ 764, (2013).
  - –5σ Δz = 3.5 at 0.5”, Δz = 4.5 at 1.0”

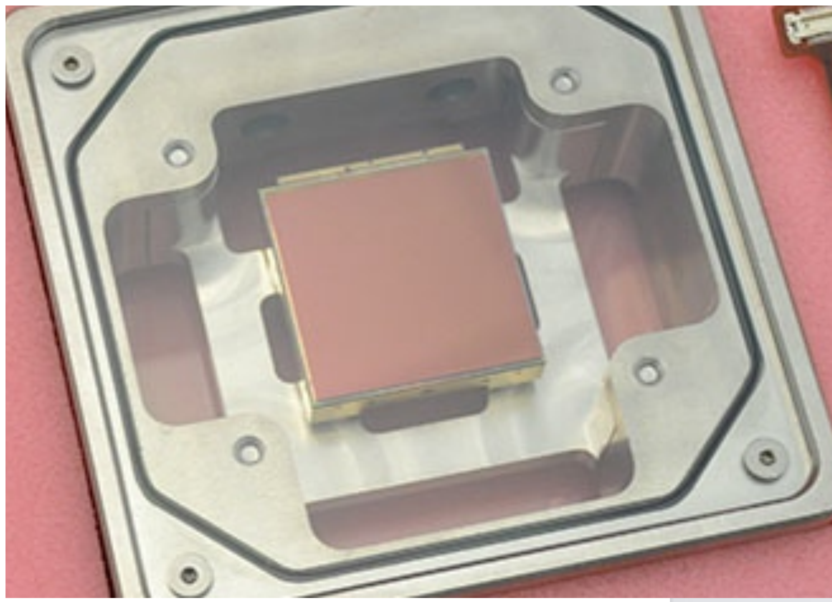


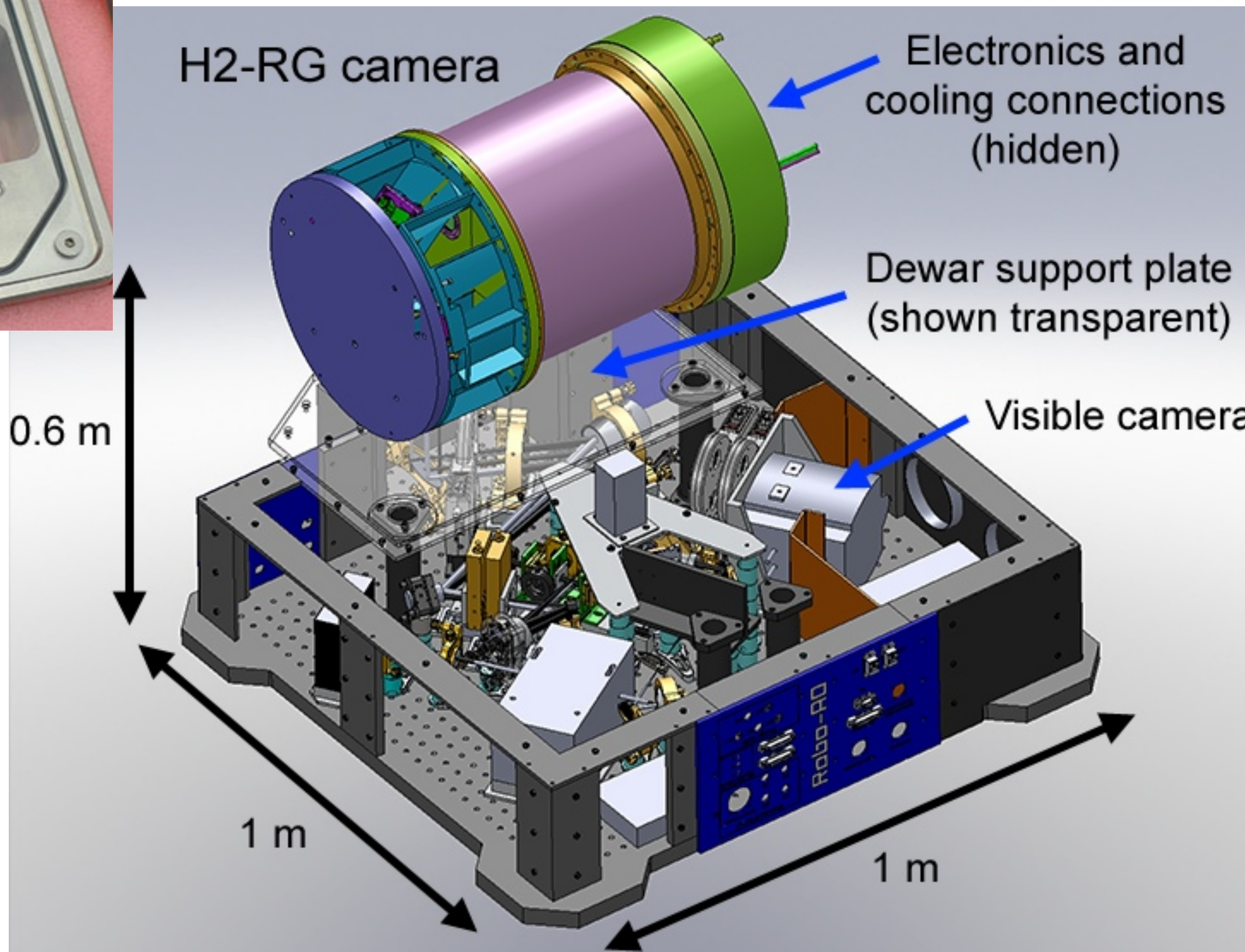
- **KOI-256**
  - –Muirhead et al. ApJ 767 (2013).



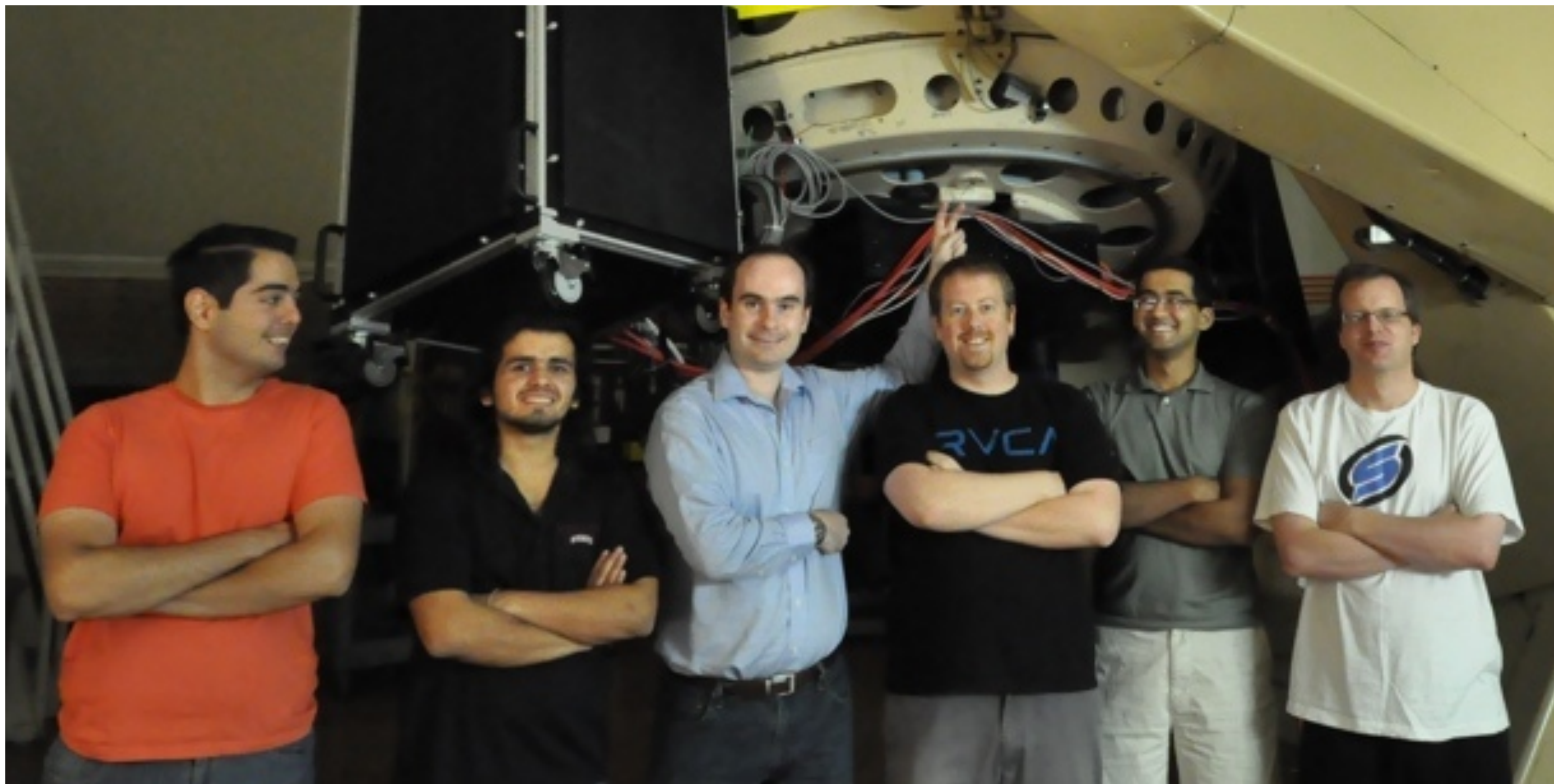


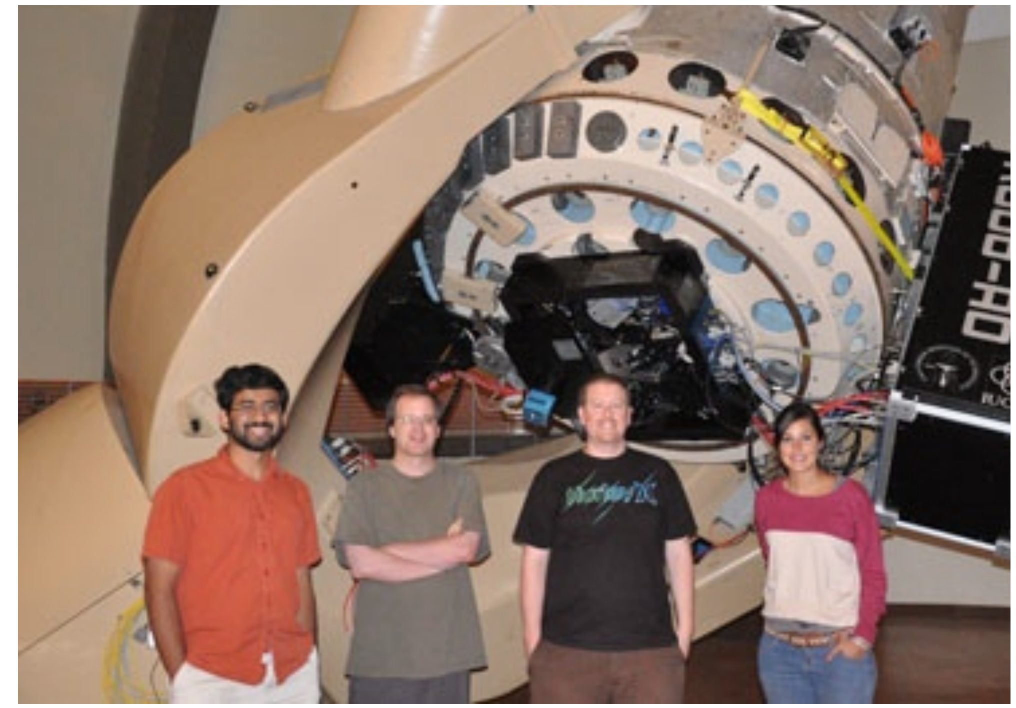
IR camera/TT upgrade



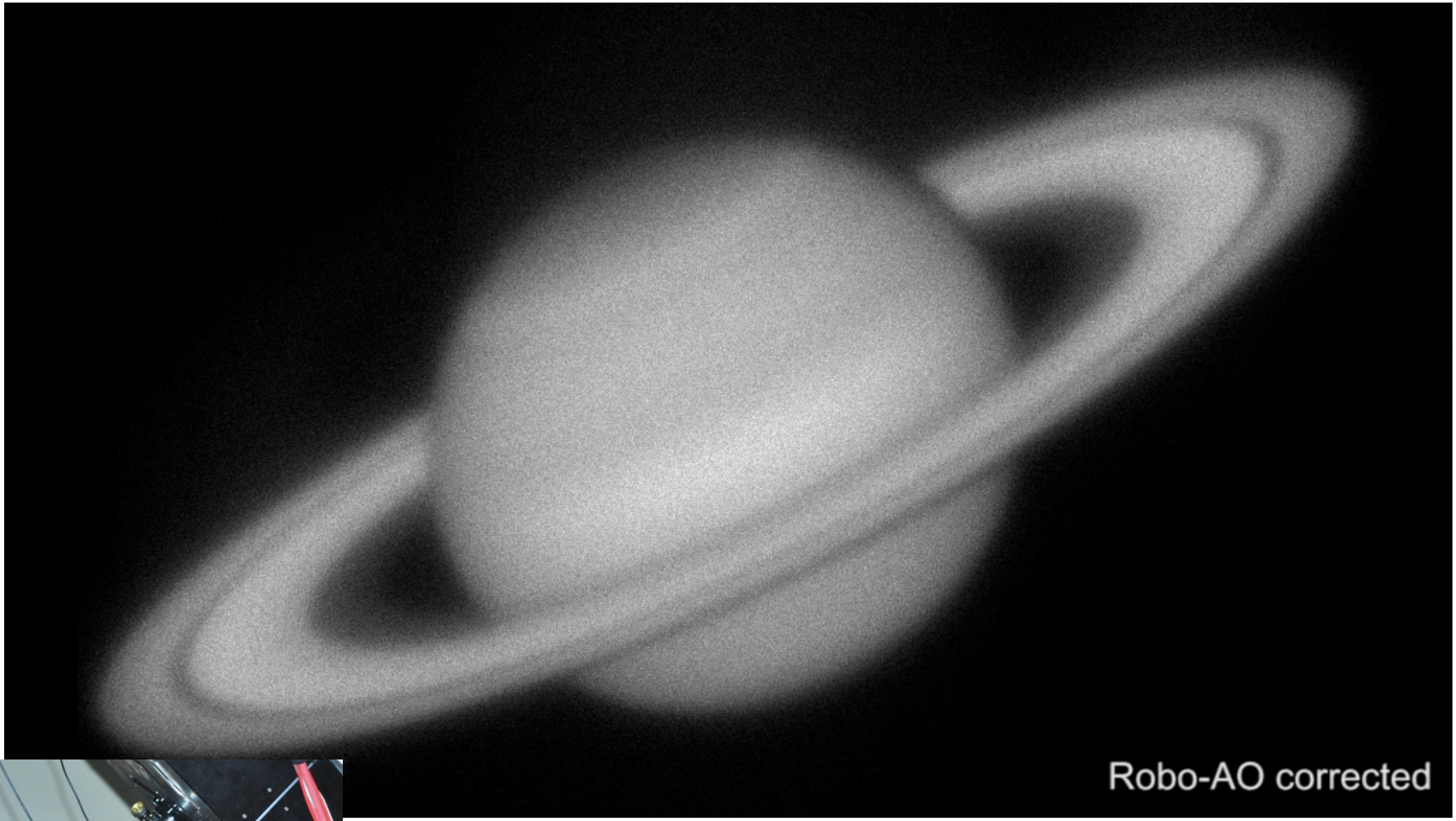


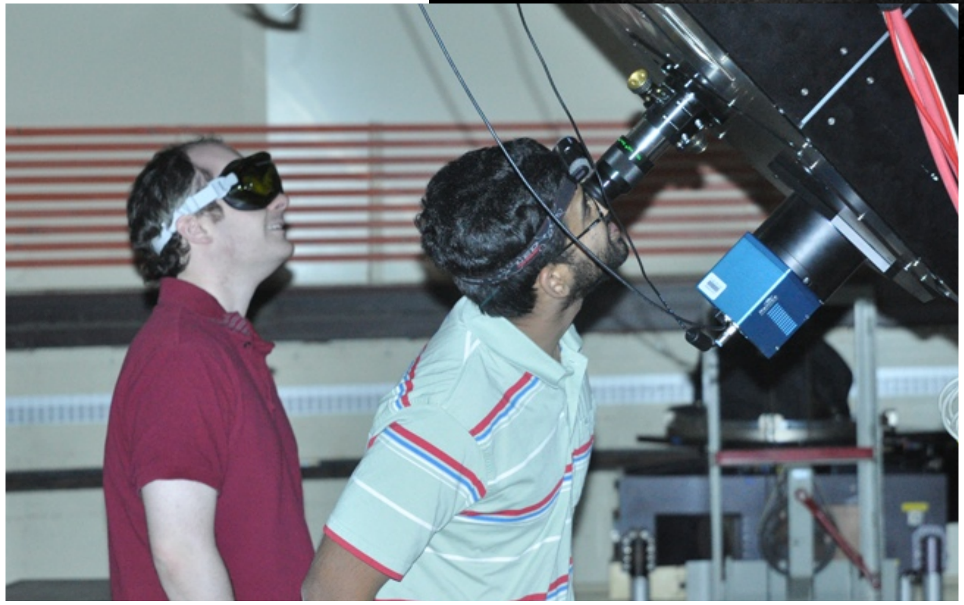
Student research





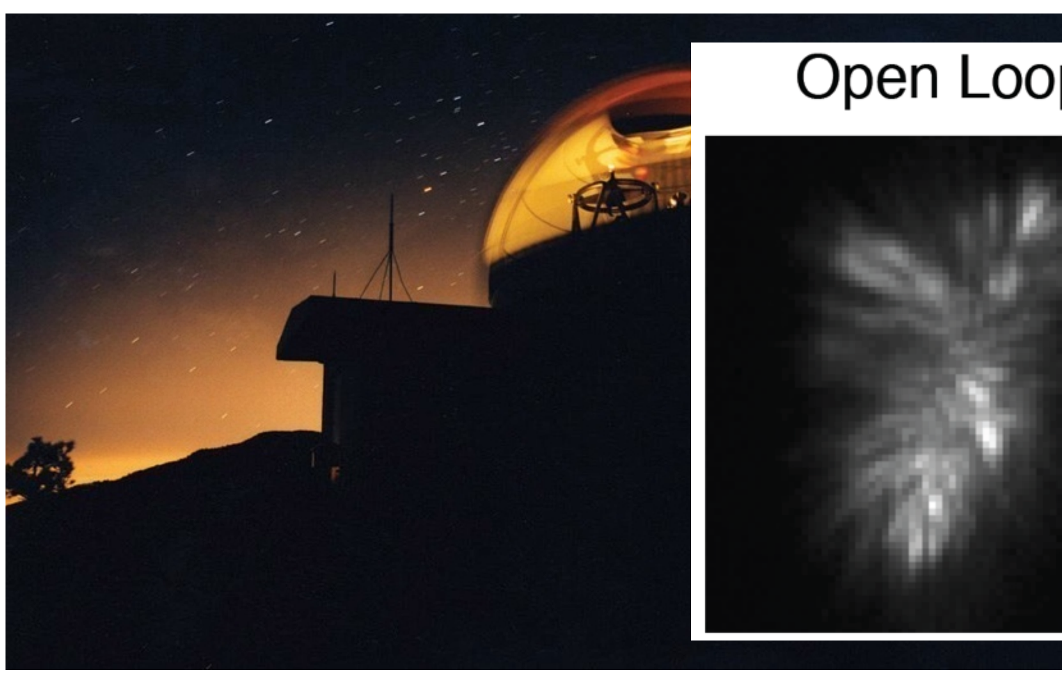
1.5-m diffraction-limited eyepiece

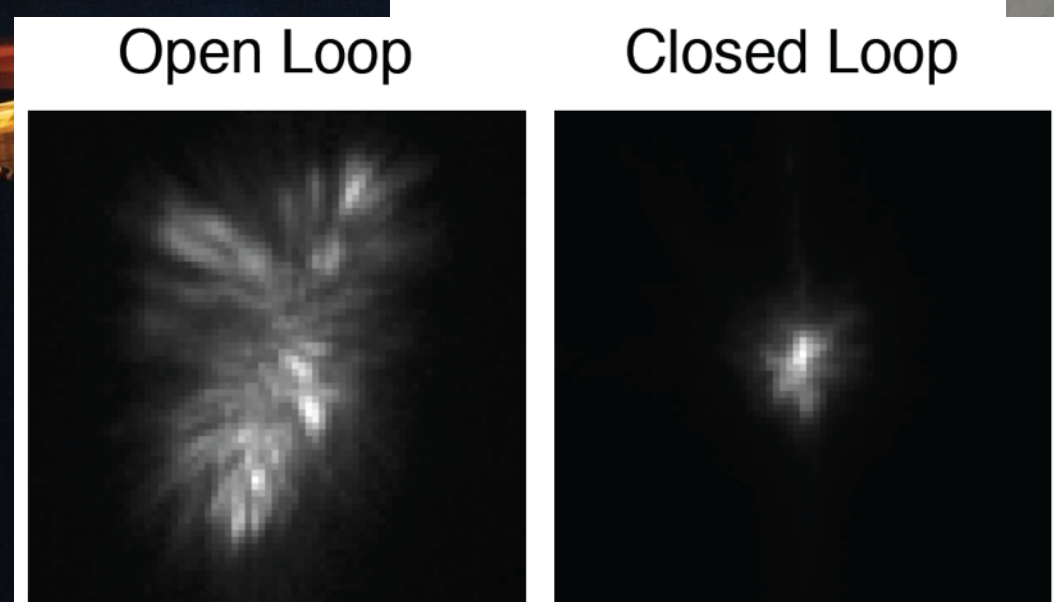




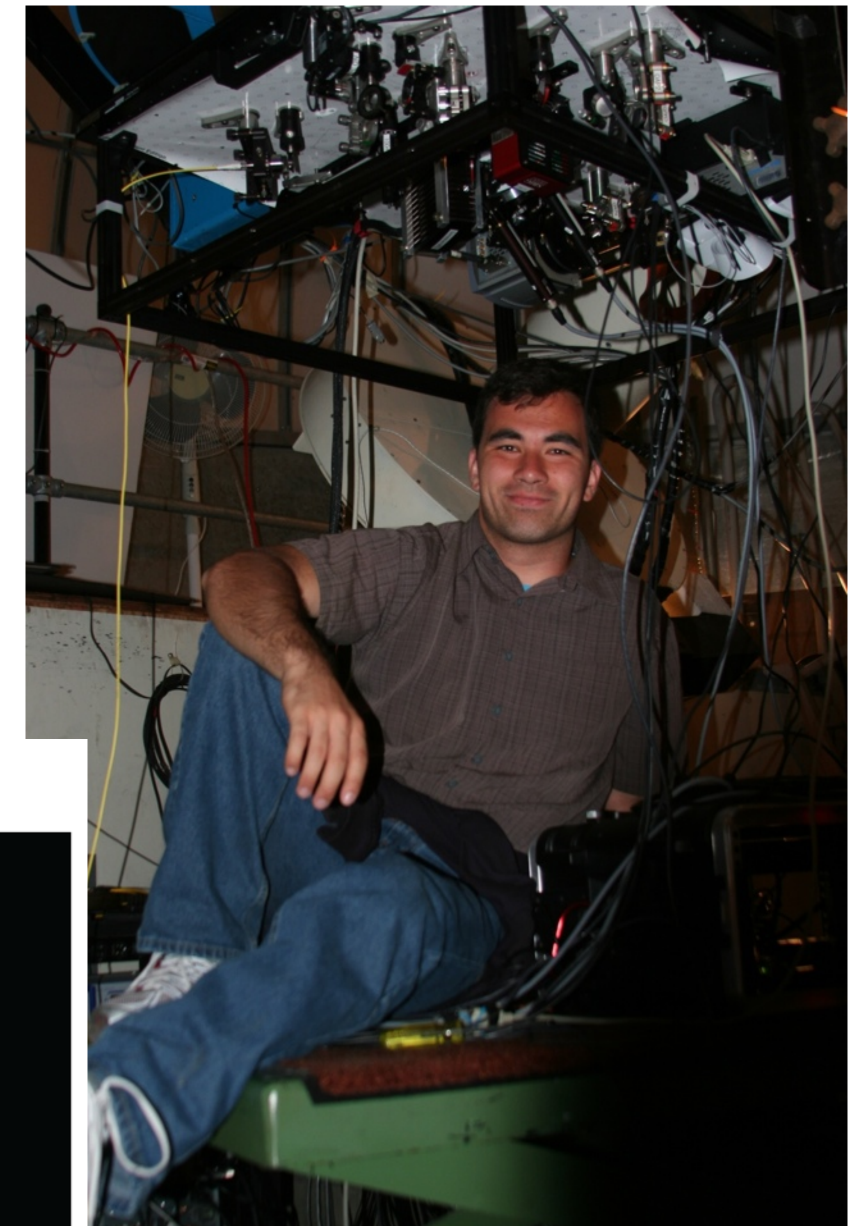
Synergistic projects

P. Choi (Pomona), S. Severson (Sonoma St.)





KAPAO: NGS AO for the
1-m Table Mt. telescope



Undergrad labor
+ Robo-AO software

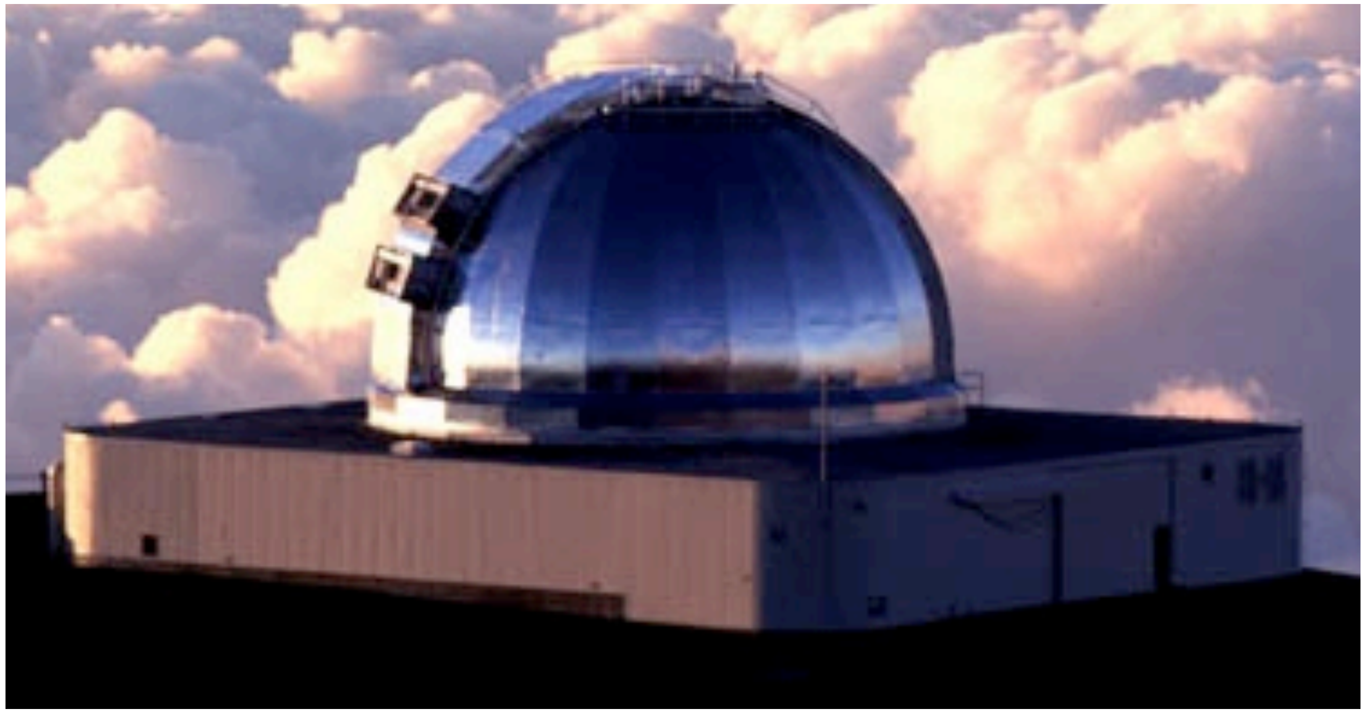
= Working adaptive optics system!!!

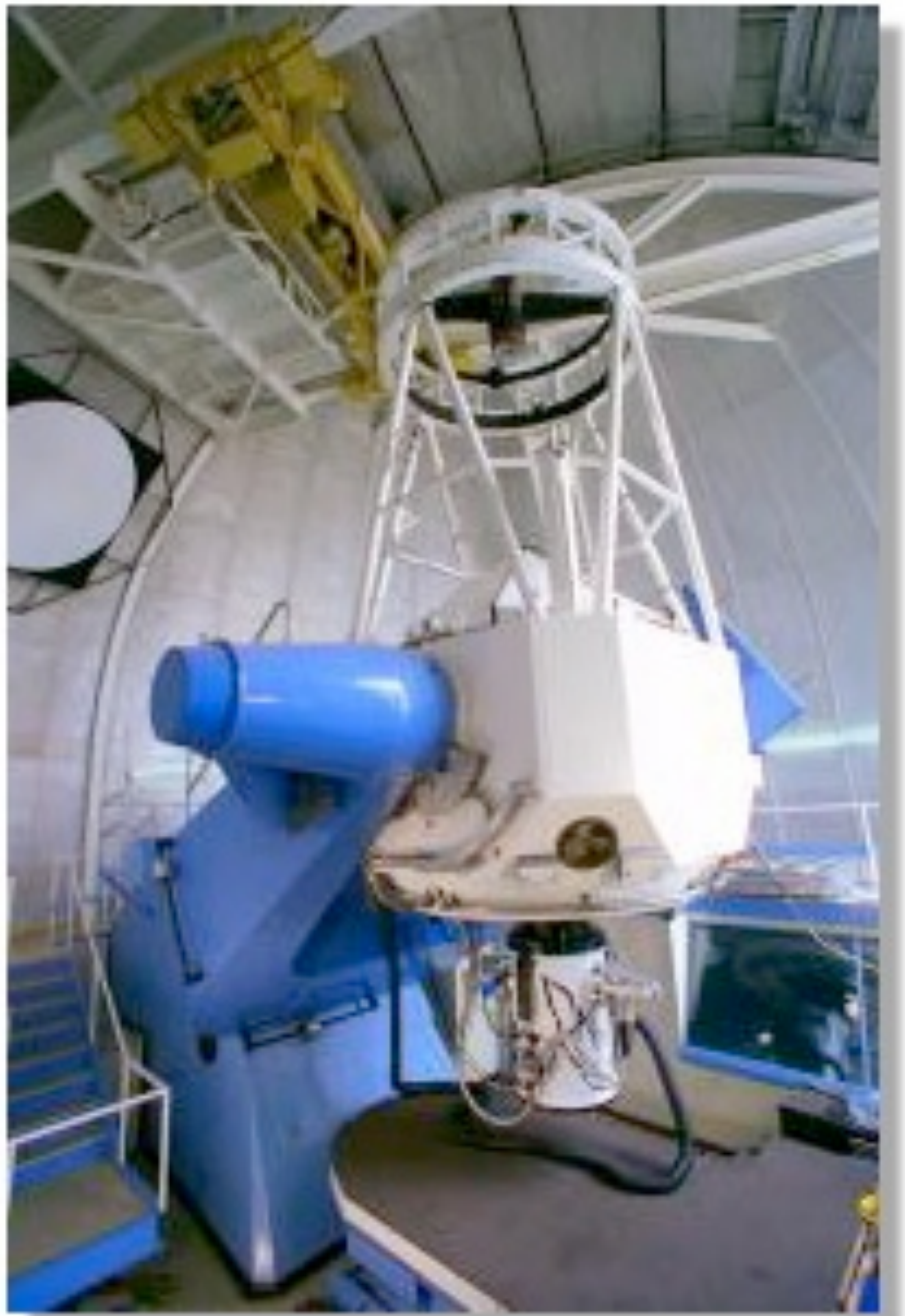
Current operations

- Safety oversight by individual at Palomar P60
- ~20x 90s observations per hour
- 60 nights on sky: **~6,300 observations**
- Auto data reduction and registration pipeline
- 10 more nights in 2013A (~27 req. 2013B)
- Available at least through 2014 per director

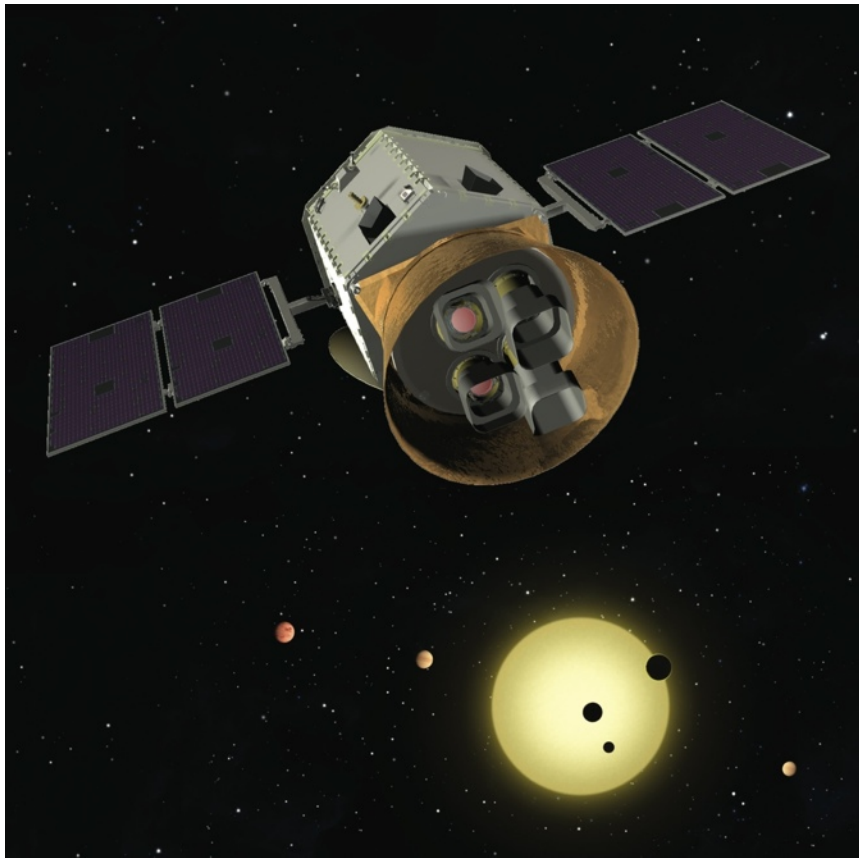
Robo-AO post Palomar

- Transfer to new host (in return for time)
- National access:
  - 2.1-m at Kitt Peak
  - 3-m IRTF



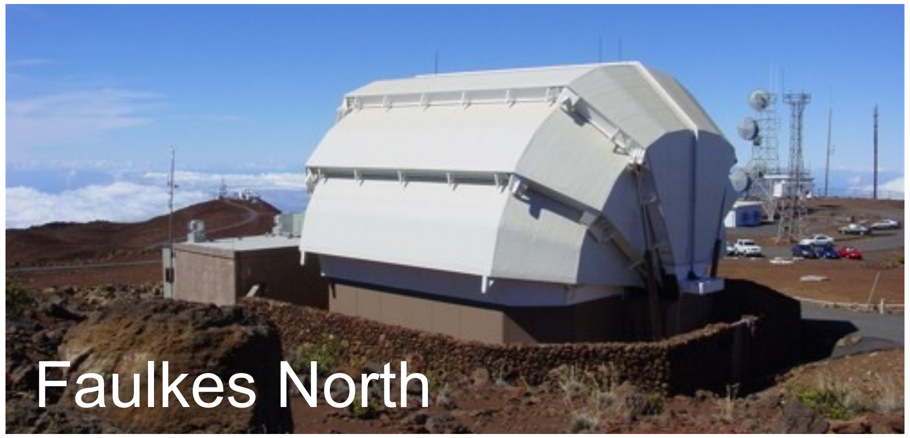


TESS exoplanet validation



- Transiting Exoplanet Survey Satellite
- Up to 10K+ candidate earth/ super-earth transits
- Require validation akin to Kepler but all-sky

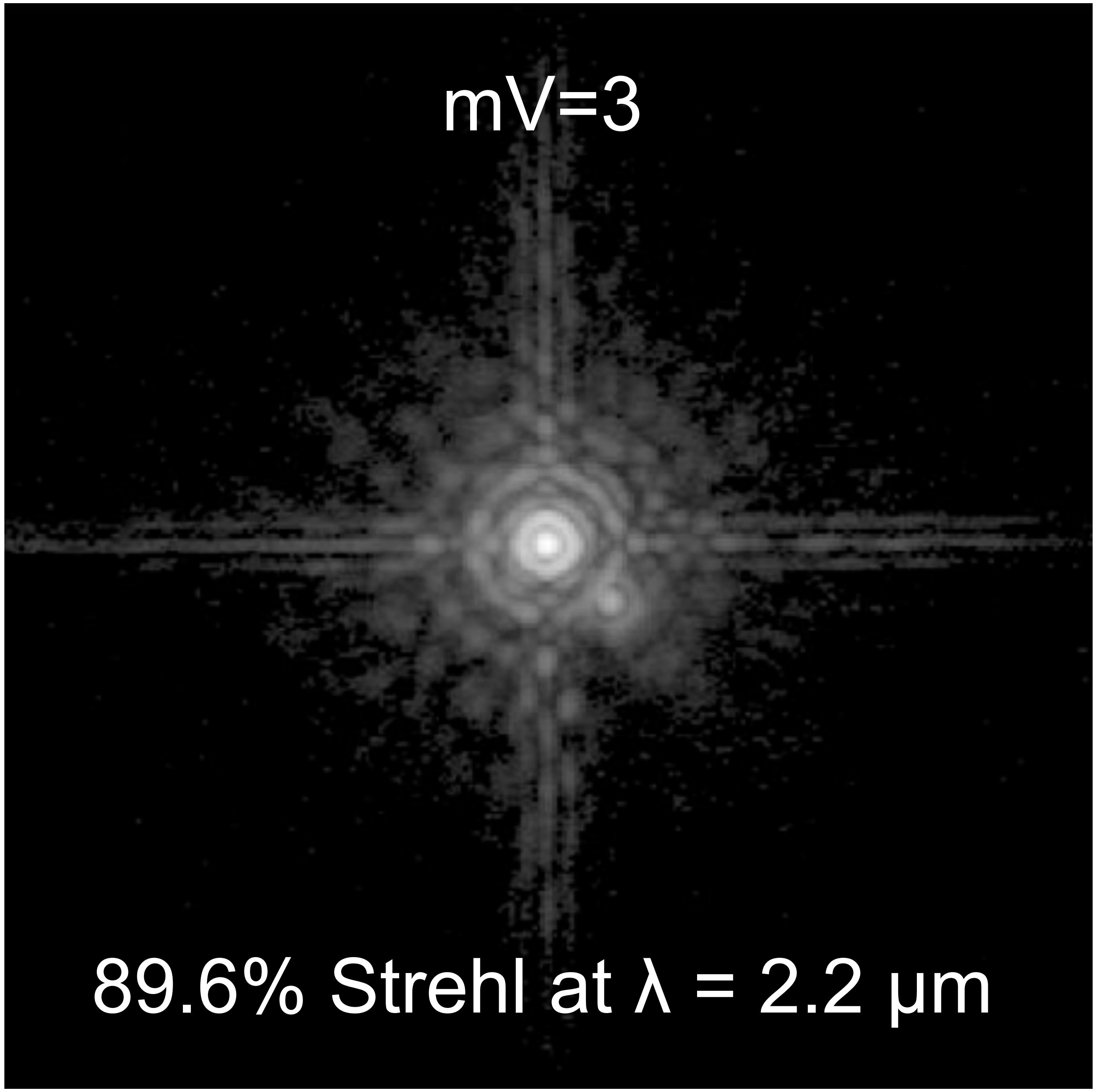
Robo-AO Twins ➔ LCOGT 2-m



Extreme Adaptive Optics

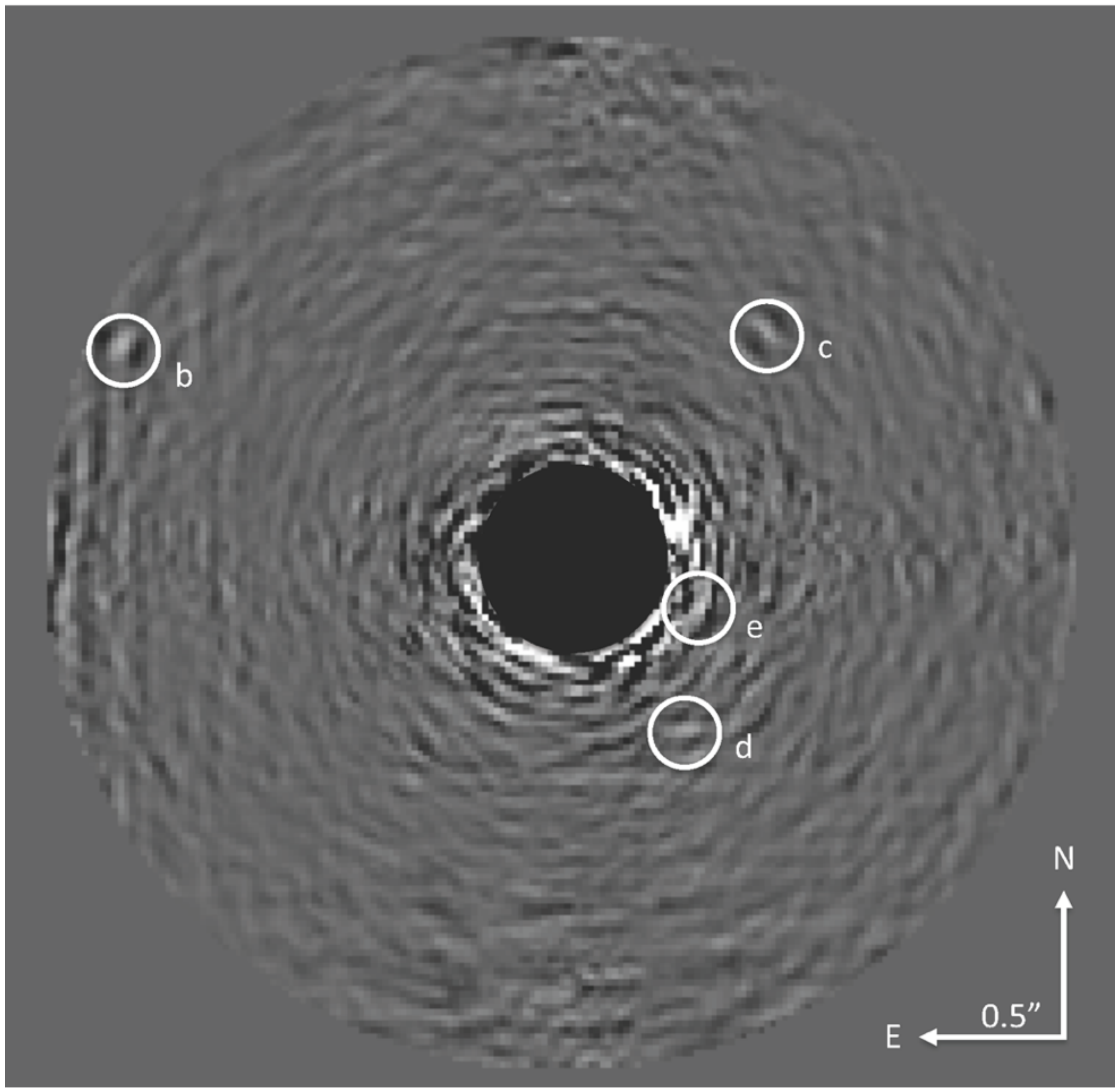
- At the limits of current technology
- Requires bright natural guide sources
- Residual wavefront errors at ~100nm
- Short wavelength AO on large apertures
- Exoplanet imaging and spectroscopy

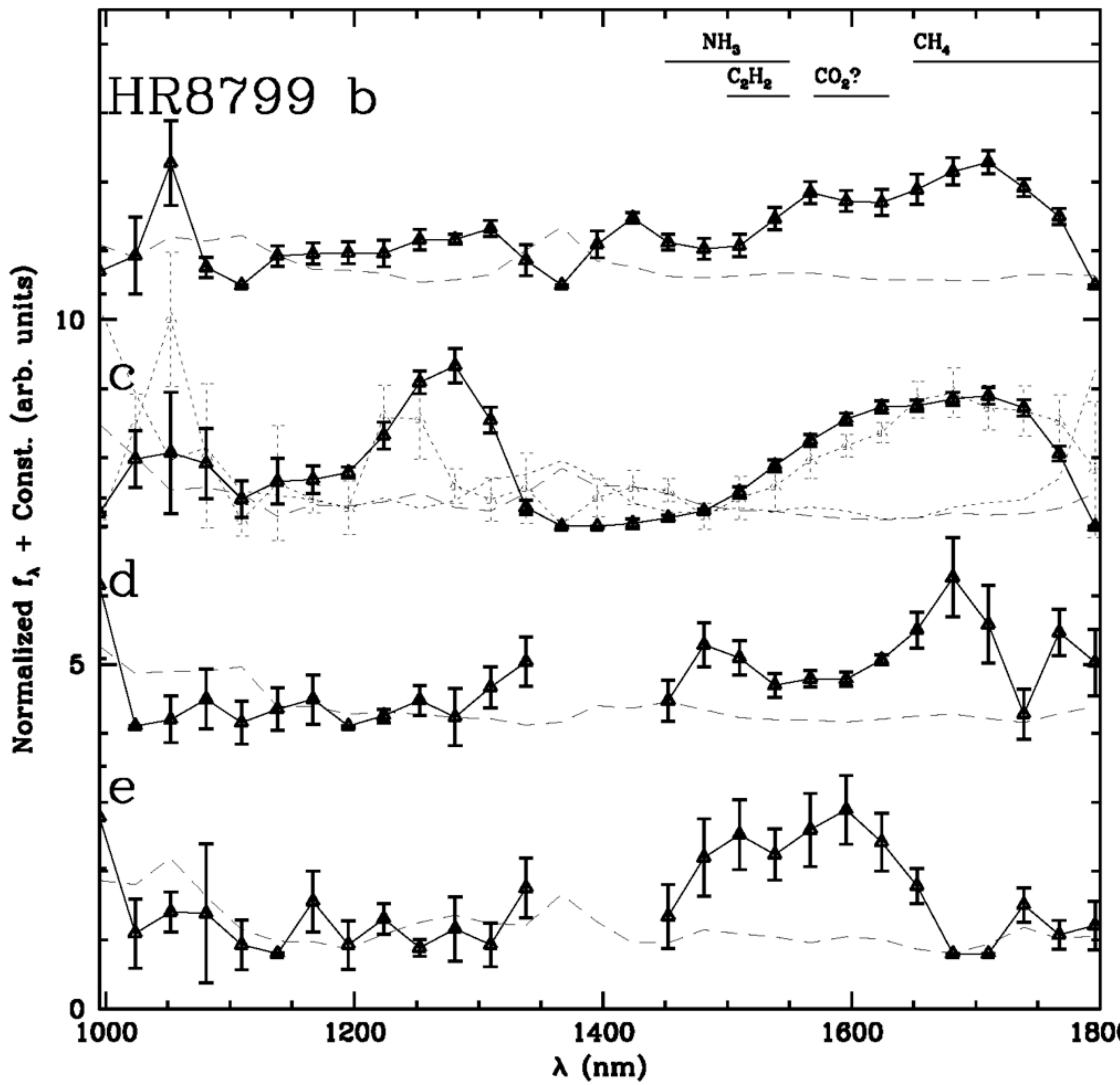
PALM-3000 at 5.1-m Hale



Dekany (PI), Baranec, PALM-3000 team, *in prep.*

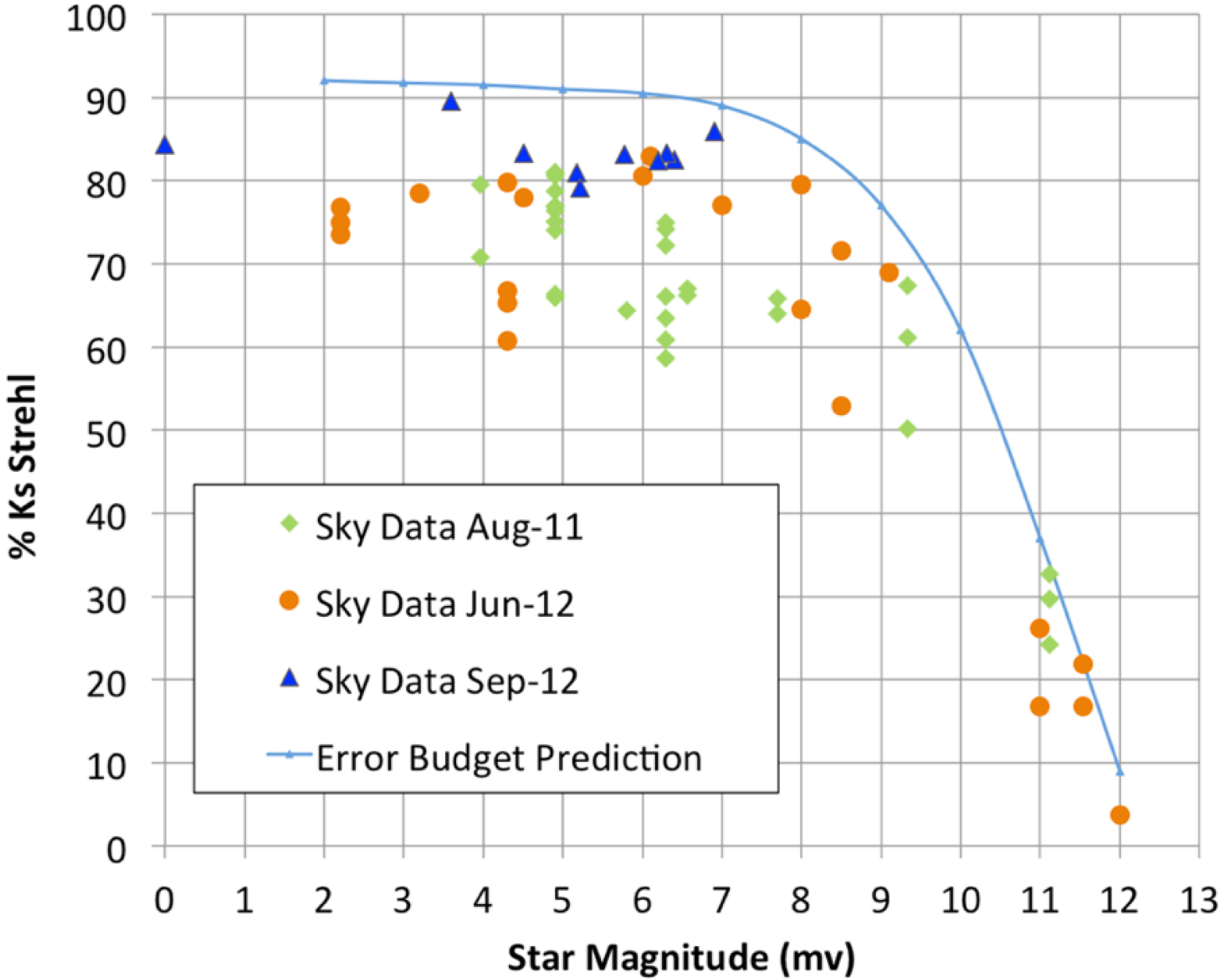
P3K + P1640 imaging spectroscopy



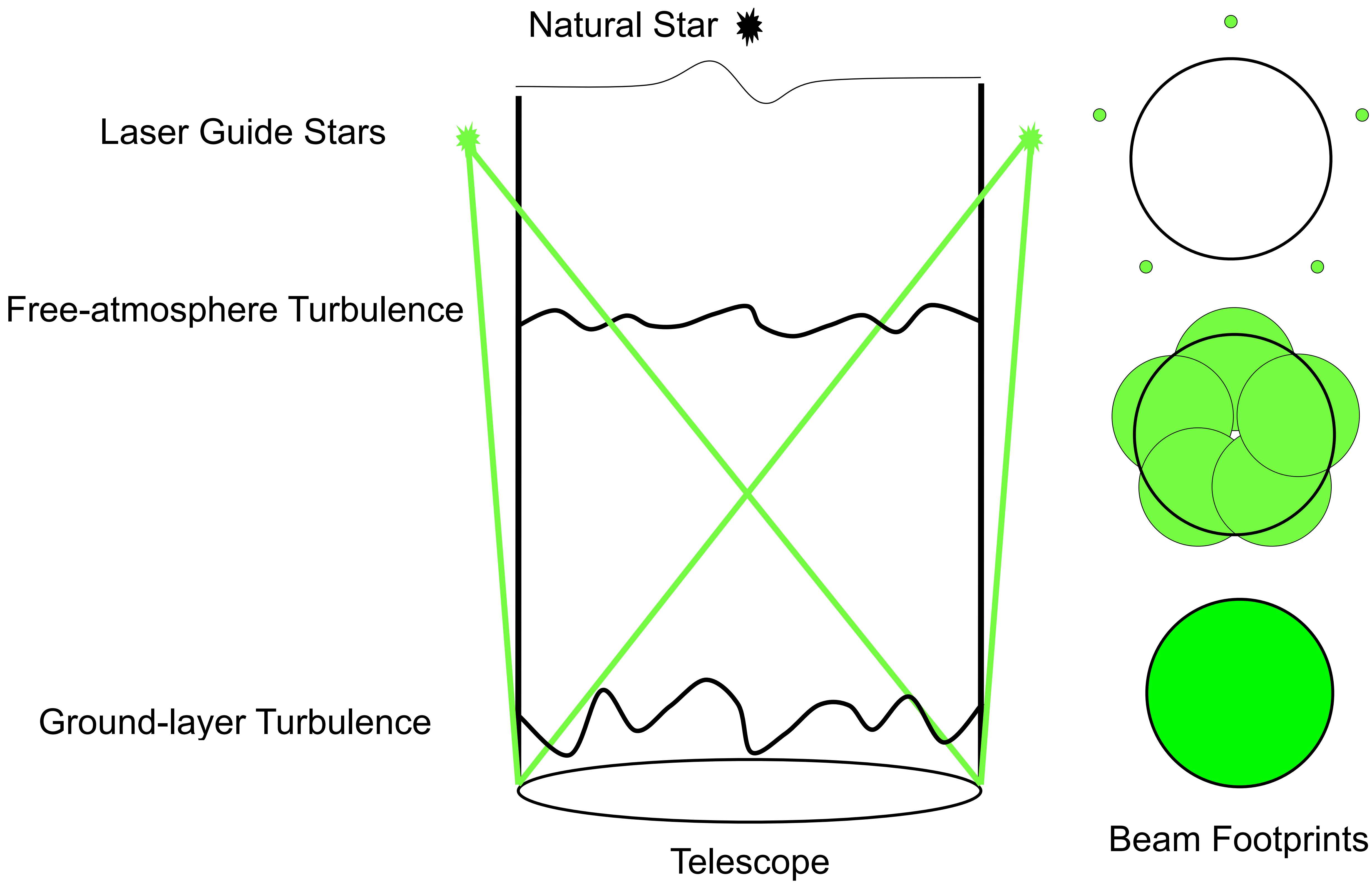


Oppenheimer, Baranec, et al., ApJ 768, (2013).

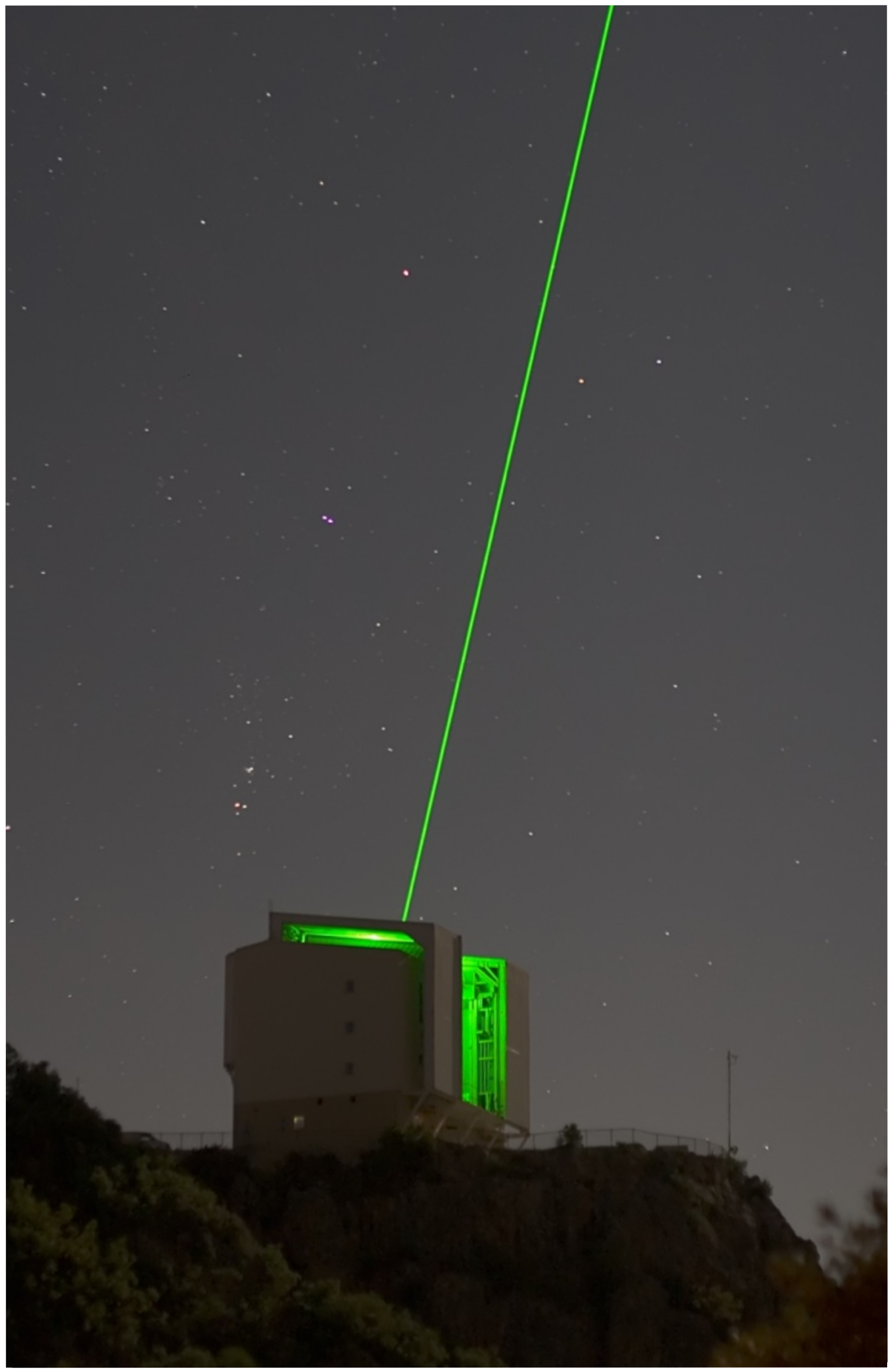
Limitation to ExAO is guide star magnitude

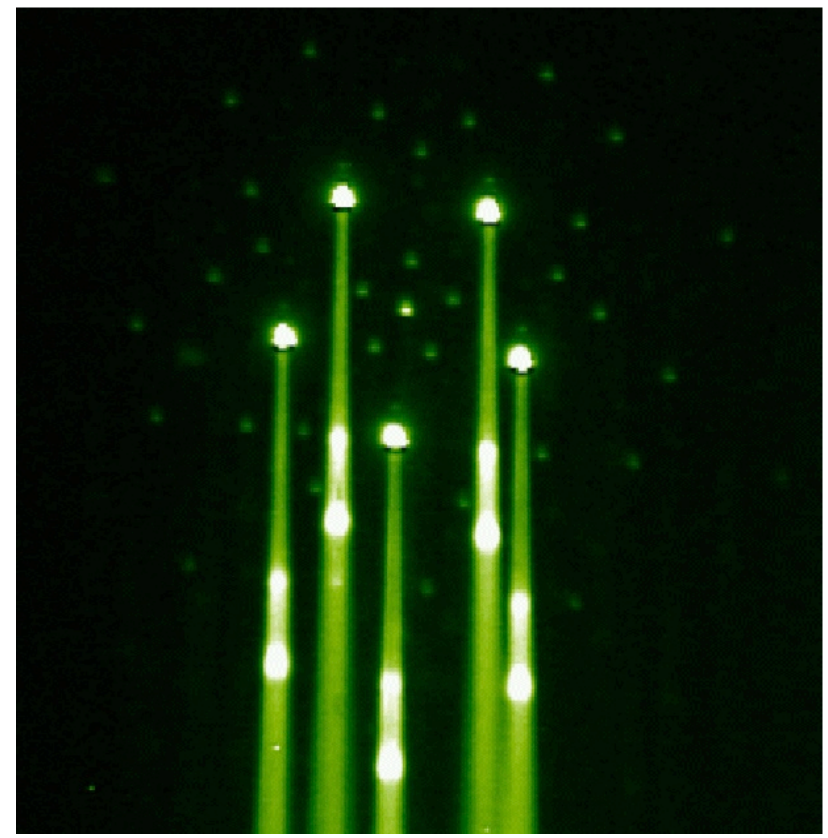


Beyond (i.e. Wide Field) Adaptive Optics



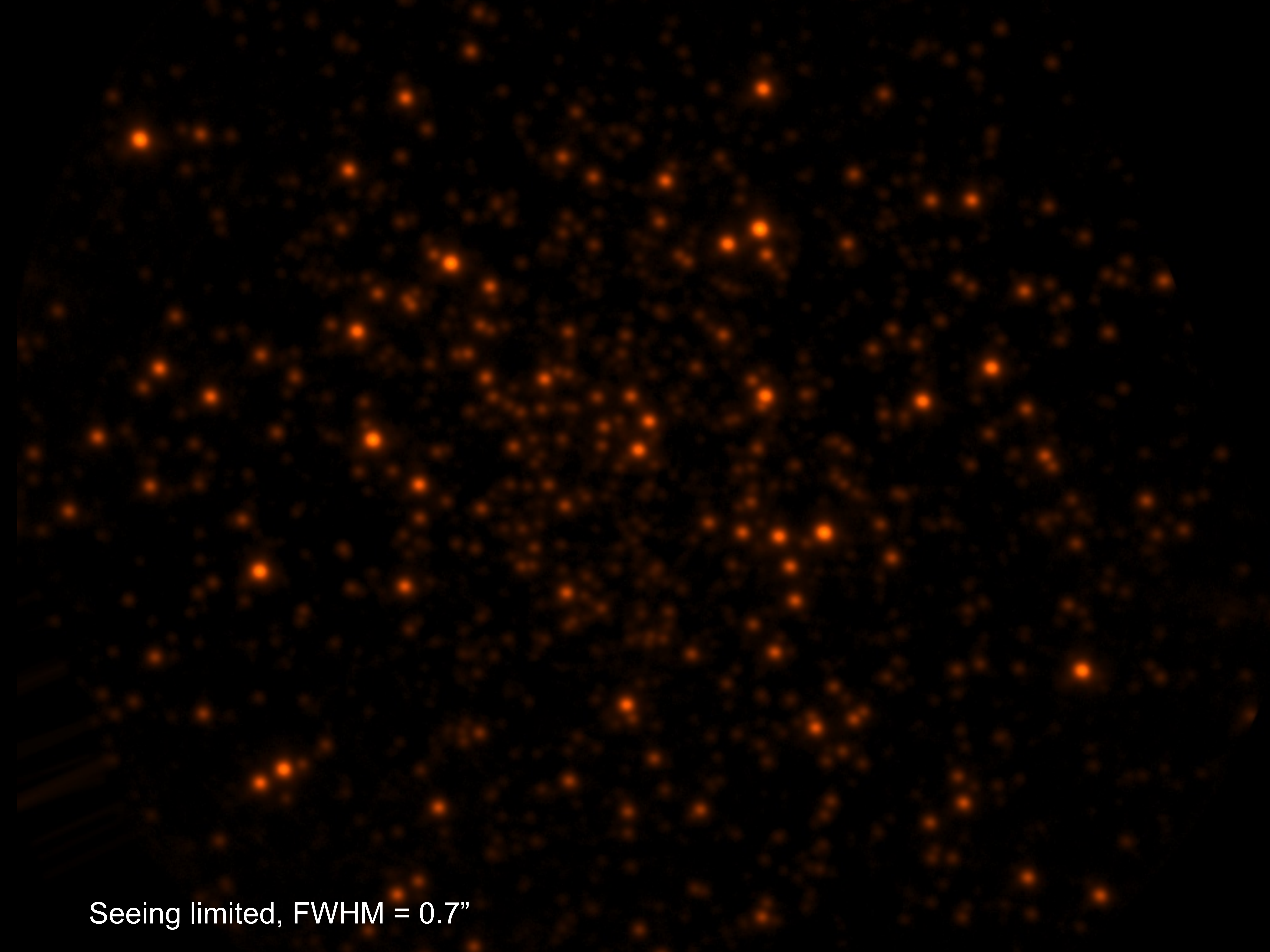
6.5-m MMT laser system



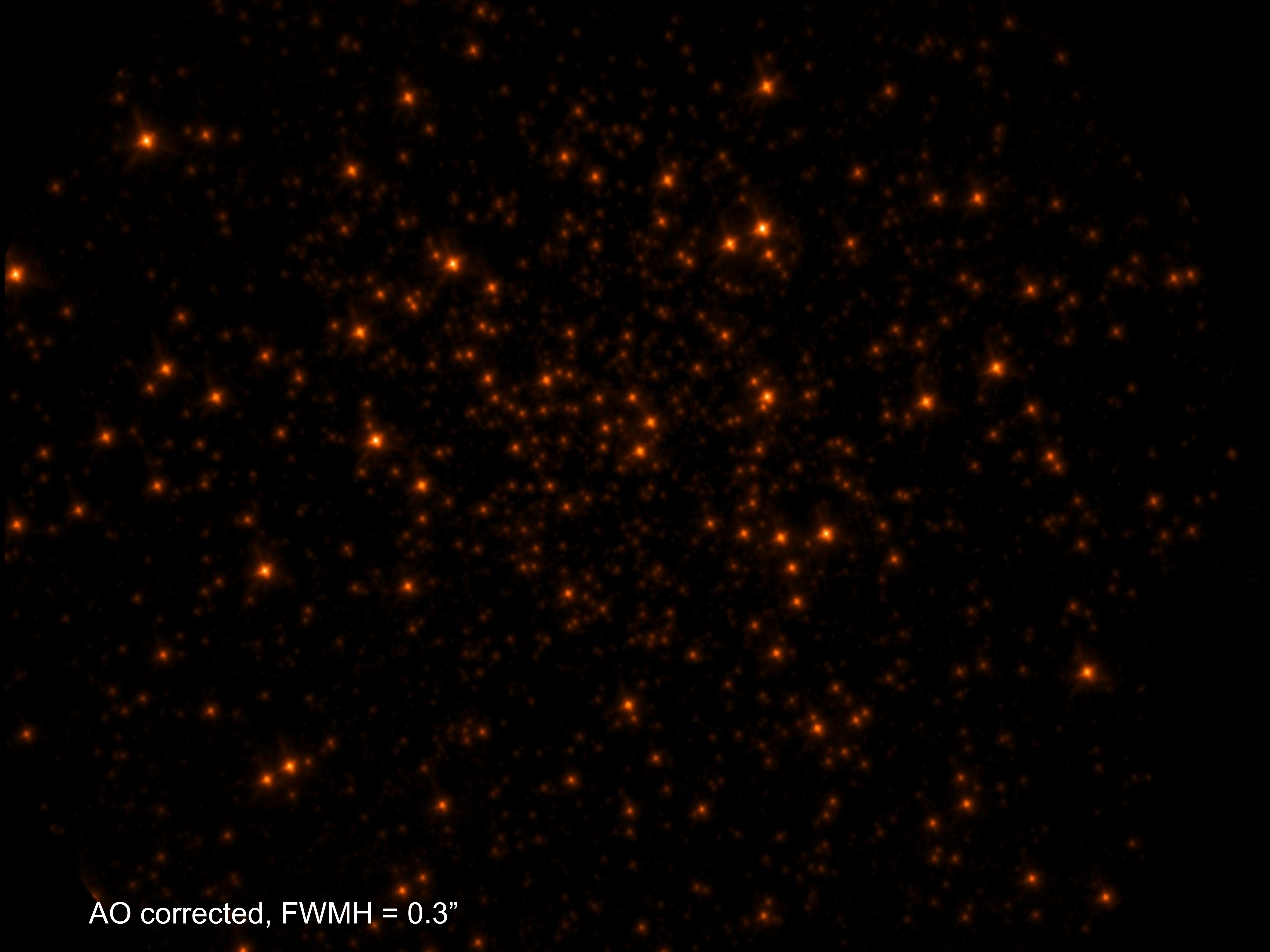


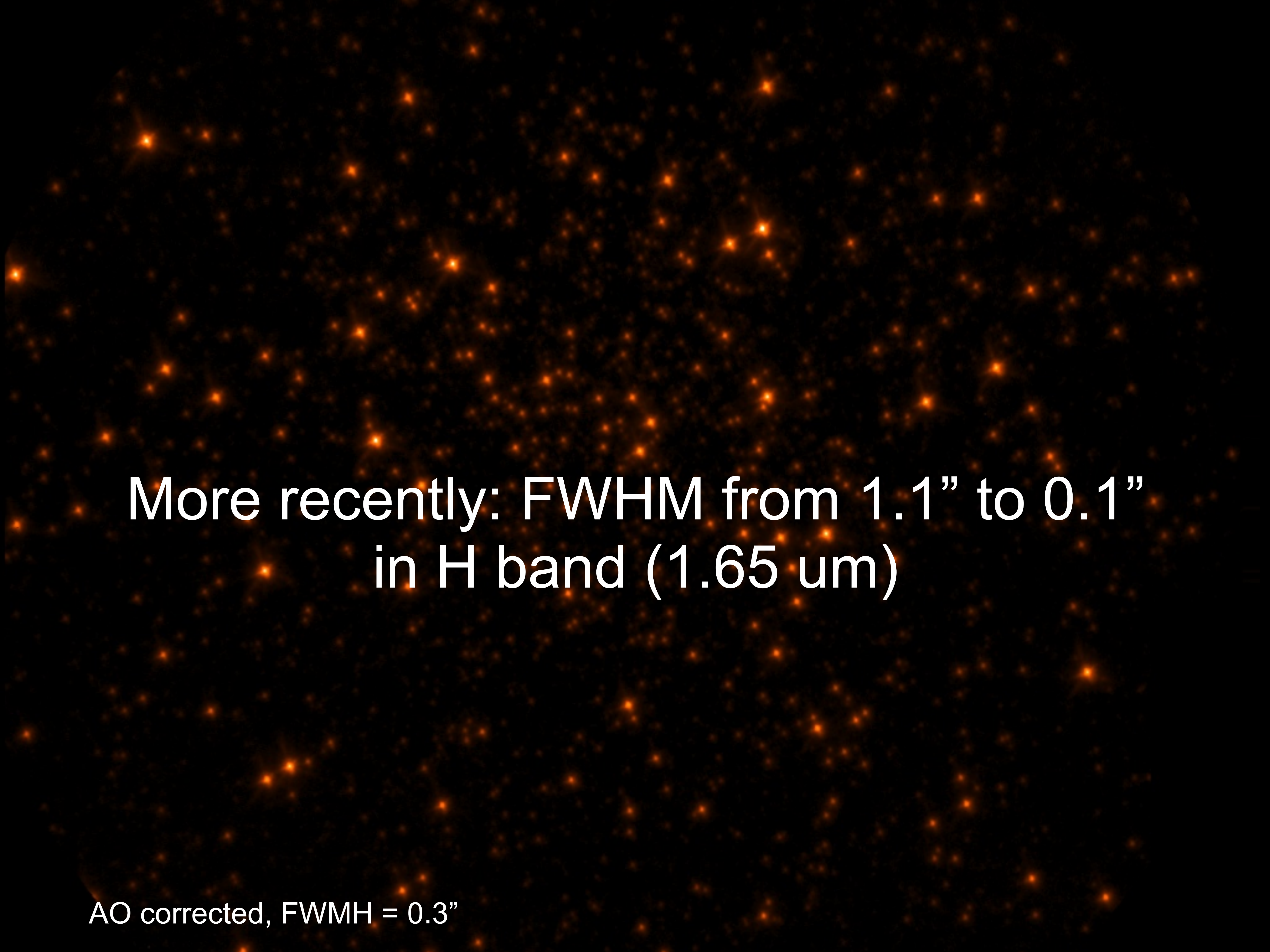
5x laser guide stars on 2' diameter

Hart, Milton, Baranec, et al., Nature, (2010).



Seeing limited, FWHM = 0.7”


AO corrected, FWMH = 0.3”



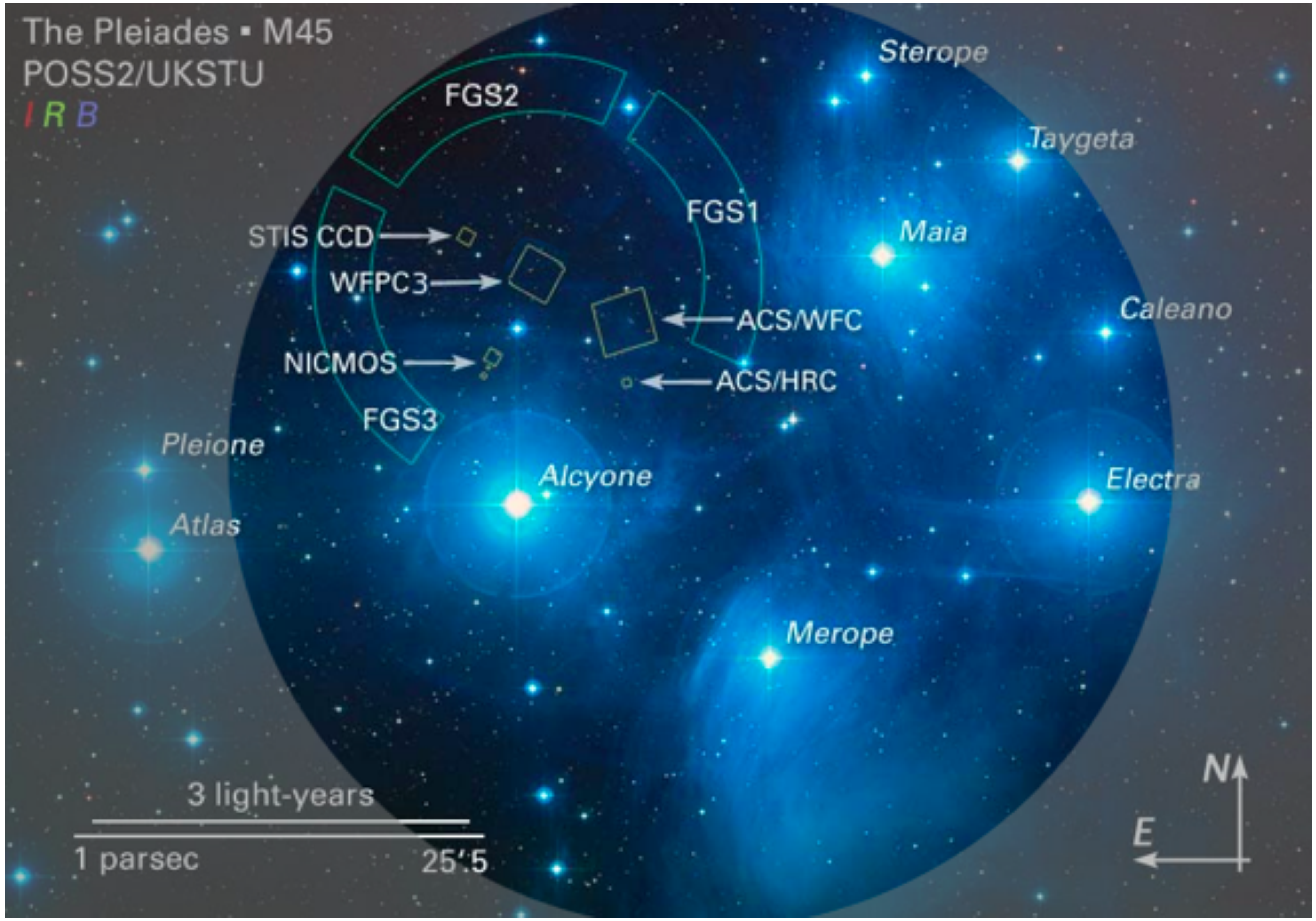
More recently: FWHM from 1.1” to 0.1” in H band (1.65 um)

AO corrected, FWMH = 0.3”

2x 8.4-m Large Binocular Telescope

- 3 Rayleigh lasers per aperture
- Upgrade path to tomographic correction with an additional Sodium laser
- Science instruments: LUCI(FER)
  - 4’ FoV, 0.1” resolution
  - Imager and multi-object spectrograph with cold slit mask changer
- “Next year”

`IMAKA



0.3” (or better) over ~degree fields of view

Proposed by Mark Chun (UH-IfA), et al.

`IMAKA

Patrolling NGS wavefront sensors are complicated

Proposing constellation of Rayleigh lasers instead

- No moving wavefront sensors
- Predictable photoreturn
- No field dependent optimization
- More stable and isotropic PSFs
- Less thinking, more science!

Rayleigh lasers for astronomy

enable the Robo-AO firehose,

make extreme AO systems even more extreme,

...and enable the widest and sharpest views.

Thank you!