Robo-AO

The First Autonomous Laser Guide Star Adaptive Optics Instrument

Dr. Reed Riddle

California Institute of Technology

USNO Workshop on Automation and Robotic Operation of Moderate-sized Telescopes for Speckle Interferometry

June 2nd, 2014

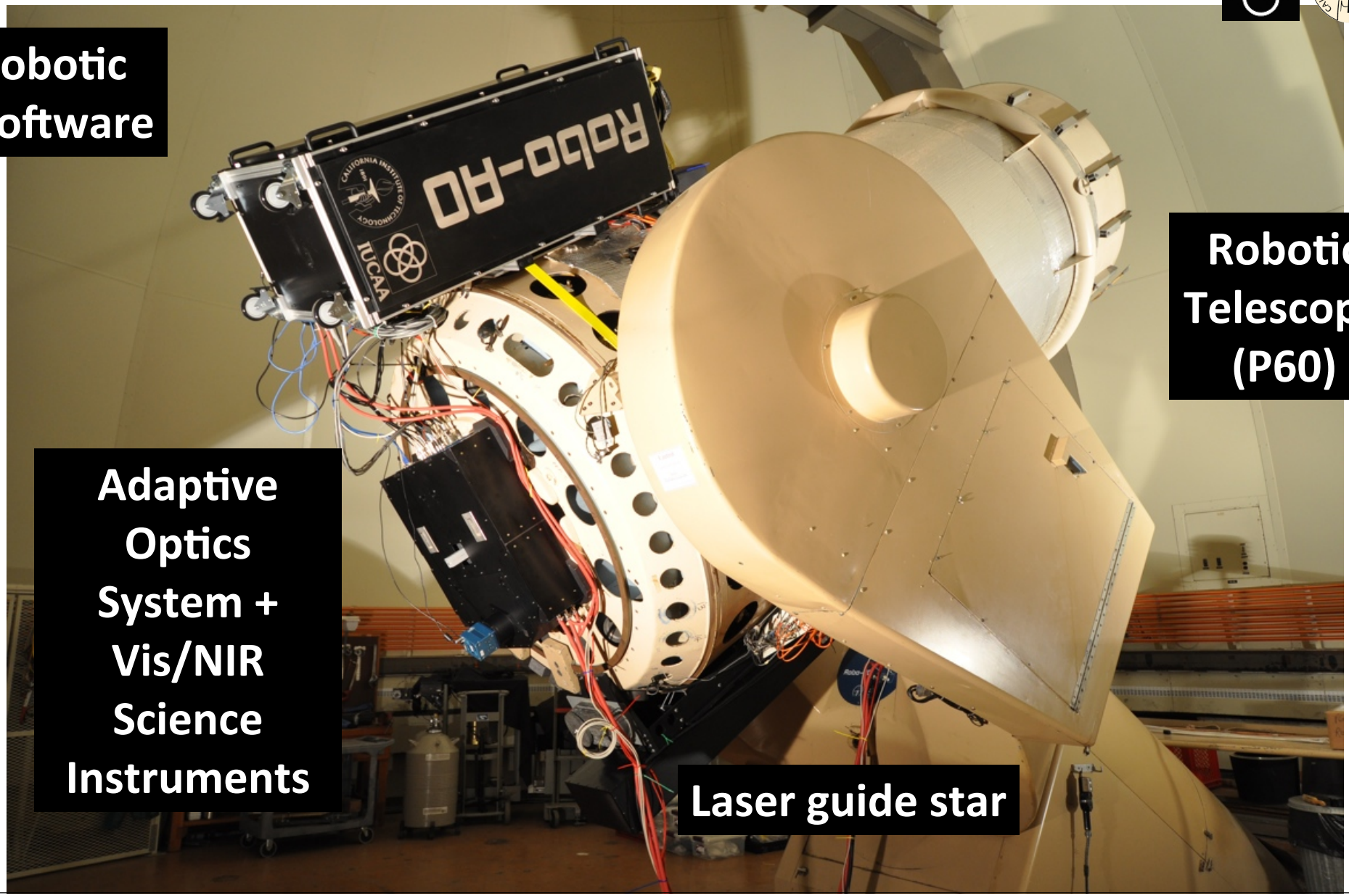
IUCAA

Robo-AO is a collaboration between the Inter-University Centre for Astronomy and Astrophysics and the California Institute of Technology

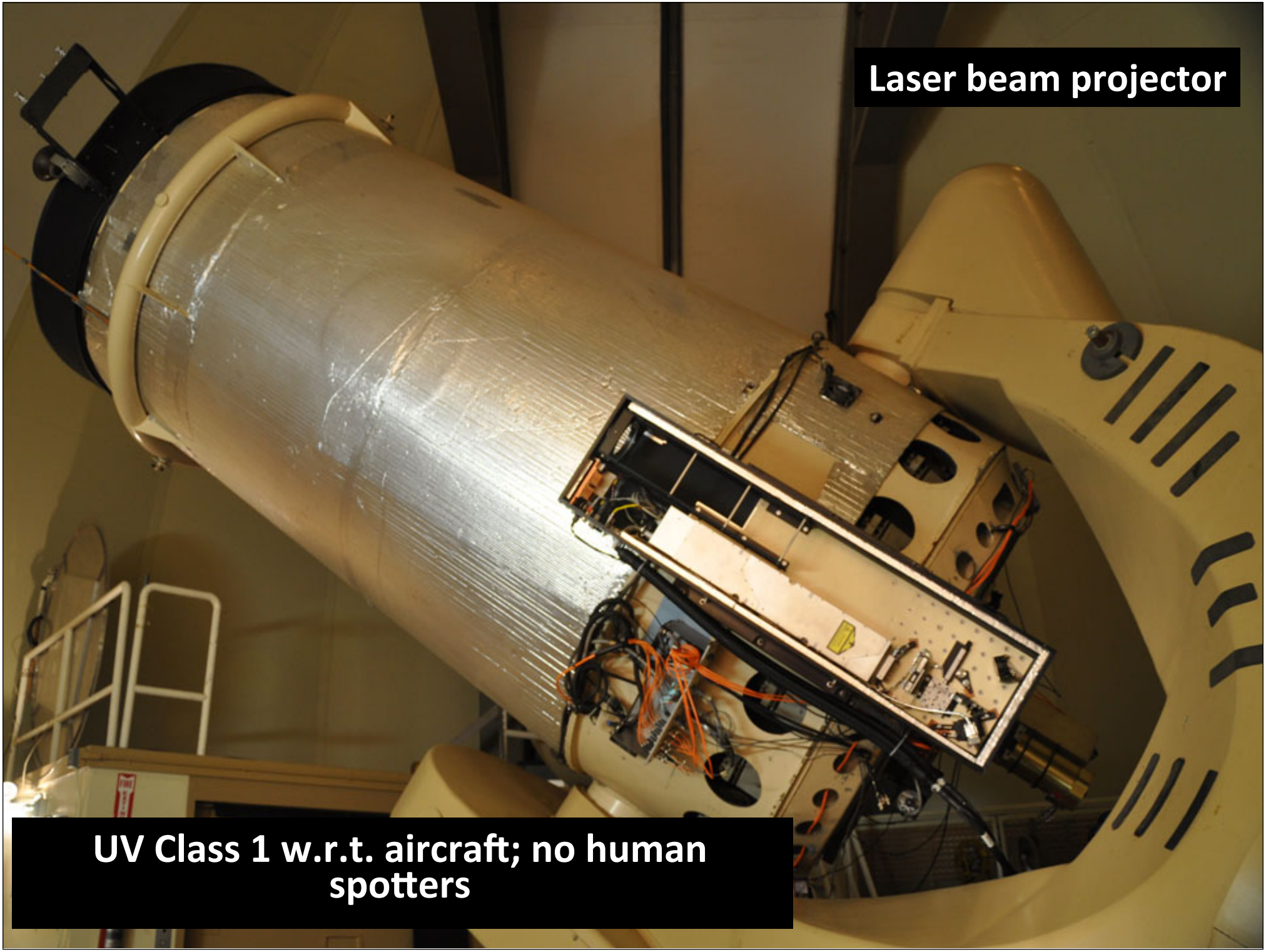
Robo-AO Vision

- Design and deploy an AO system for 1-3 m telescopes
  - Laser Guide Star
  - Robotic
- Do high throughput science
  - Lots of small telescope time available
  - Unique science capability
- Make it affordable
- Put copies on 1-3 m telescopes around the world

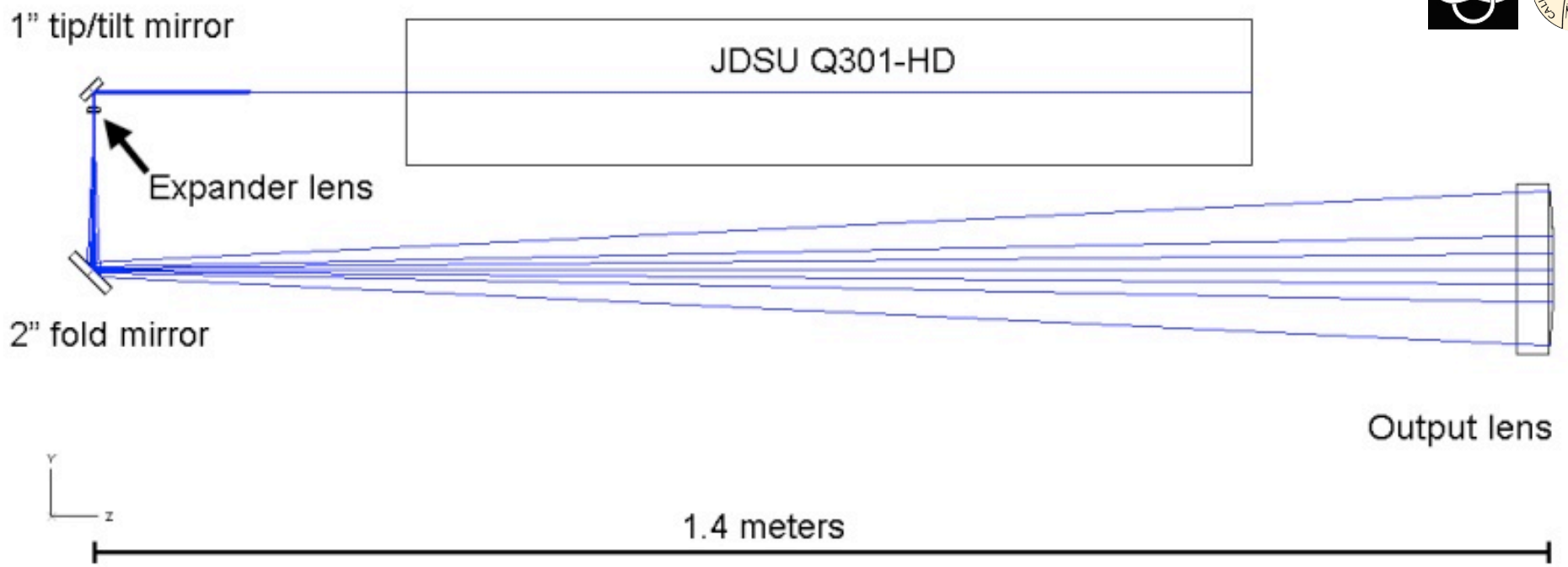
Robo-AO on the Palomar 60”



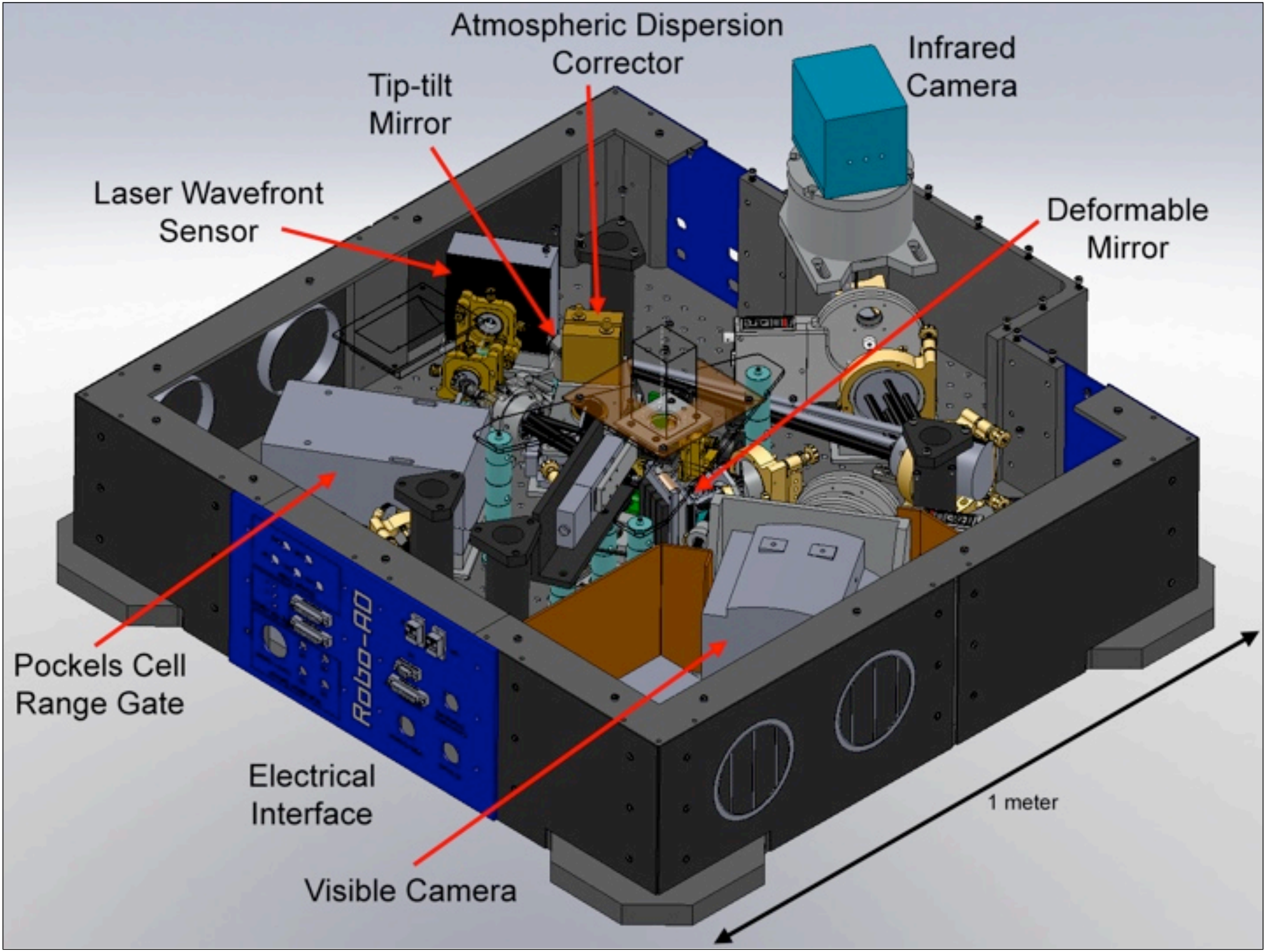
Robo-AO on the Palomar 60”

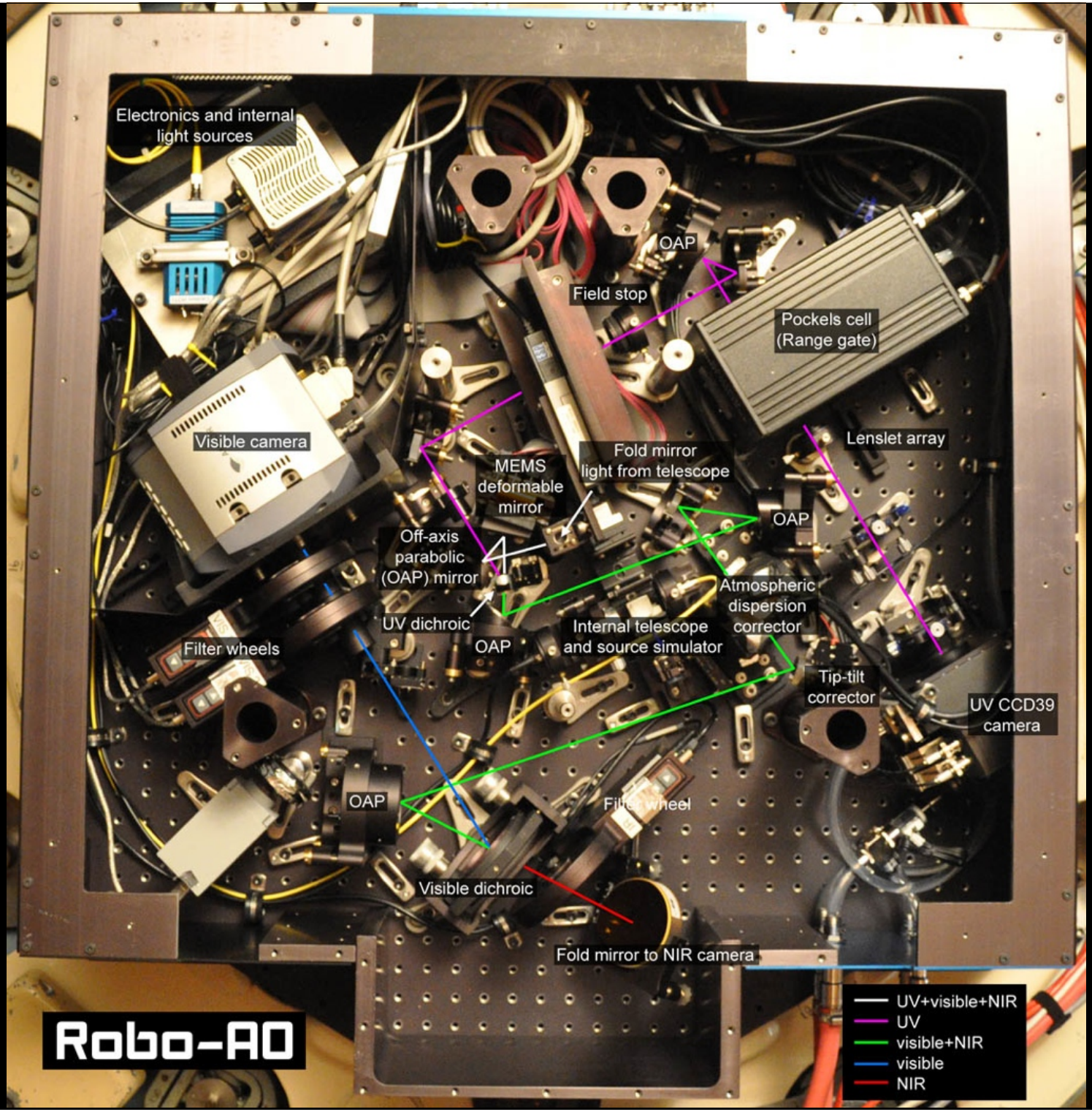

Laser beam projector
UV Class 1 w.r.t. aircraft; no human spotters

Laser Beam Projector

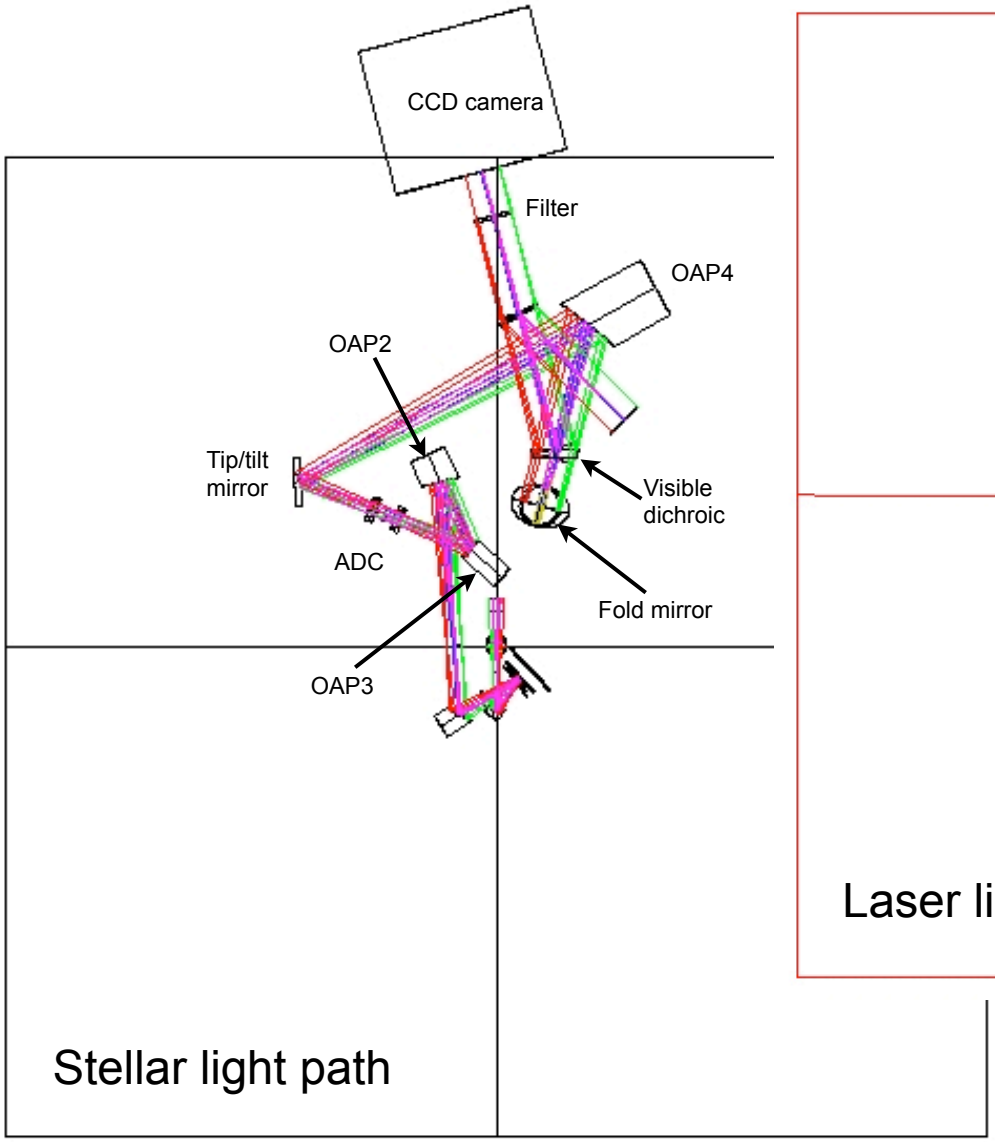


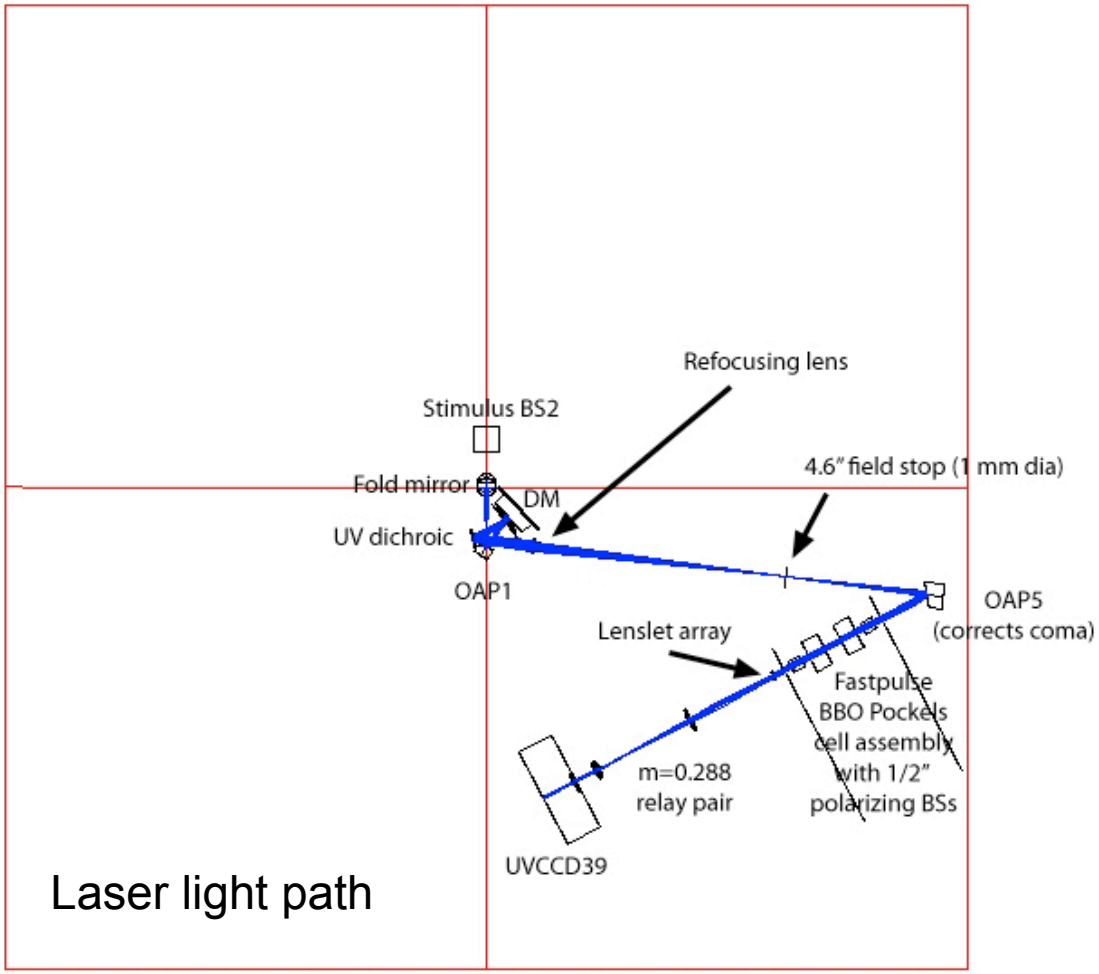
- JDSU commercial laser
  - 12 W @ 10 kHz, λ=355nm
  - Robust and reliable
- Optional periscope
- Uplink jitter correction with AO loop


Atmospheric Dispersion Corrector
Infrared Camera
Tip-tilt Mirror
Laser Wavefront Sensor
Deformable Mirror
Pockels Cell Range Gate
Electrical Interface
Visible Camera
1 meter
Robo-AO


Electronics and internal light sources
OAP
Field stop
Pockels cell (Range gate)
Visible camera
Lenslet array
MEMS deformable mirror
Fold mirror light from telescope
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

Robo-AO Optical Design

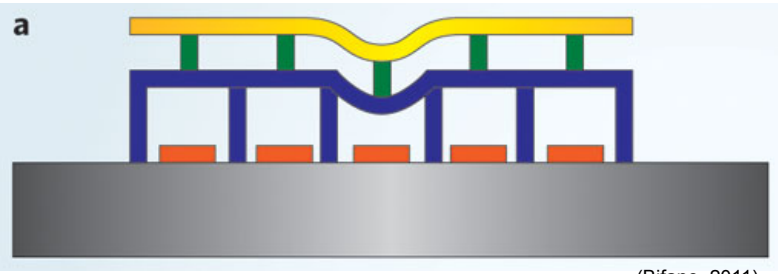




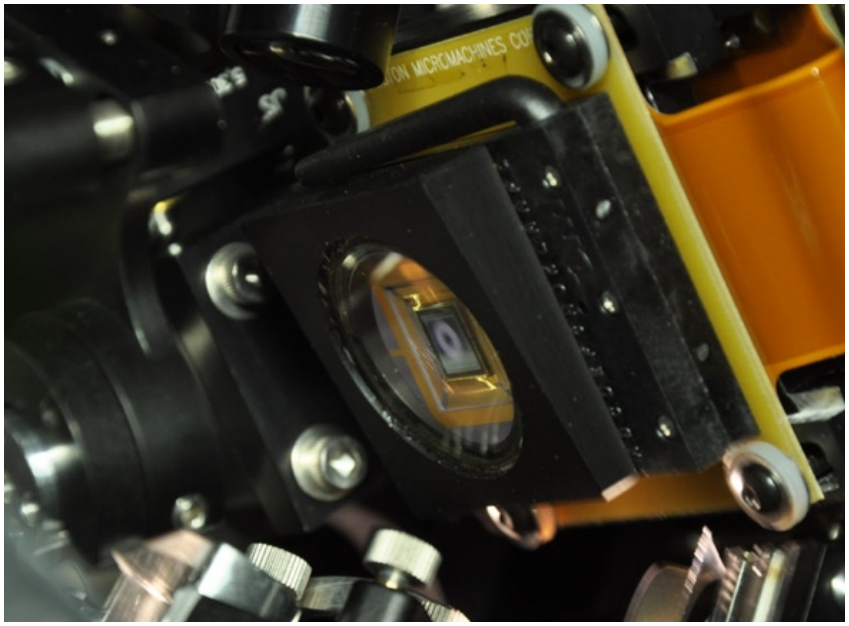
Wavefront Correctors

MEMS deformable mirror

- 12 x 12 actuators
- 3.5 µm stroke
- UV-NIR AR window

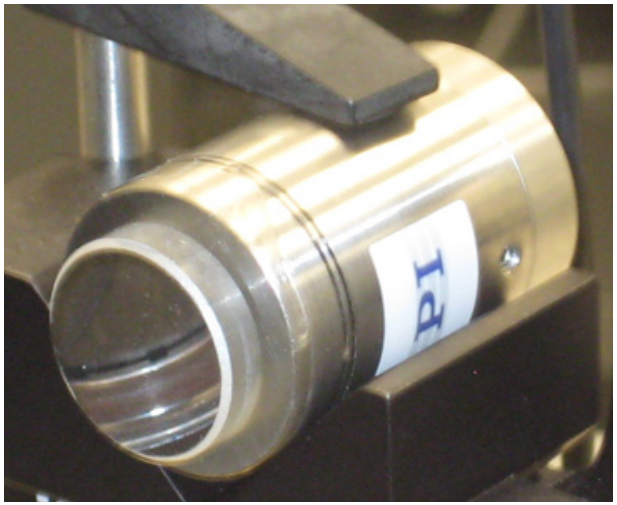


(Bifano, 2011)



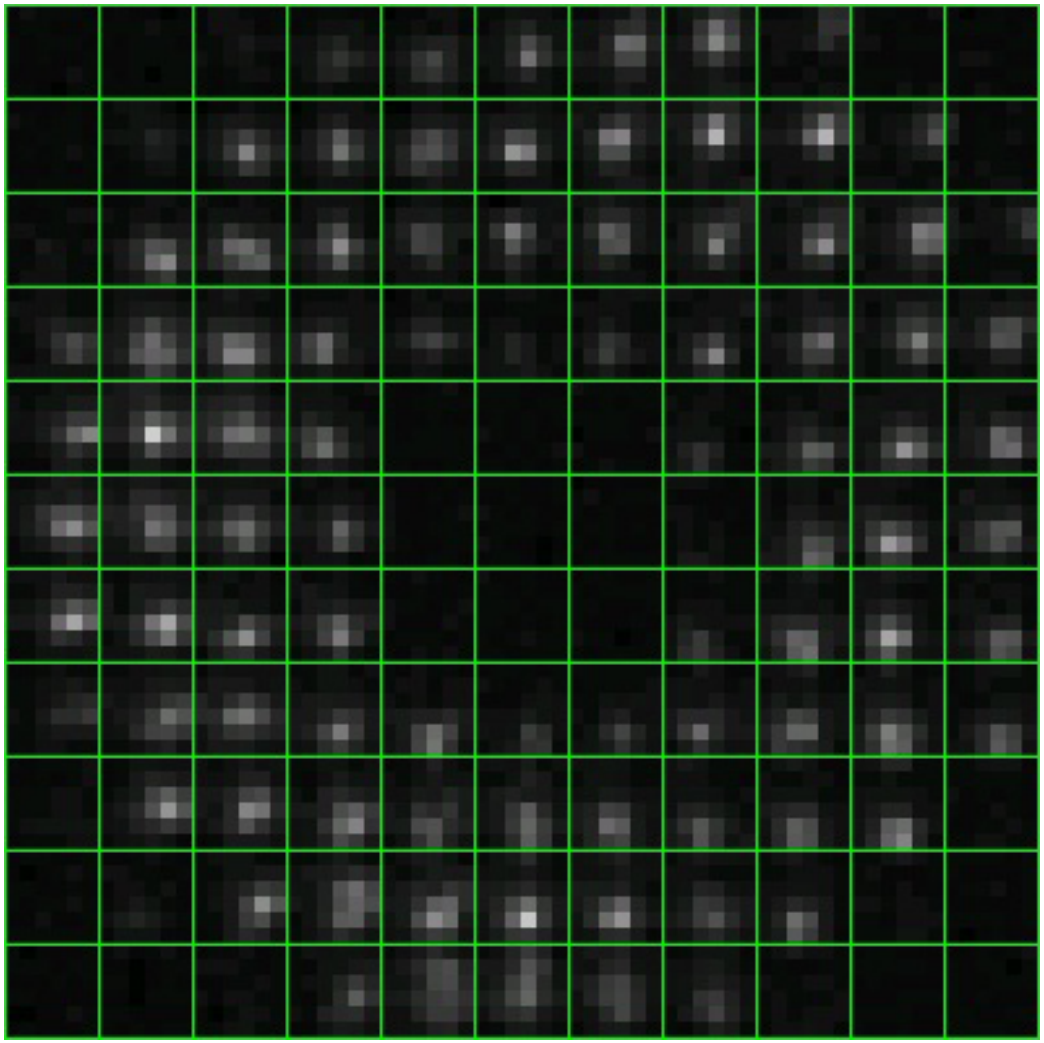
Piezo fast steering mirror

- Up to 4” tip/tilt correction

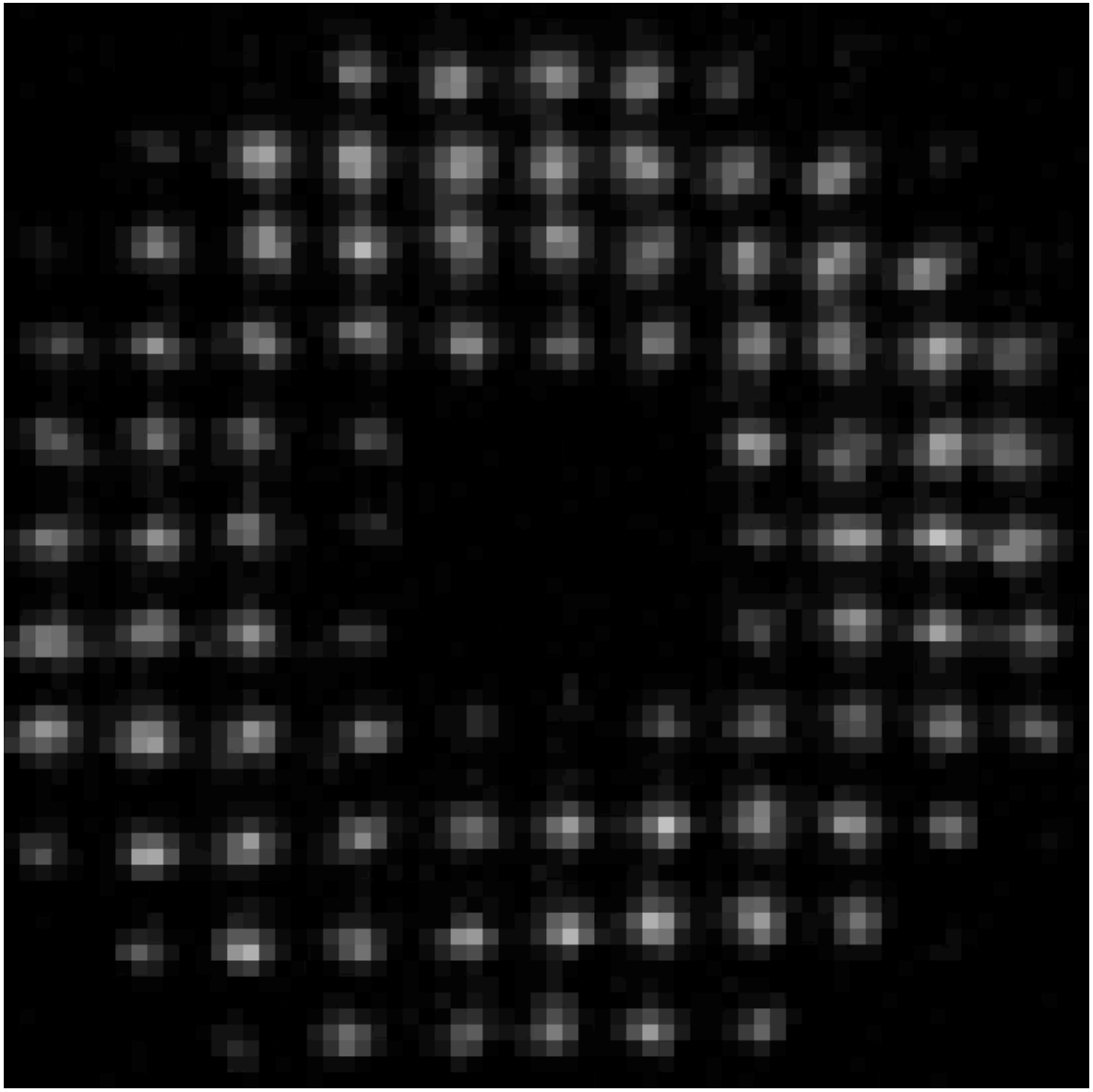


Wavefront Sensors

- Shack-Hartmann HOWFS
  - 11 x 11 subapertures
  - QE = 72% (at 350 nm)
  - Pockels cell range-gate
- HOWFS tip-tilt signal controls laser uplink tip-tilt correction
- Image motion (tip-tilt) measured with one of the two science instruments

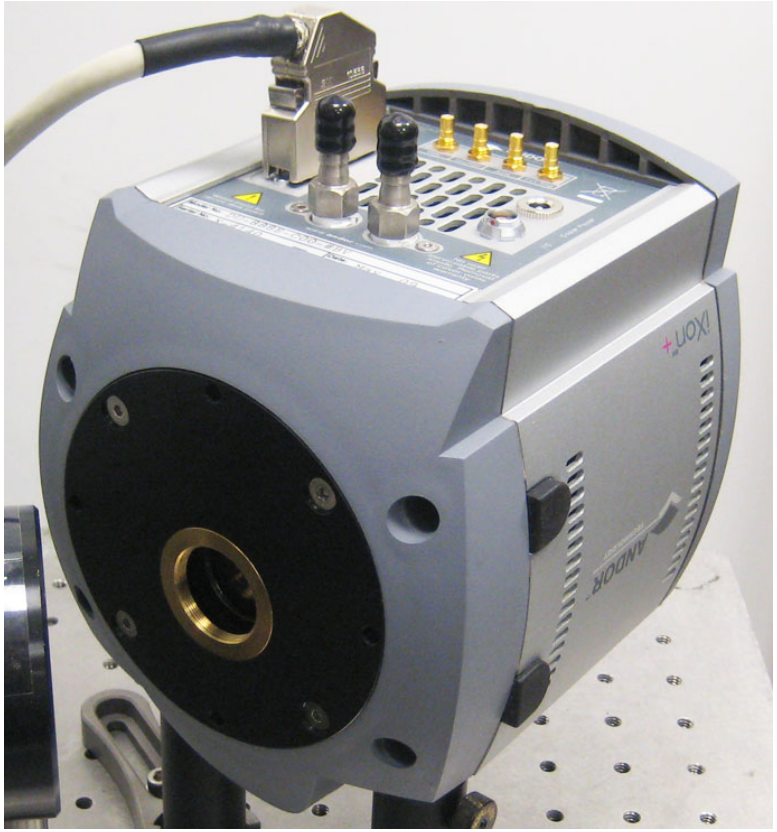


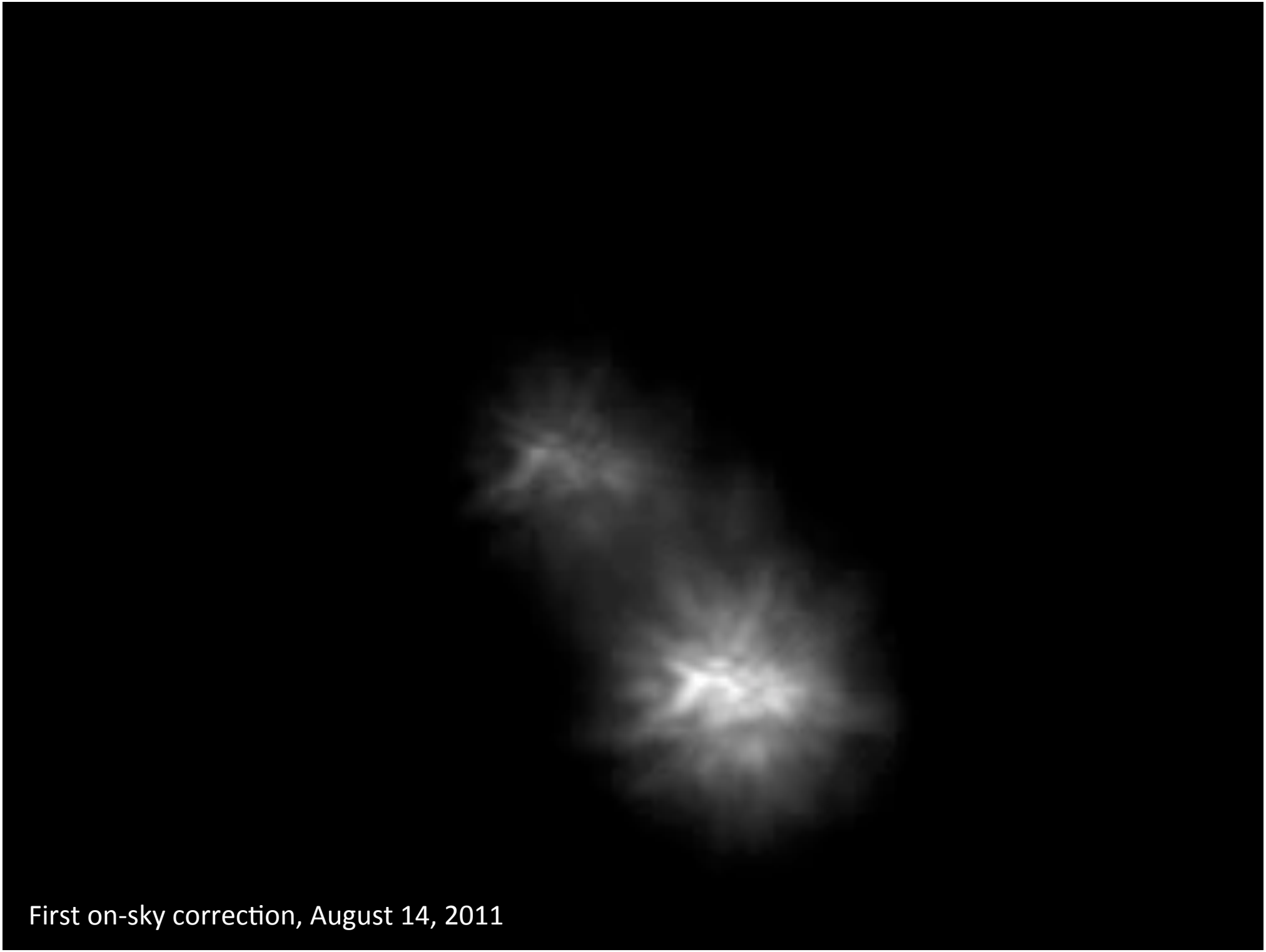
High-order Wavefront Sensor



Visible science camera

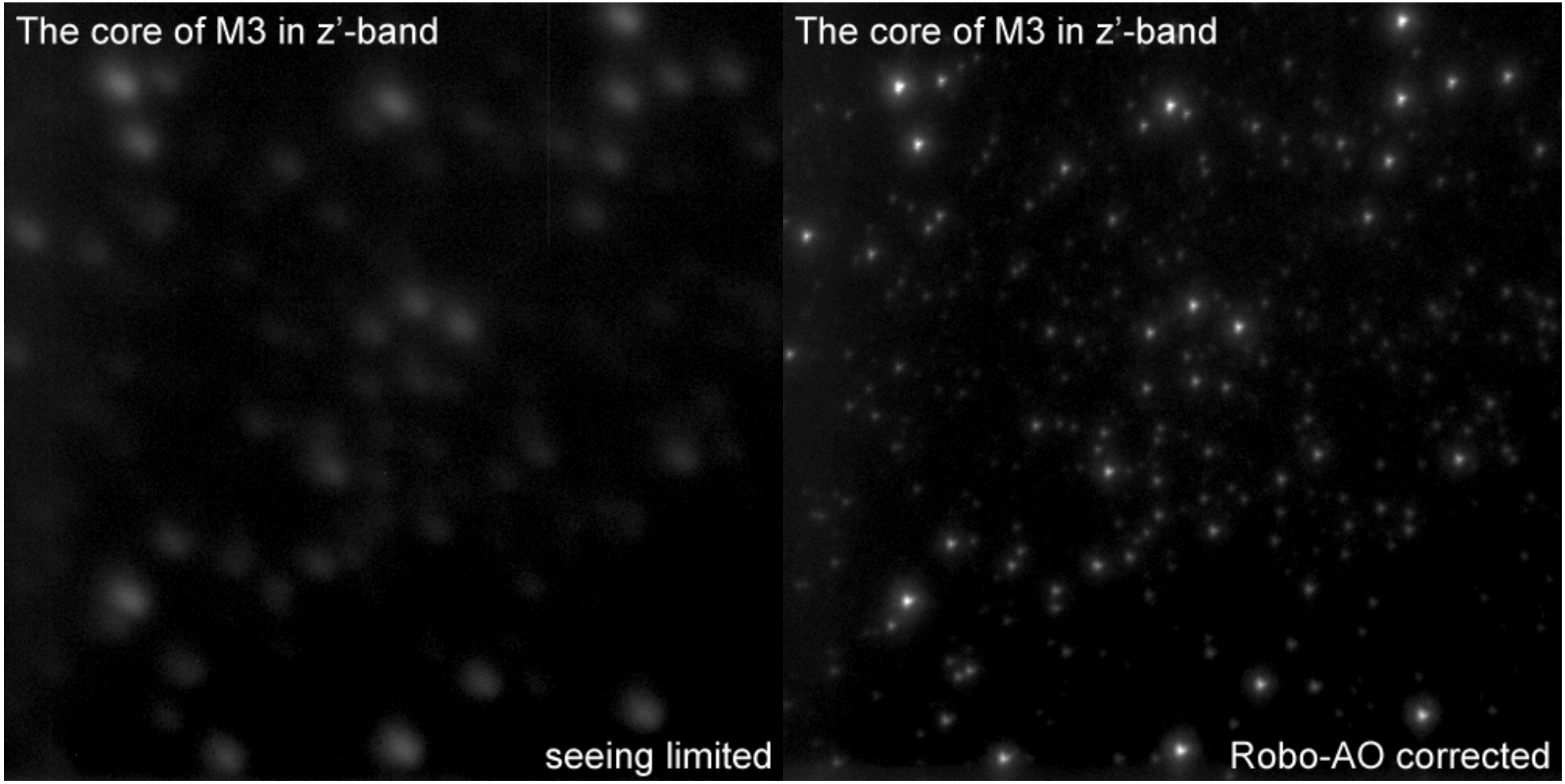
- Andor iXonEM+ DU-888
- Electron Multiplying CCD
- 44” x 44” square FoV
- 0.043” pixels
  - Nyquist at λ = 620 nm
- Full frame rate: 8.6 Hz
- Sub frame rate: ~300 Hz

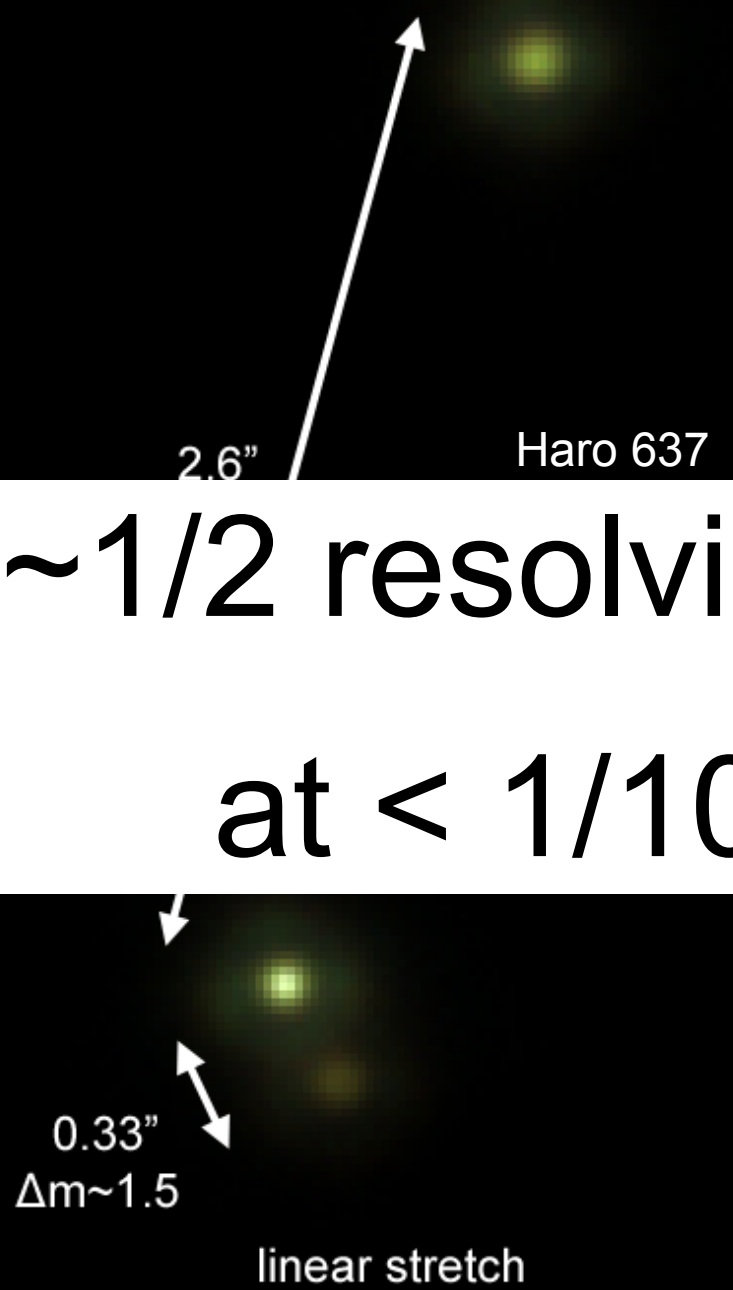




First on-sky correction, August 14, 2011

Wavefront Correction





λ			RMS
890	0.14”	20.4%	178

~1/2 resolving power of HST

at < 1/1000th the cost

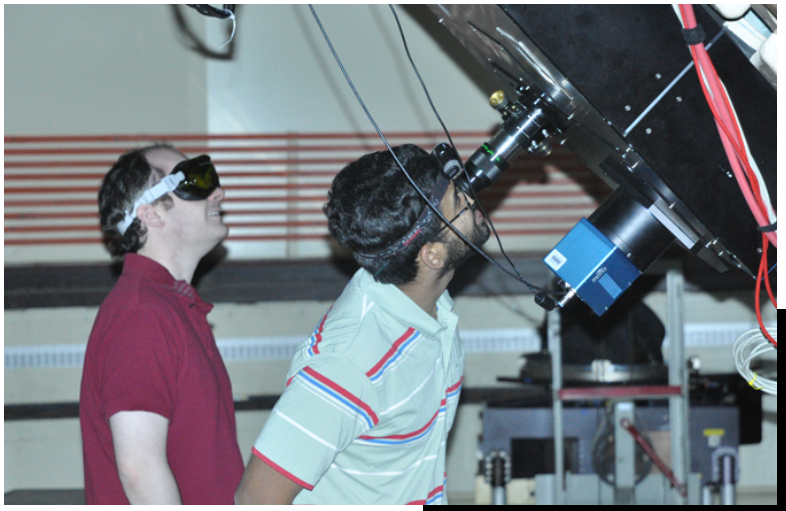
Robo-AO

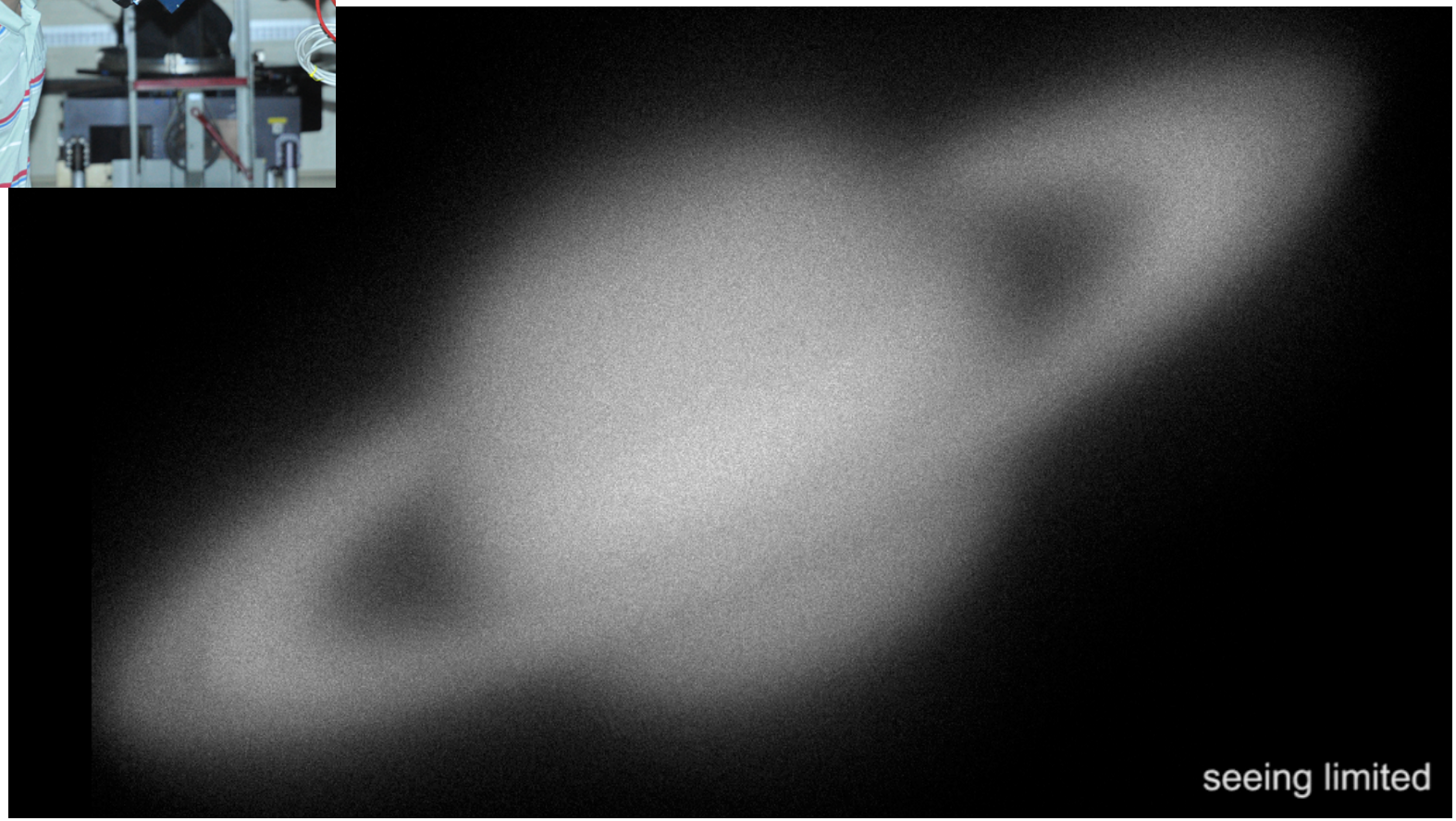
Robo-AO

Observations of Jupiter from the Palomar Observatory 60" telescope using the Robo-AO laser adaptive optics system

January 11th, 2012 5:13-5:42 UTC

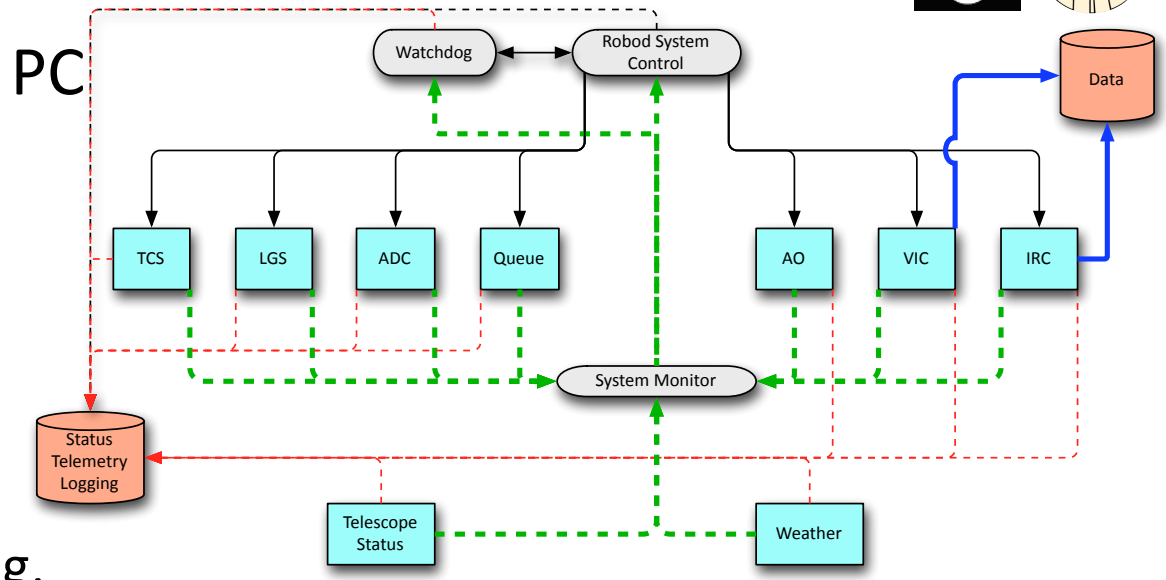
Eyepiece Adaptive Optics!

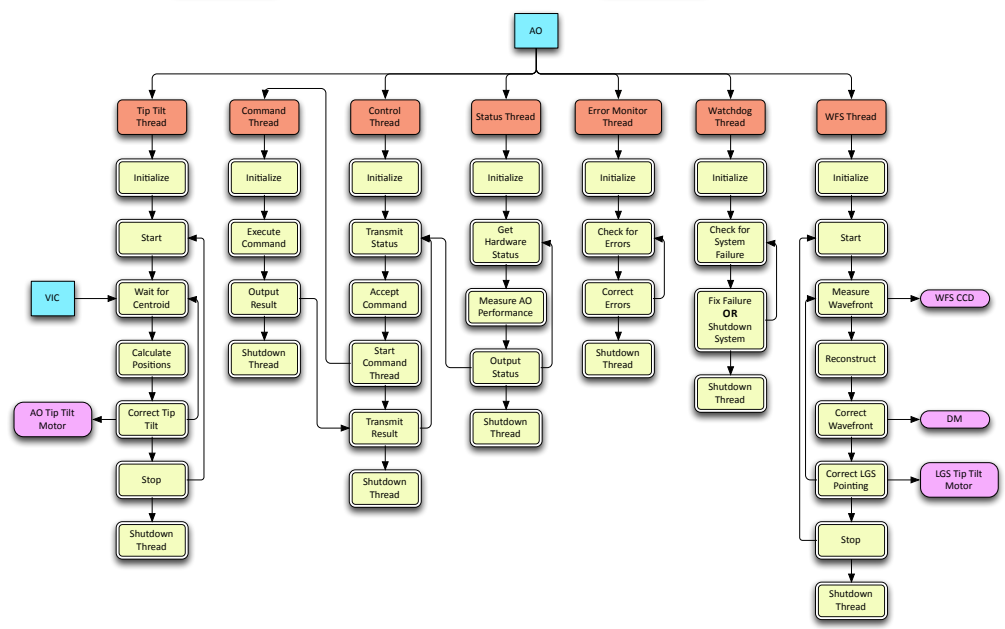




Robotic Control Software

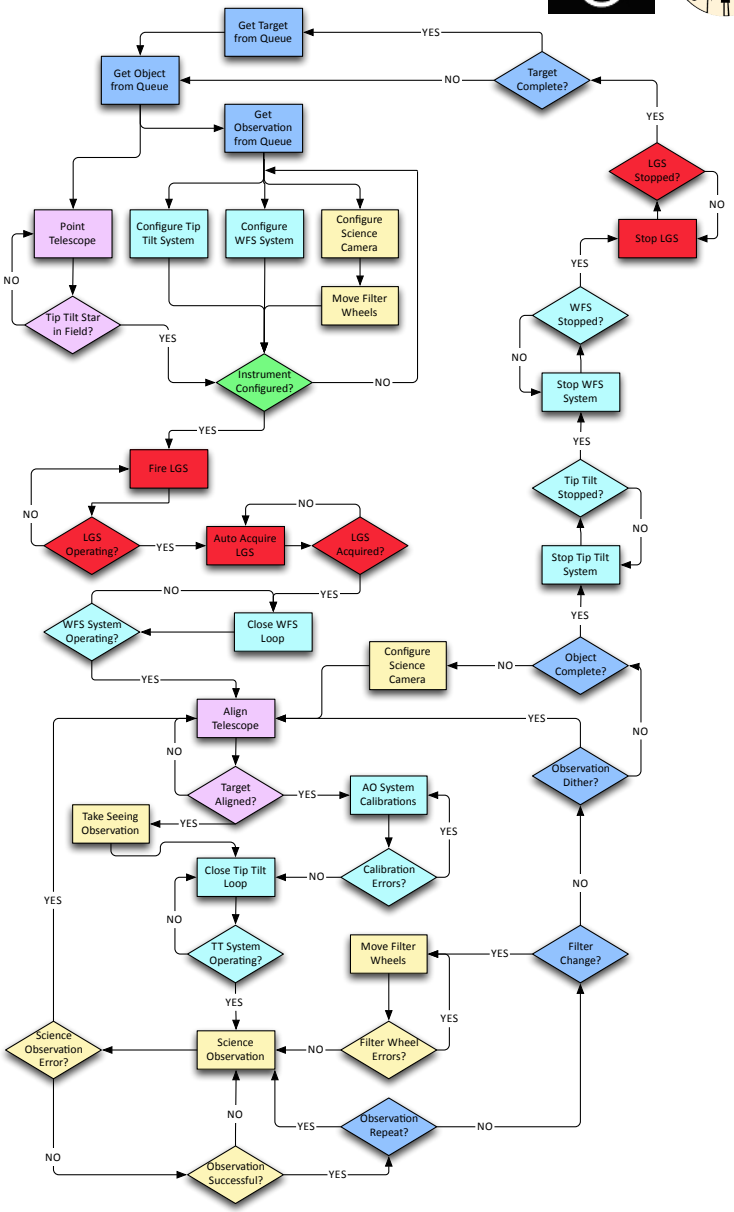
- Fedora 13 Linux on one PC
- Developed in C++
  - Extensive multithreading
  - Server-Client architecture
  - Data management, logging, telemetry
- 120,000+ lines of code
  - Modular design
  - Can be used as framework for other robotic systems

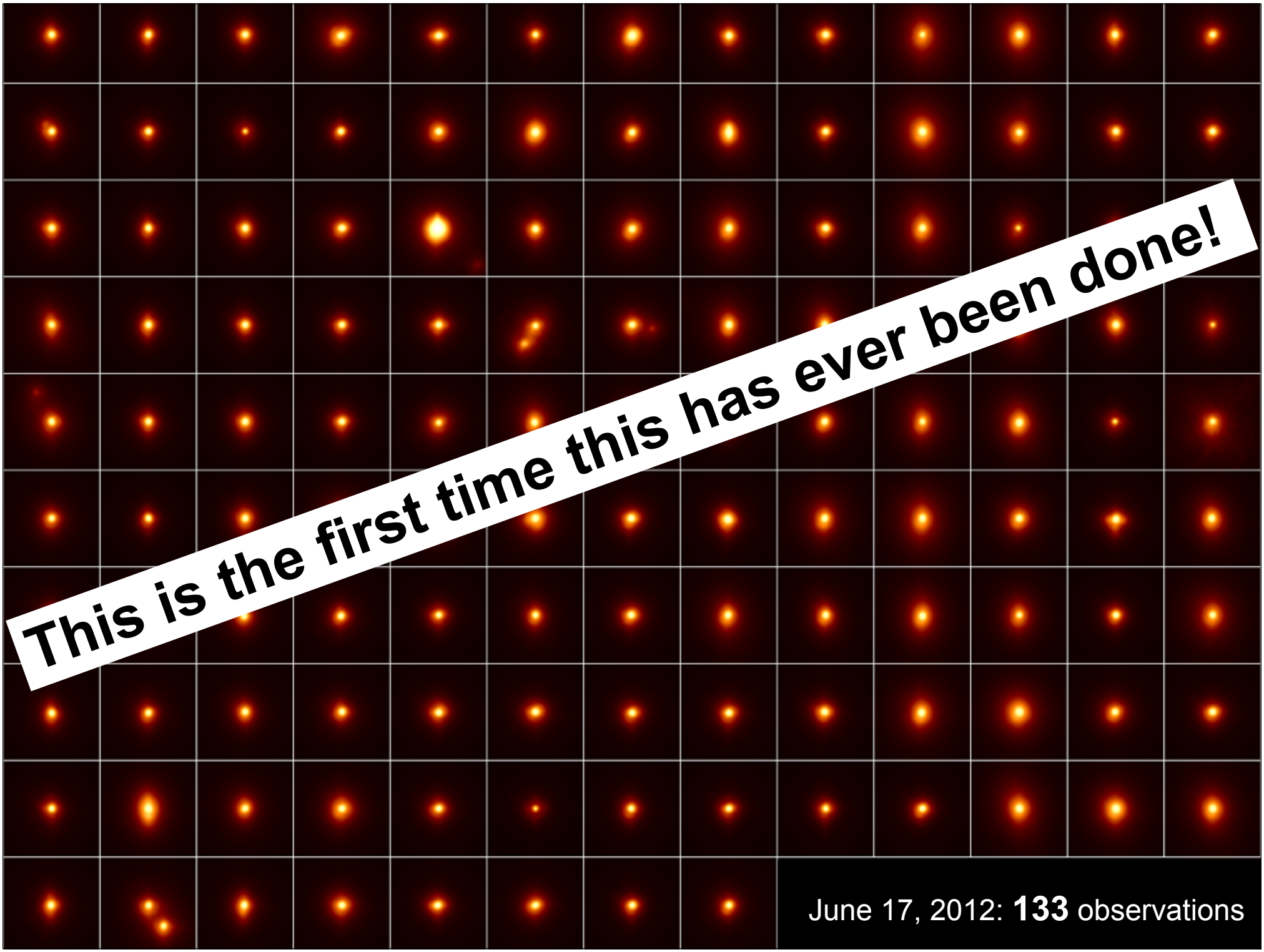




Robotic Control Software

- Fully robotic control system
  - Supervisor software controls scheduling, operations
  - Watchdog processes
- Safety system
  - Laser safety a priority
- Final system design very close to initial system design
  - Three years from design to robotic operations

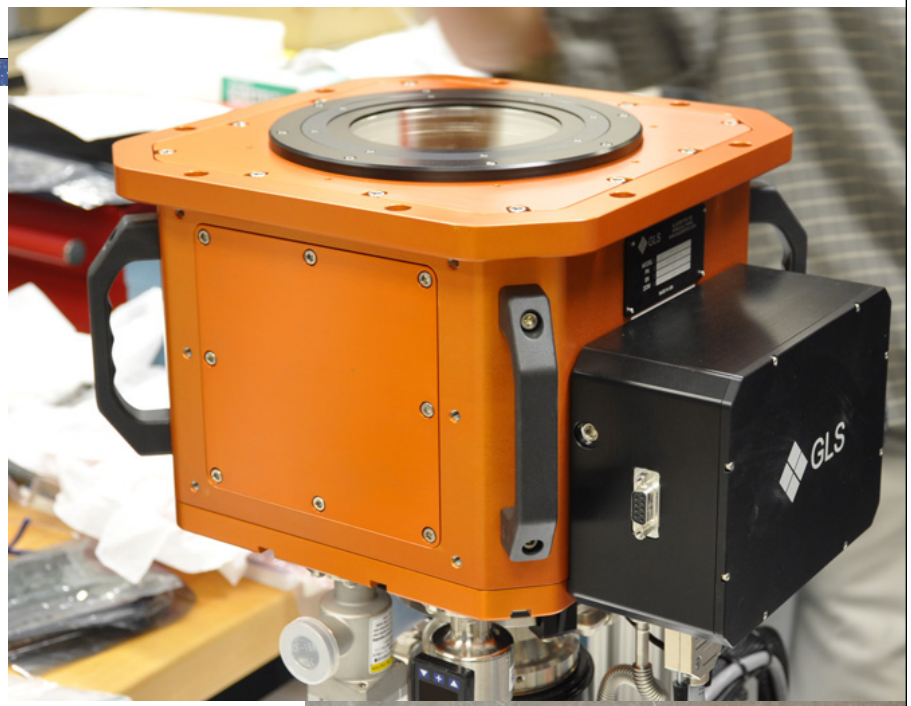



This is the first time this has ever been done!
June 17, 2012: **133** observations

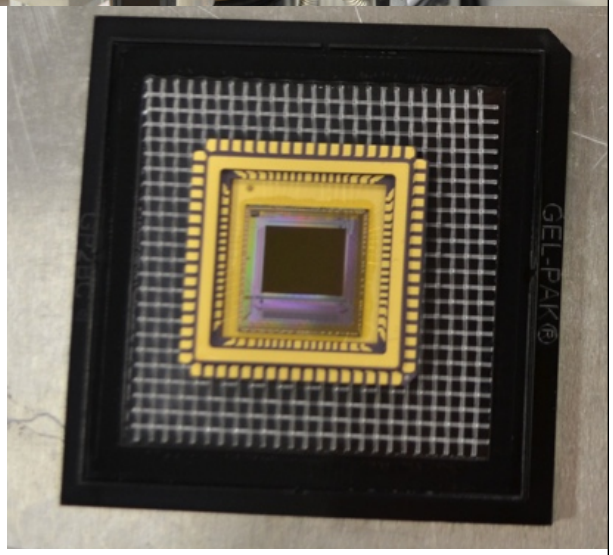
Current Operations

- About 20 observations per hour
  - Record of 240 observations in one night
  - Over 10,000 total robotic observations
  - ~85 second overhead time between science observations
    - 40-50 seconds to set up AO system
    - ~55% of robotic observing time is open shutter science time
- Intelligent queue scheduler
- Safety oversight by individual at P60
- Automatic data reduction pipeline

HiloCam IR Camera



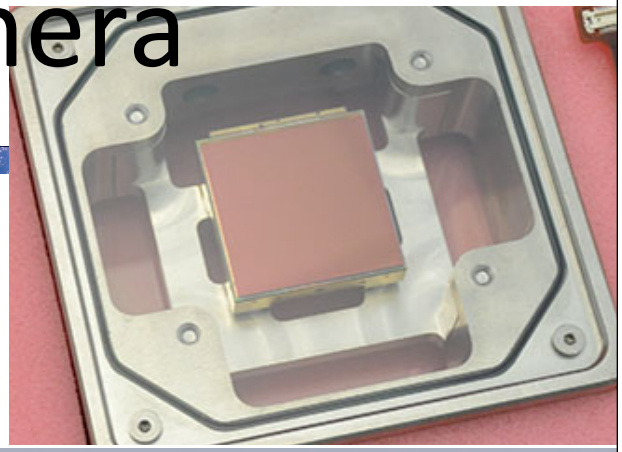
- IR APD array
  - High speed imaging
  - Tip-tilt
- 320x256 Selex SAPHIRA HgCdTe
- Full frame readout @100Hz
- << 1 e- readout noise



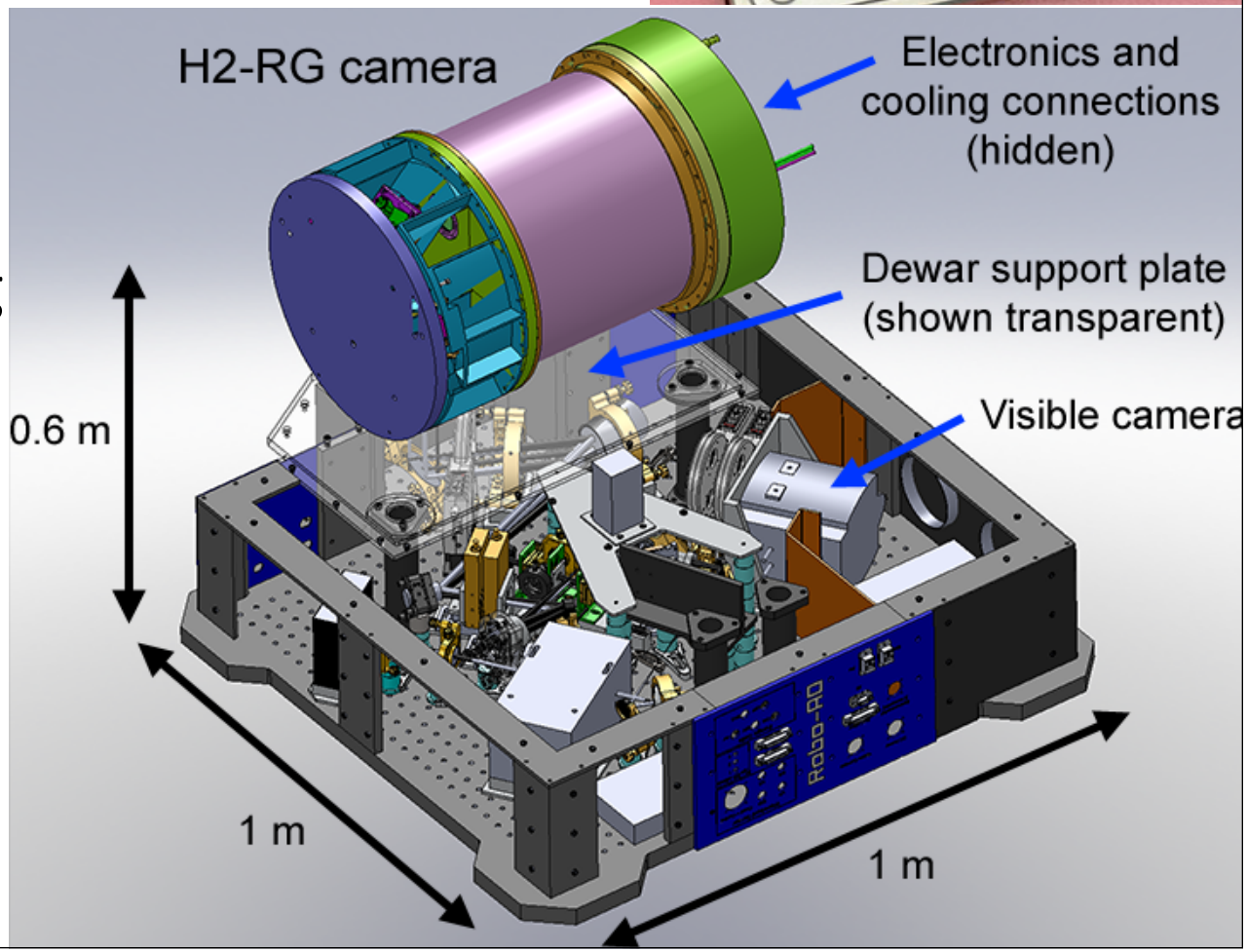
- Tested at IRTF
- Installed on **Robo-AO** next week

C. Baranec, D. Hall, D. Atkinson, S. Jacobson, K. Hodapp, R. Riddle

IUCAA Infrared Camera

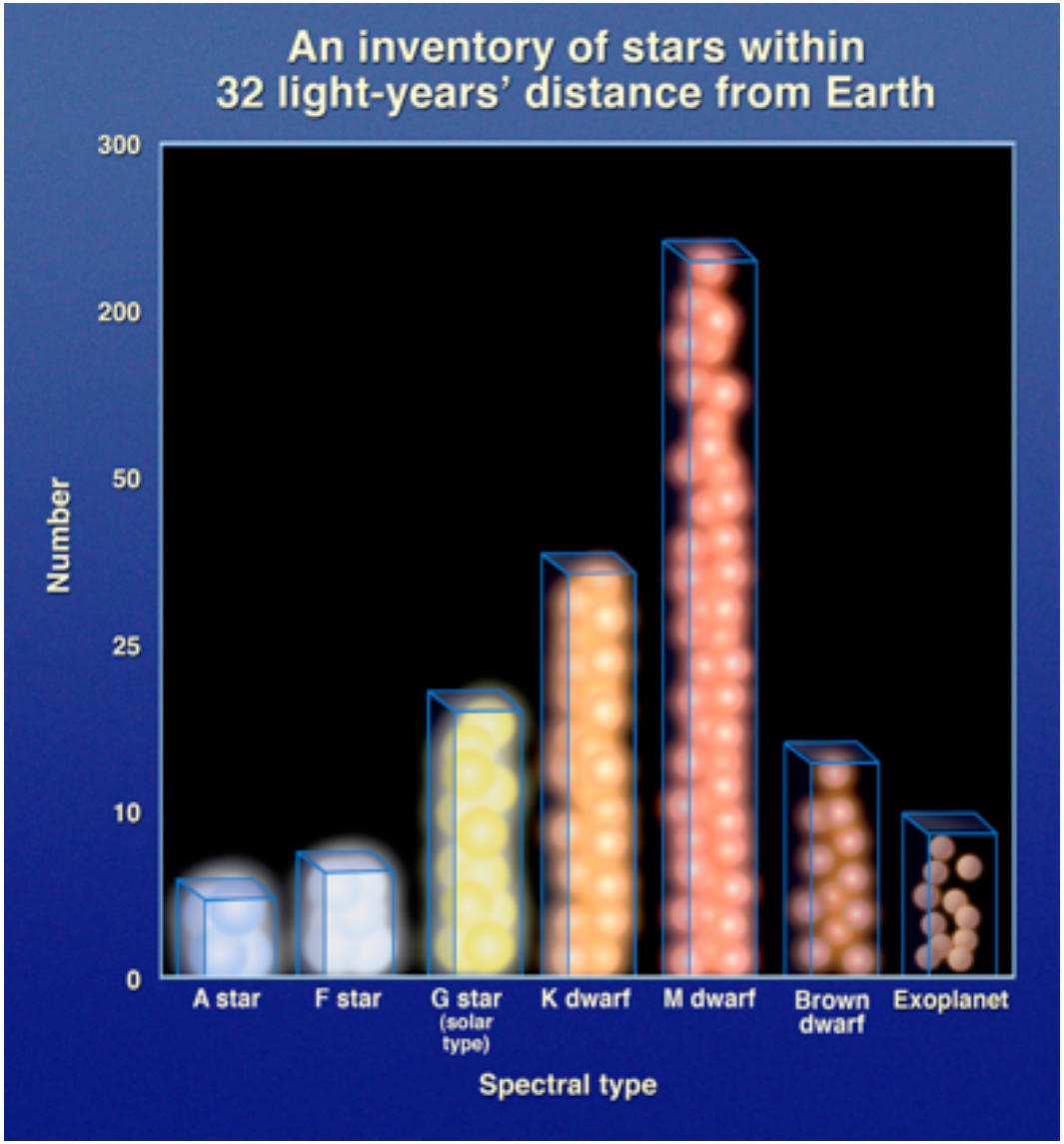


- H2RG detector
  - 2048x2048 pixels
  - Supplied by Navy DURIP grant
- IUCAA is developing the dewar and electronics
  - J, H, K filters
- First tests later this year



Science with Robo-AO

Ultimate AO Binarity Survey (N. Law)



Survey for binary stars over all spectral types and companions down to brown dwarfs for most

RECONS is covering wide (>100 AU) companions with proper motion surveys (>1"-2" separation)

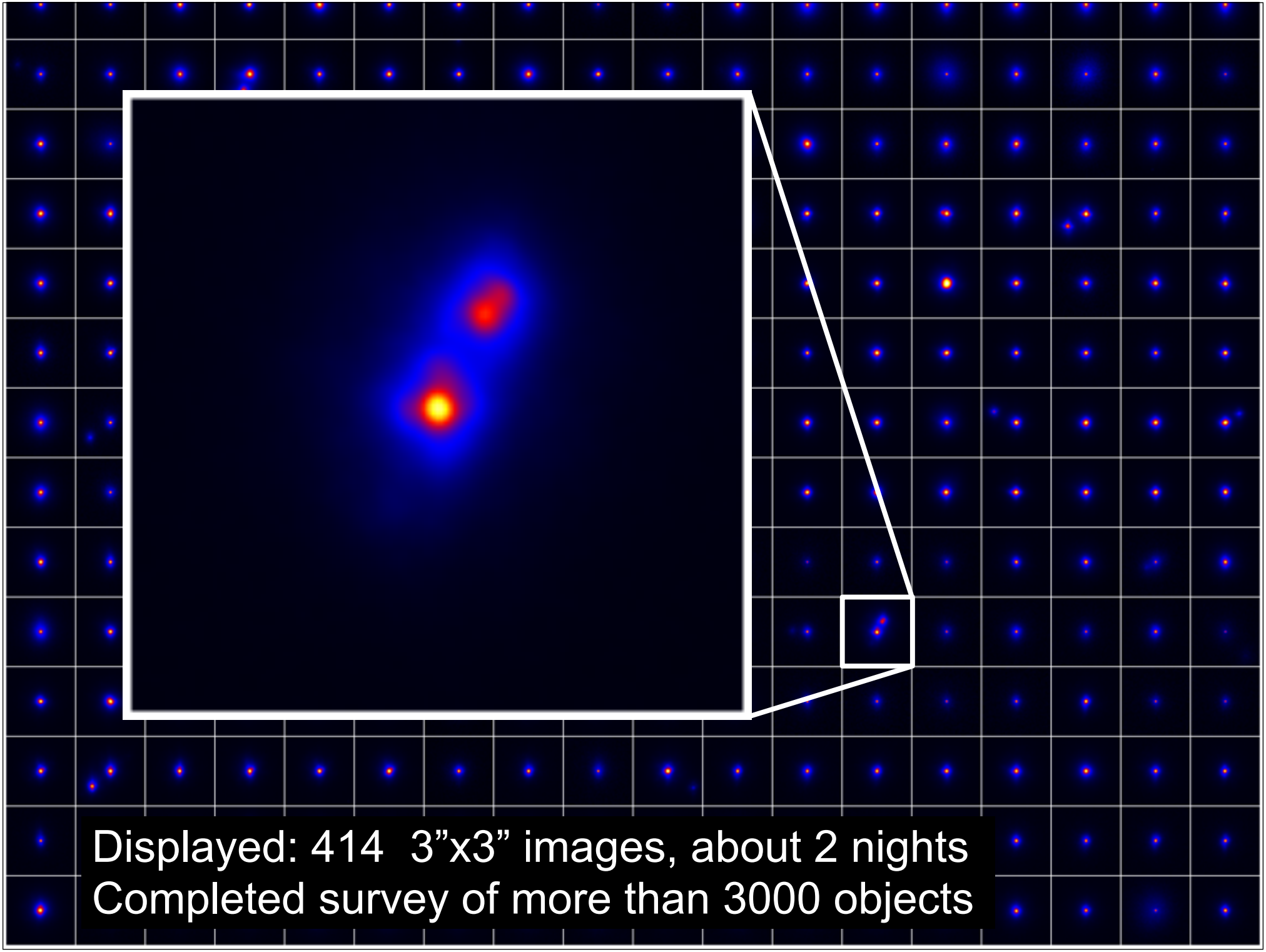
Robo-AO:

0.1" - 1.0" separation

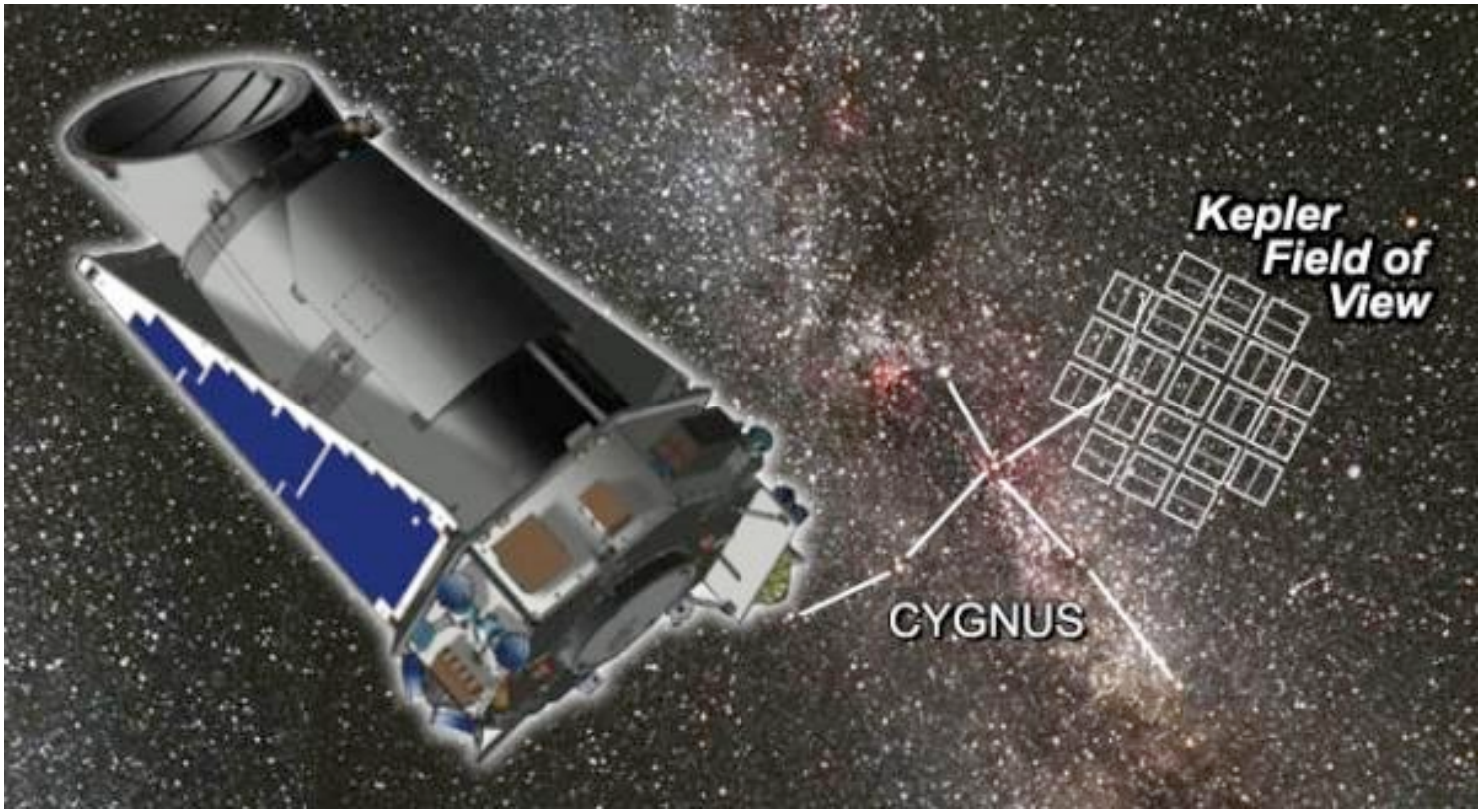
1 AU to 100 AU

One instrument

One coherent survey

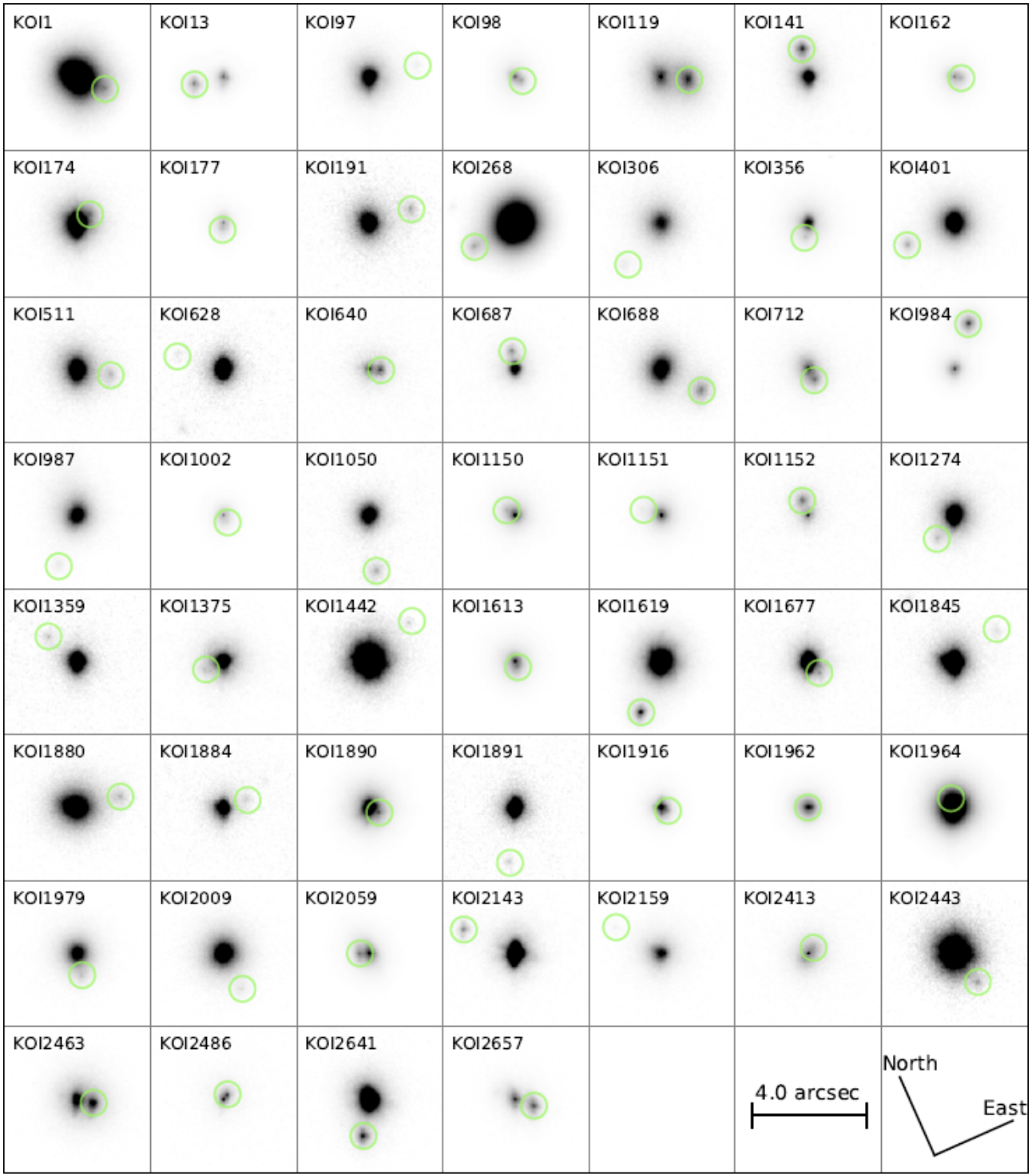

Displayed: 414 3”x3” images, about 2 nights
Completed survey of more than 3000 objects

Kepler Planetary Candidates



Identify blended binary systems

Photometry in Kepler visible bandpass

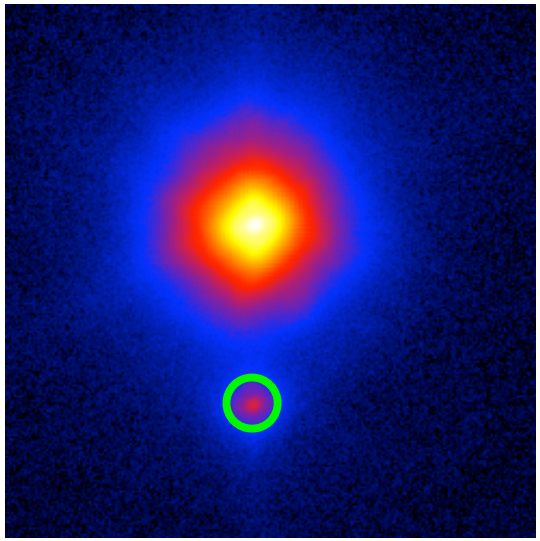


First Kepler paper accepted, 715 KOIs, 53 companions

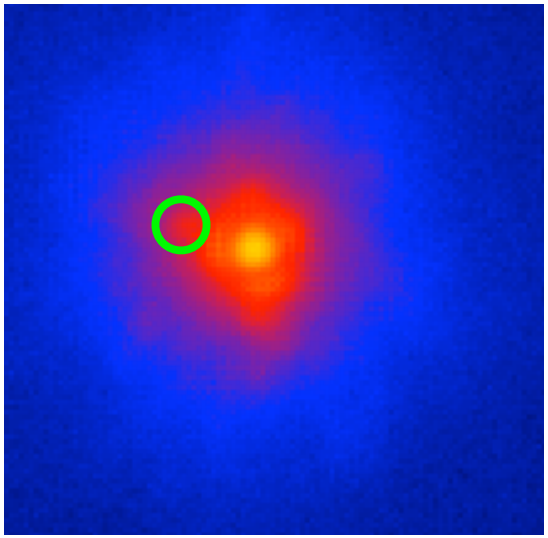
Second paper, ~1,100 KOIs, in preparation

Stellar Multiplicity Survey

Known Astrometric Binary Stars

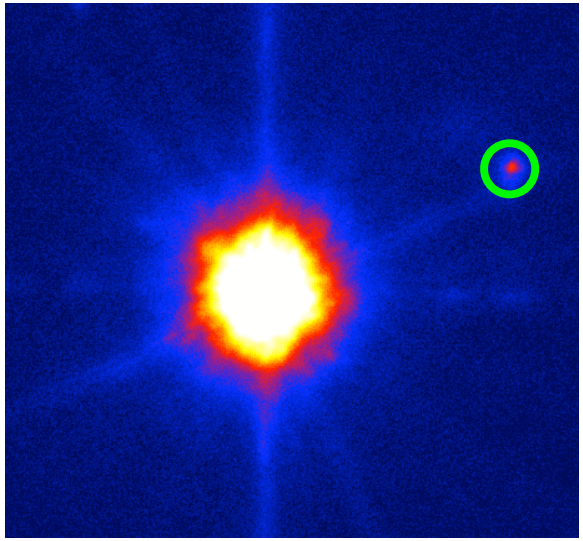


Separation = 1.78”
Position Angle =204deg
ΔI = 4.0



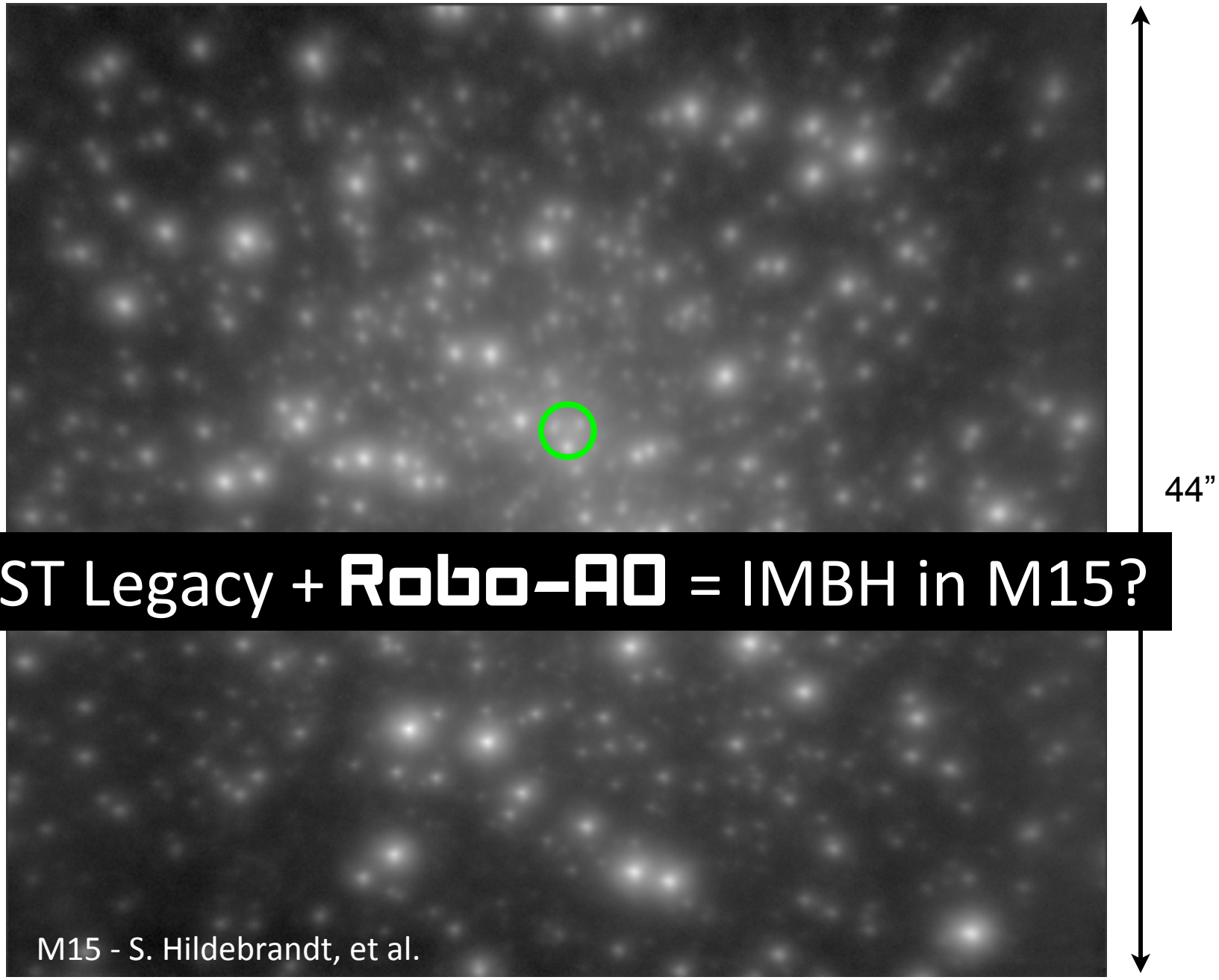
Separation = 0.32”
Position Angle =317deg
ΔI= 2.85

Spectroscopic Binary



Separation = 4.78”
Position Angle =87deg
ΔI = 6.55

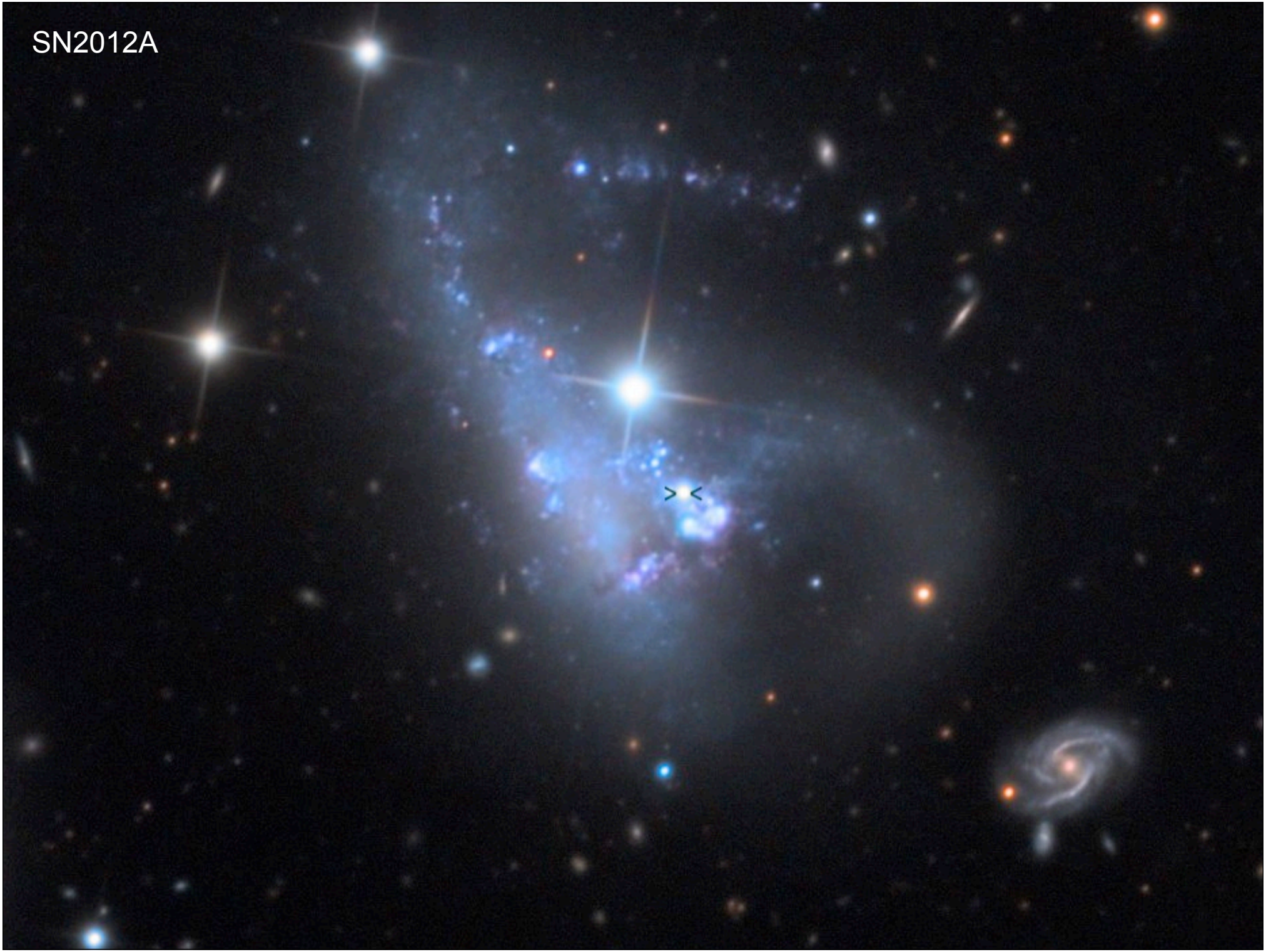
R. Riddle, A. Tokovinin (NOAO), L. Roberts (JPL), B. Mason (USNO), B. Hartkopf (USNO)

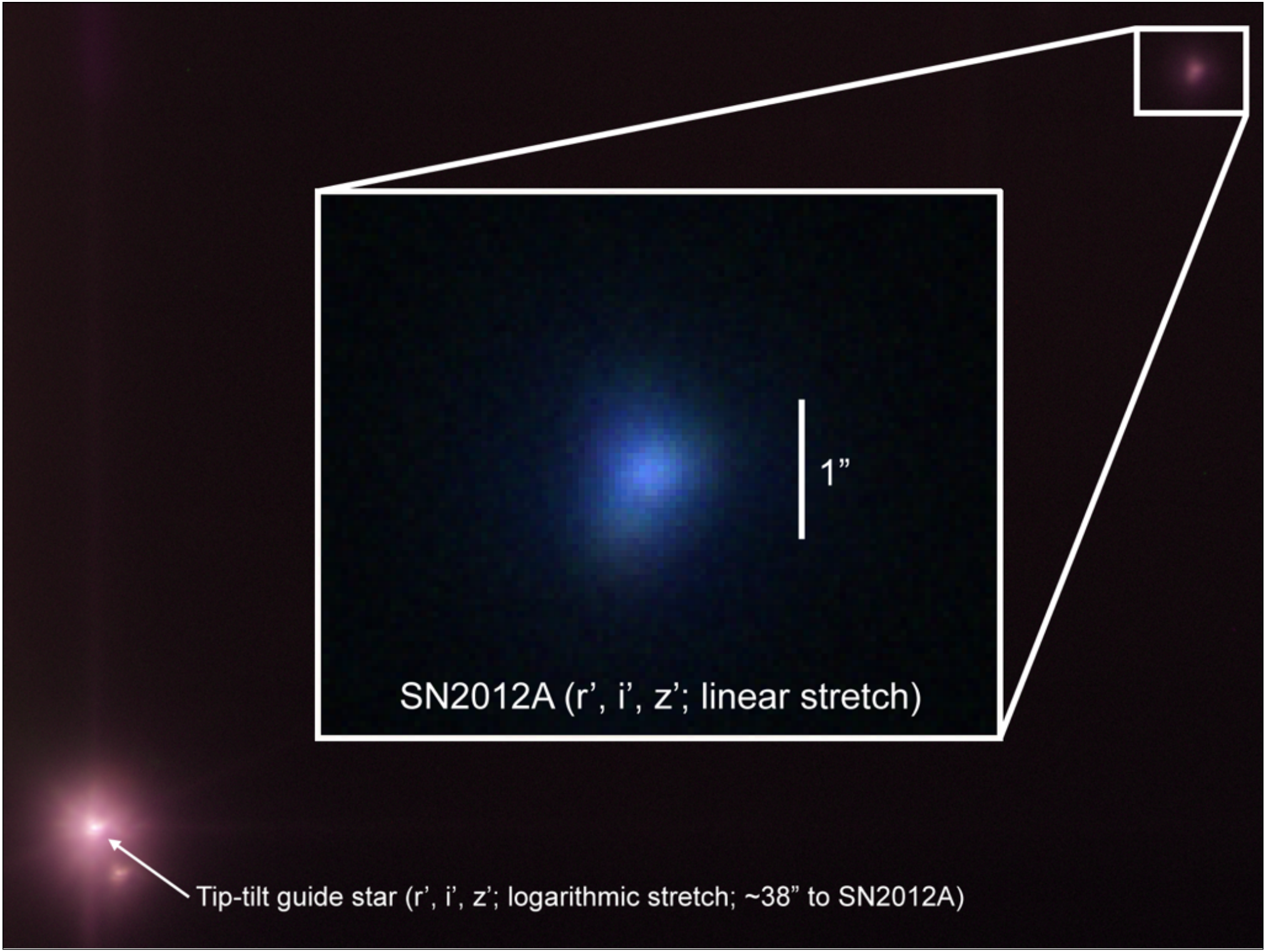


HST Legacy + Robo-AO = IMBH in M15?

Demonstrated: 200 µas in 30 minutes

Expected: 50 µas in 8 hours


SN2012A


1”
SN2012A (r’, i’, z’; linear stretch)
Tip-tilt guide star (r’, i’, z’; logarithmic stretch; ~38” to SN2012A)

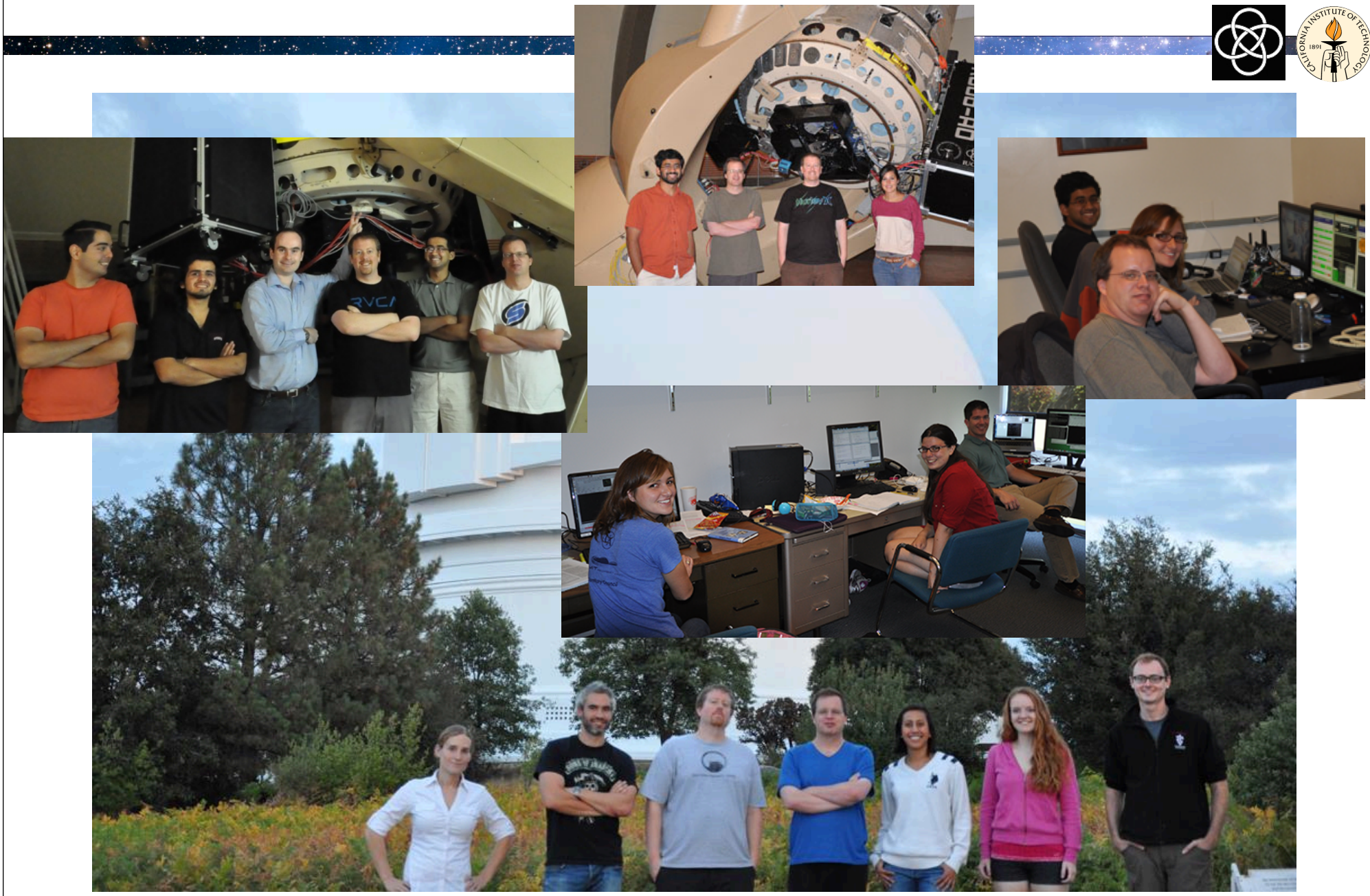
Automated AO Target of Opportunity

- Multi-color robotic observations the first night following discovery

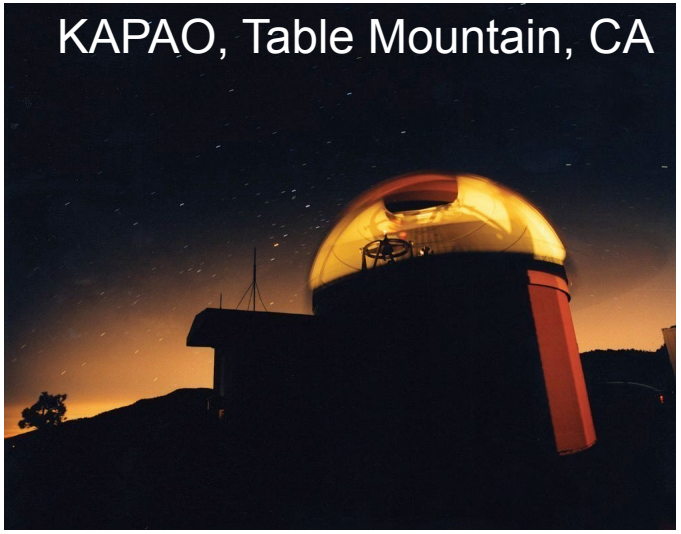
Robo-AO Survey Performance

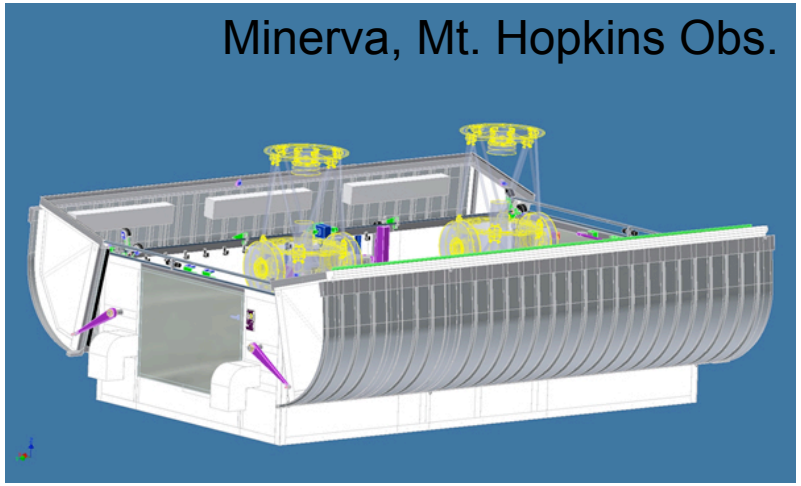
Survey	Tel./Instrument	Method	Targets	Time	Reference
Binarity of the solar neighborhood	**P60 (Robo-AO)**	**LGS AO**	**3,081**	**172 hours**	**Law, et al. in prep.**
Solar-type dwarf multiplicity	**P60 (Robo-AO)**	**LGS AO**	**1,115**	**49 hours**	**Tokovinin, et al. in prep.**
M-Dwarf multiplicity	Calar Alto 2.2-m (AstraLux), NTT (AstraLux)	Lucky	761	300 hours	Janson, et al. 2012 [14]
Washington Double Star Catalog	SOAR (HRCam)	Speckle, AO+Speckle	639	16 nights	Hartkopf, et al. 2012 [15]
Young Solar analogs	KeckII (NIRC2), Hale (PHARO)	NGS AO	266	47 nights	Metchev & Hillenbrand, 2009 [16]
Planets around low-mass stars	KeckII (NIRC2), Subaru (HiCIAO)	NGS AO	125	12 nights	Bowler et al. 2012 [17], Bowler et al. in prep.
Gemini deep planet survey	GeminiN (NIRI)	NGS AO	85	84 hours (w.o. overheads)	Lafrenière, et al. 2007 [18]
Multiplicity at the bottom of the IMF	KeckII (NIRC2)	LGS AO	78 (87 obs.)	10 nights	Kraus & Hillenbrand, 2012 [19]
Kepler KOI validation	**P60 (Robo-AO)**	**LGS AO**	**>1,700**	**104 hours**	**Law, et al. in prep.**
Kepler KOI validation	MMT (Aries), Hale (PHARO)	NGS AO	90	12 nights	Adams, et al. 2012 [20]
Kepler KOI validation	Calar Alto 2.2-m (AstraLux)	Lucky	98	19 nights	Lillo-Box, et al. 2012 [21]

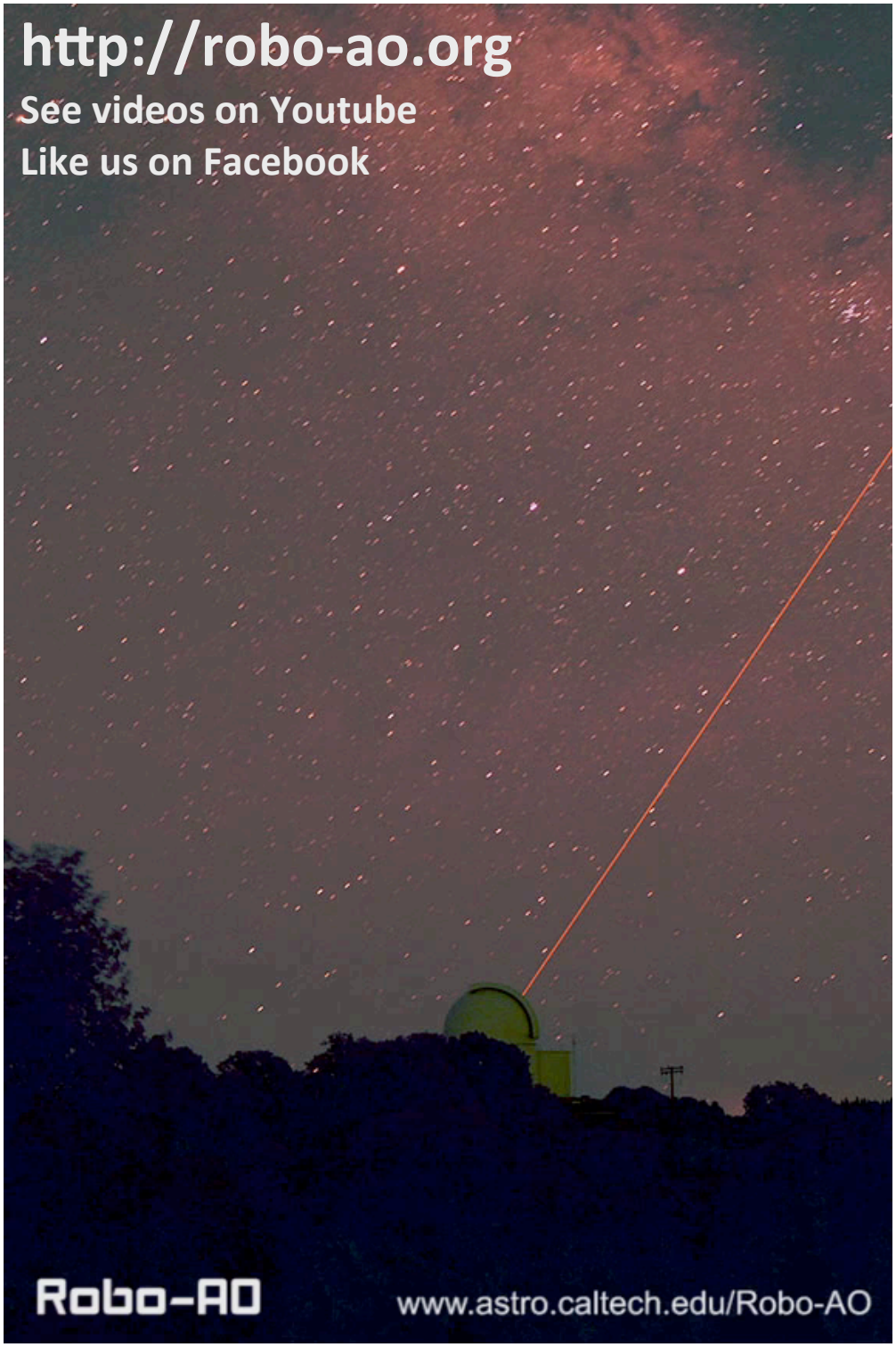
Student Research



Worldwide Replication







The Robo-AO Team

Principal Investigator	Christoph Baranec (U. Hawai'i)
Project Scientist	Nicholas Law (UNC Chapel Hill)
Co-Investigator	A. N. Ramaprakash (IUCAA)
Software Lead	Reed Riddle (Caltech)

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	Gina Duggan (Caltech)
	Kristina Hogstrom (Caltech)
	Shriharsh Tendulkar (Caltech)
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	Alexander Rudy (Pomona '11)
	Ankit Arya (Mississippi State '12)
	Athanasios Papadopoulos (Aristotle U., Thessaloniki '13)
	Victoria "Ashley" Villar (MIT '14)
	Corinne Vassallo (Carnegie Mellon '13)
	Dan Filler (Univ. of Utah '13)
	Chatarin "Mee" Wong-u-railertkun (Caltech '14)
	Rachel Thorp (Caltech '16)
	Bianca Avalani (Caltech '17)

Science team

Christoph Baranec	Richard Dekany
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Shri Kulkarni	Nicholas Law
Timothy Morton	Eran Ofek
A. N. Ramaprakash	Reed Riddle
Shriharsh Tendulkar	Lynne Hillenbrand
Sergi Hildebrandt	Gregg Hallinan
Michał Drahus	Leon Harding

Technical team

Christoph Baranec	Khanh Bui
Mahesh Burse	Pravin Chordia
Hillol Das	Jack Davis
Ernest Croner	Richard Dekany
Jason Fucik	Nicholas Law
Sujit Punnadi	A. N. Ramaprakash
Reed Riddle	Roger Smith
Shriharsh Tendulkar	Jeff Zolkower
Kristina Hogstrom	Sabyasachi Chattopadhyay