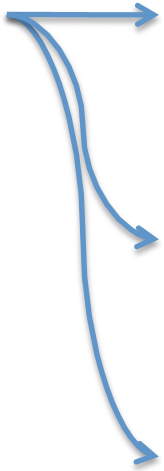

IUCAA
Caltech
Robo-AO
Shriharsh P. Tendulkar
(Caltech)
on behalf of the
Robo-AO Collaboration

Small Telescopes

Are Awesome!

BUT ...

Small Telescopes



Small Instruments

Small Instrument Budget

Small Operating Budget

Automation: No personnel

Reliability: No maintenance

Robo-AO

Demonstrate a robotic laser adaptive optics and visible/NIR science system

Design an affordable and easy to duplicate system

Replicate and deploy Robo-AO around the world

Benefits

Small Telescopes	-	Availability
Robotic	-	Efficient Observing
Adaptive Optics	-	High Resolution
Laser Guide Star	-	Sky Coverage

AO Capabilities

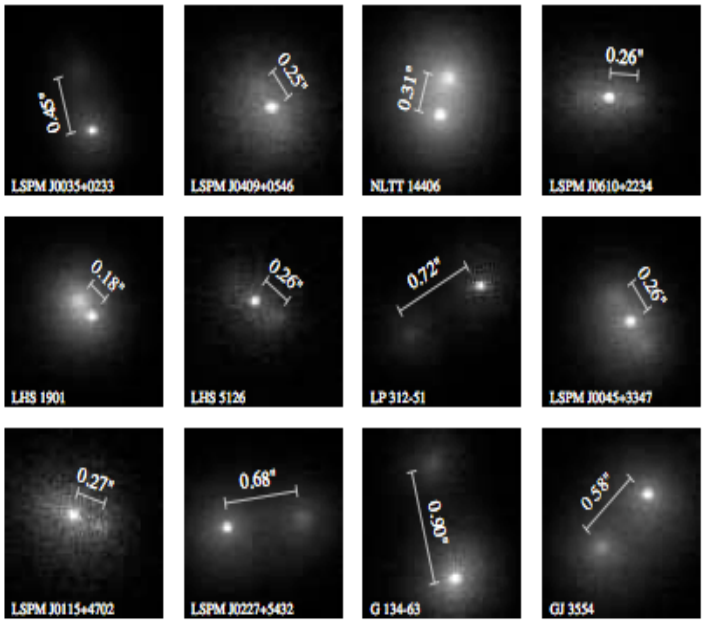
- Diffraction-limited resolution
- 100-150 mas PSF (Vis)
- ~1’ field of view
- ~30% sky coverage (m_{TT}~15.5)
- LUCKY imaging (no tip/tilt)

AO on small telescopes

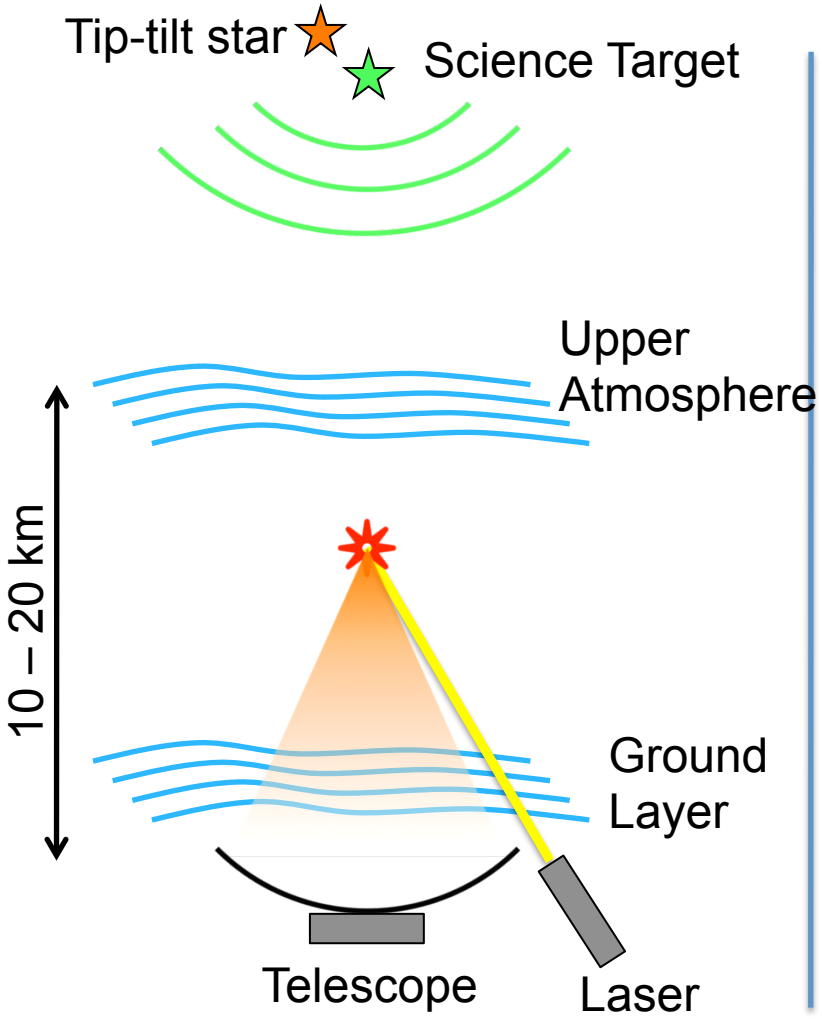
	Traditional LGS-AO	**Robo-AO (with LGS)**
Telescope Diameter	4 – 10 meters	1.5 – 3 meters
Number of Telescopes	~ 20	~ 100 – 150
AO bands	IR only	Visible and IR
Personnel	1 astronomer, 1 telescope operator, 1 laser engineer + few spotters	1 astronomer (sleeping)
Lock-in Time	5 – 15 min	1 min
Number of Targets	Tens	~ Hundred
Program Length	Few nights	Few weeks/months
Targets per program	~ Hundred	Thousands

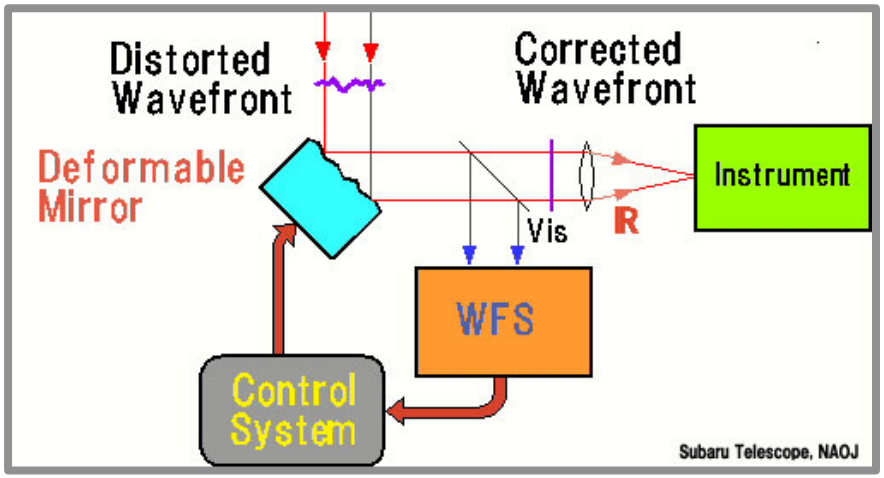
AO on small telescopes

- Large surveys (Area + Time)
- Transient response
- Survey followup (Kepler)
- Target monitoring



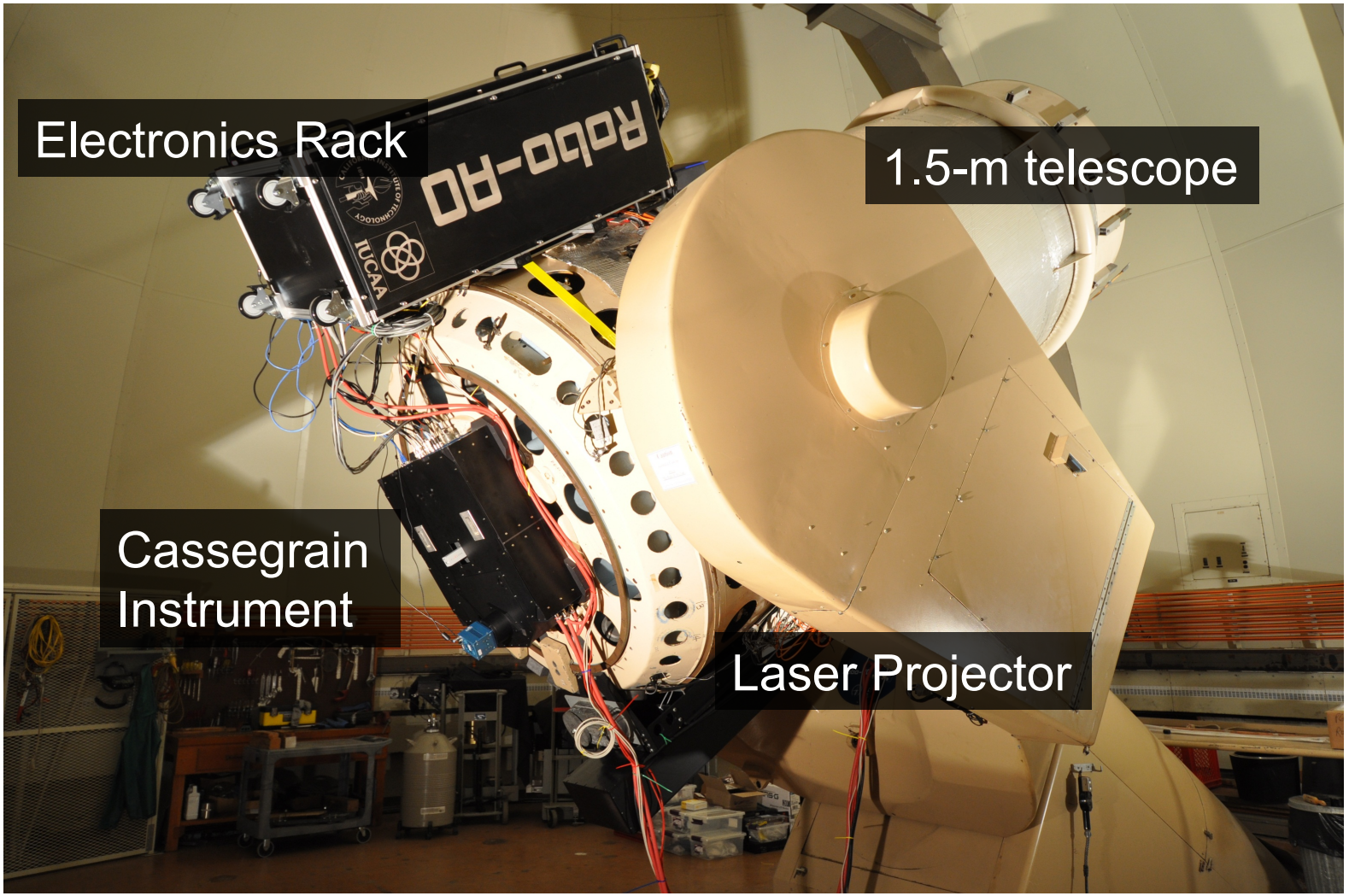
Rayleigh Beacon Adaptive Optics

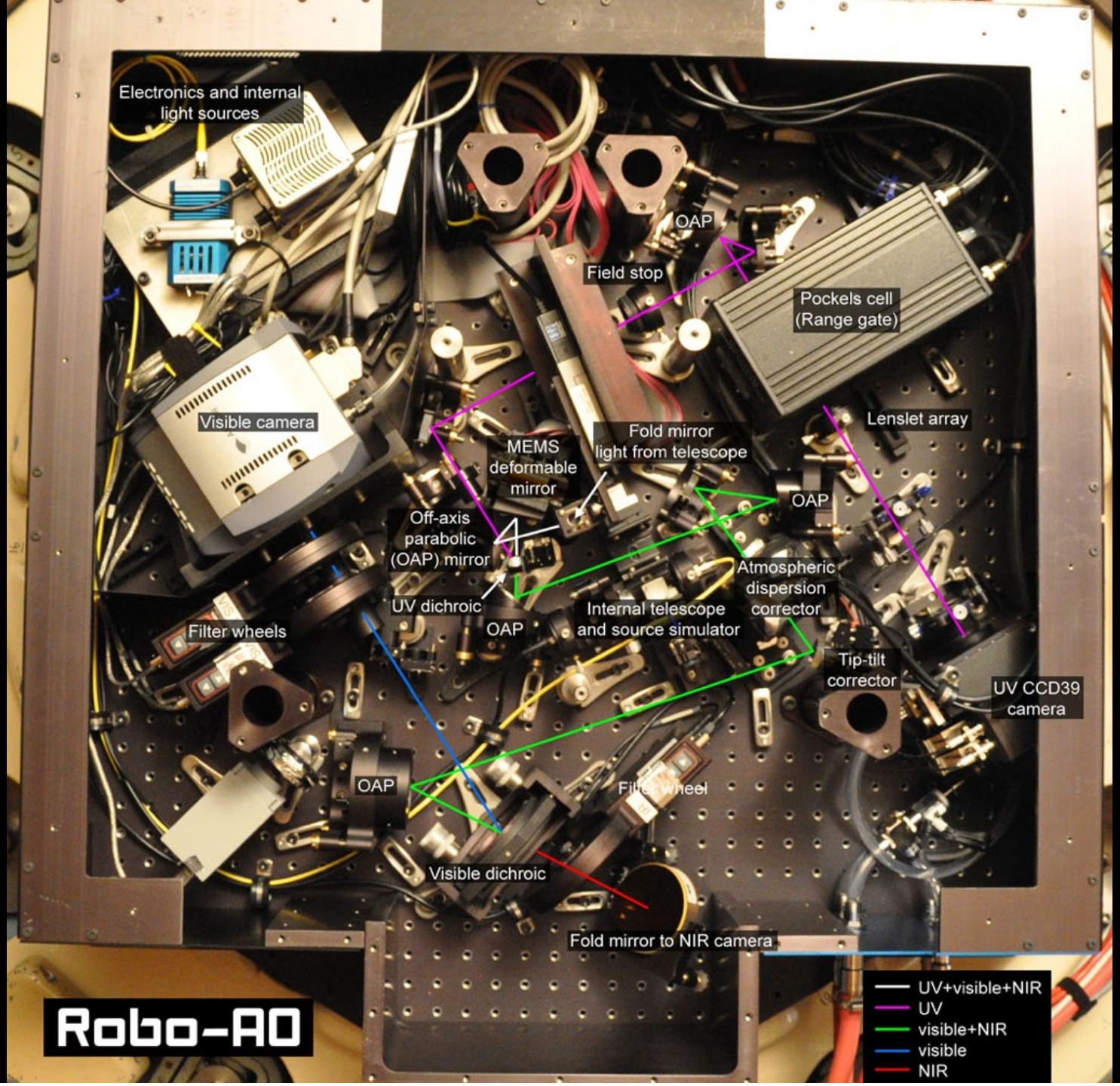




Credits: NAOJ

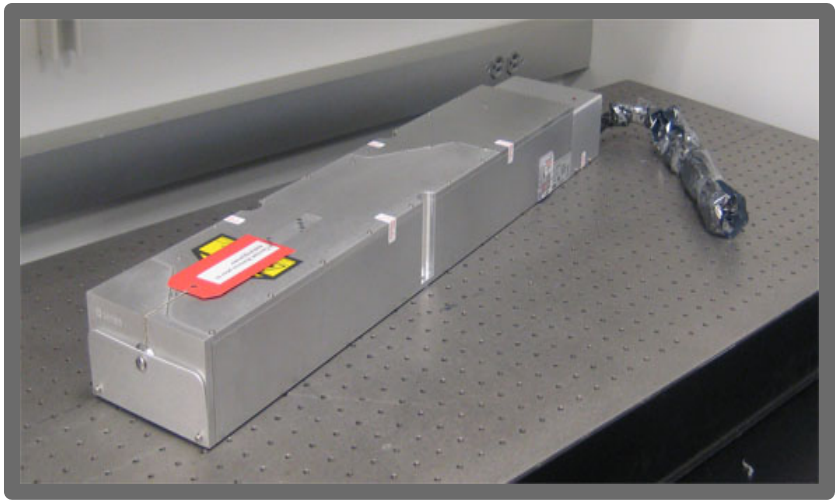
Components


Electronics Rack
Robo-AO
IUCAA
1.5-m telescope
Cassegrain
Instrument
Laser Projector


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

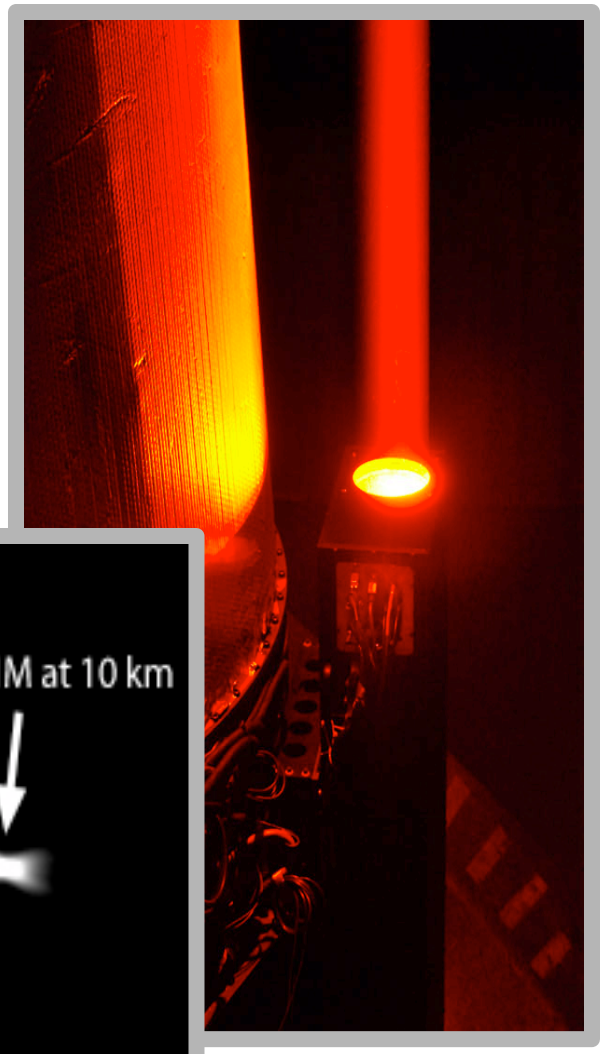
UV Laser (JDSU)

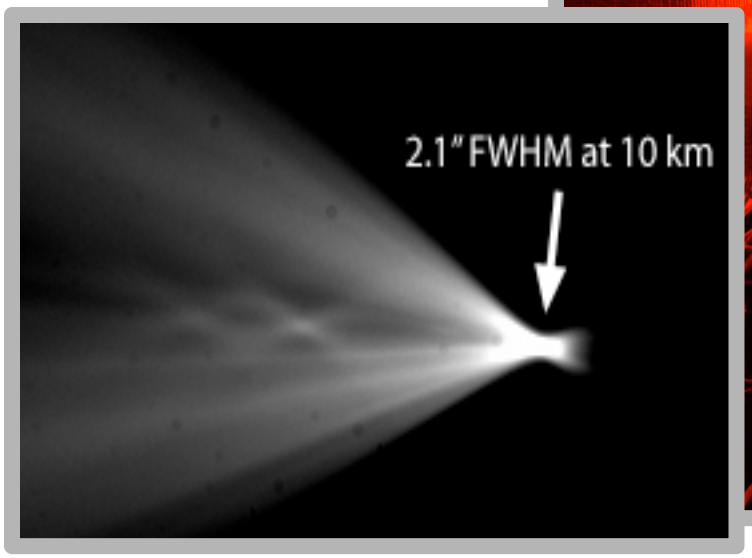
- Industrial UV laser
  - Reliable
  - Low cost
  - Invisible
- 12 W @ 355 nm
- 34 ns pulse @ 10 kHz



Laser Projector

- 15 cm beam
- Focus at 10 km
  - Focus adjustment
  - Steerable
  - Adjust dome
- FAA clearance





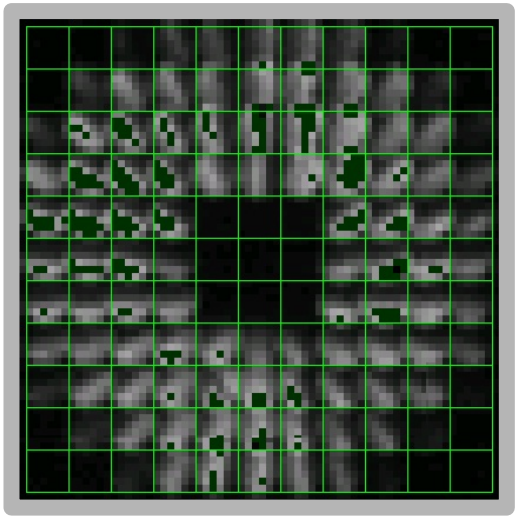
Range Gate System

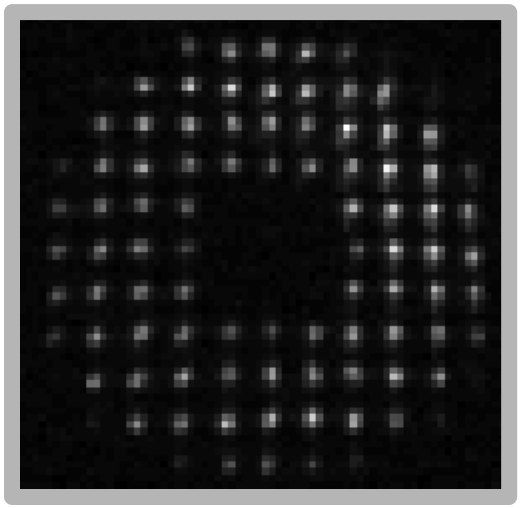
- Beta Barium Borate (BBO) Pockels Cell
  - Rotates polarization

- Optical switch at 10kHz, 2 μs gate
  - 10 km, 650m range gate

Wavefront Sensor

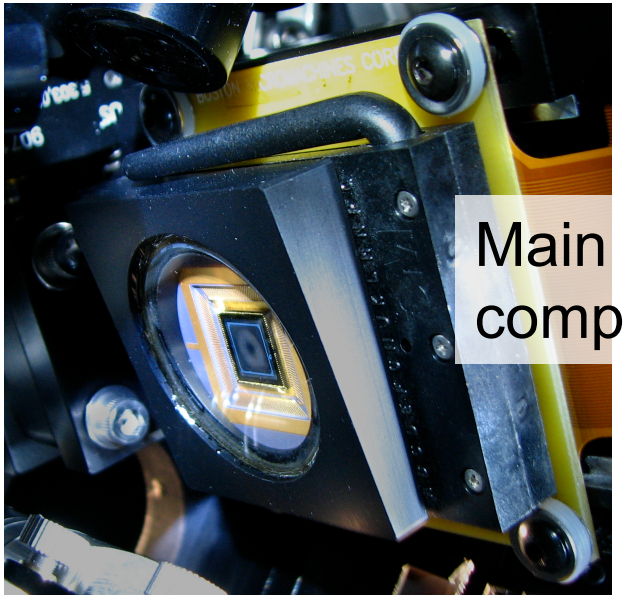
- Shack-Hartmann
  - 11 x 11 subapertures
  - E2V CCD39
  - 2 kHz at 4.5 e-
- Image motion (tip/tilt)
  - From science camera
  - Or fast frame rate (~10 Hz)





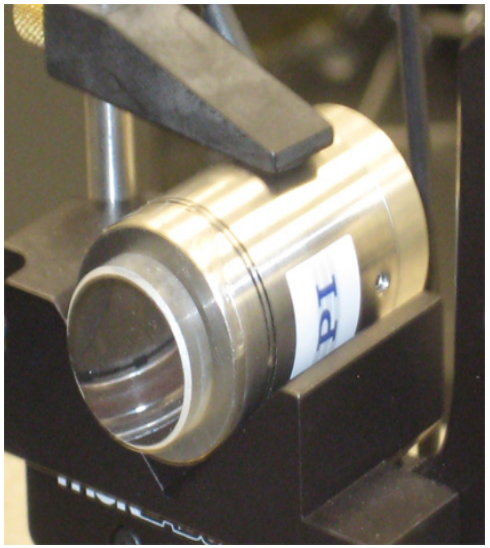
AO – Wavefront Correctors

- Deformable Mirror
  - MEMS Device
  - 12 x 12 actuators
  - 3.5 μm stroke



Main reason for compactness!

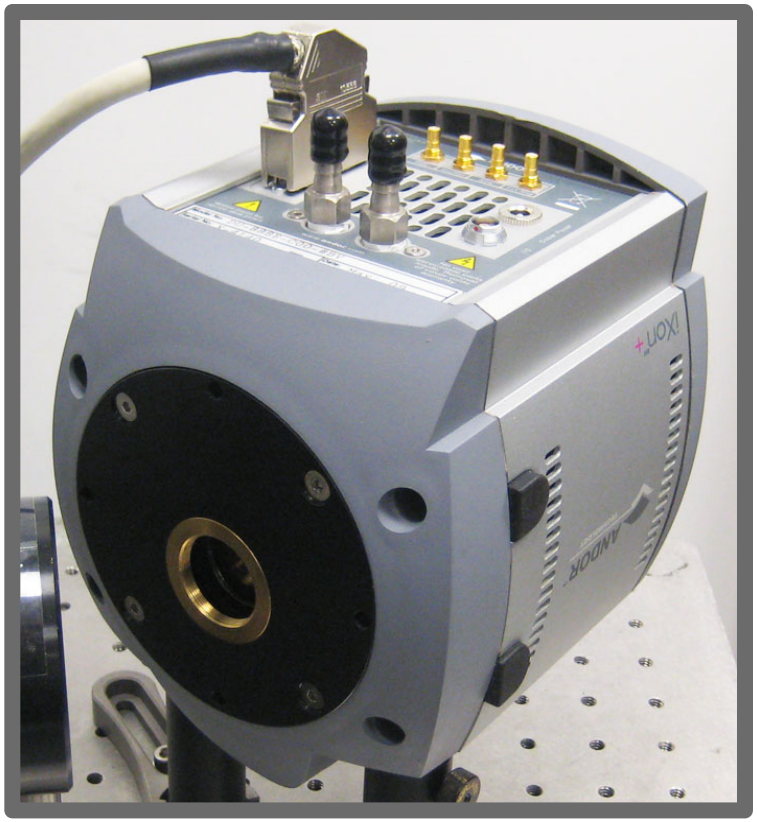
- Fast Steering Mirror
  - Piezo actuated
  - ~ 20’ range



Science Instruments

- 1024 x 1024 array
- Electron Multiplying CCD
- 44” x 44” square FoV
- “Zero” readnoise

- Full frame rate: 9 Hz
- Sub frame rate: ~200 Hz



Andor iXon DU-888

Engineering IR camera

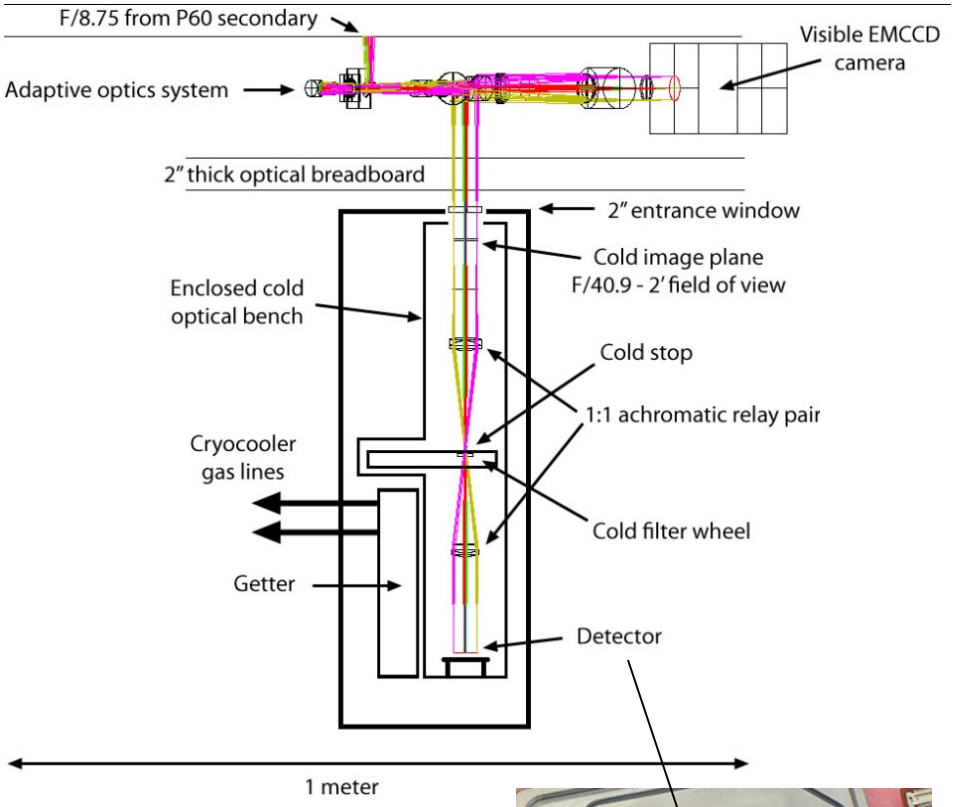
- InGaAs – (Xenics: Xeva)
  - + Affordable, readily available
  - - Noisy, small format
  - - Triple stage TE cooler
  - - 50e- read + 6000e-/s dark
  - - 320x240 pixel format
  - - 100 Hz readout

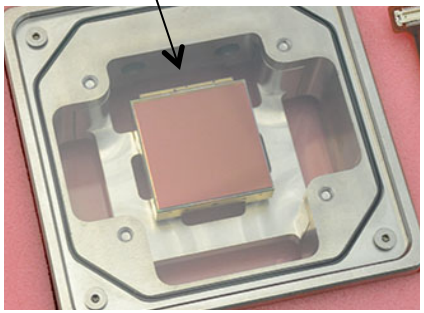
Xeva-1.7-320

Near-IR science instrument

Hawaii-2RG (HgCdTe)

- 2k by 2k format
- 0.057” pixels (Nyquist at λ = 830 nm)
- 2’ field of view
- Excellent noise – multiple non-destructive reads
- Flexible readout
  - Staring
  - Fast readout of subregions
  - Multiple ROI for better T/T
  - “Guiding” while integrating





Filter Wheels

- Thorlabs 6-position FWs
- 2 for visible camera
  - SDSS g, r, i, z
  - Narrow band + clear
- IR camera
  - J, H, clear

Atm. Dispersion Corrector

- Dispersion
  - Important for AO observing
  - Up to 2” at low altitude

- Broadband ADC
  - 400 nm to 2.2 μm
  - Correction to 20% of PSF!
  - Two triplet prisms
  - Two rotation stages (Newport)

Internal Calibration

- Dual calibration
  - UV source at “10 km” focus
  - White light source at “infinity”
  - Aligned to 35 nm wavefront error
- Used for
  - System alignment
  - AO system calibration
  - Movable switching mirror

Other hardware

- 2 computers
  - Control + Watchdog

- 2 NPS
- Chiller for laser
- Heat exchanger
- Network storage (16TB)

Software and Control

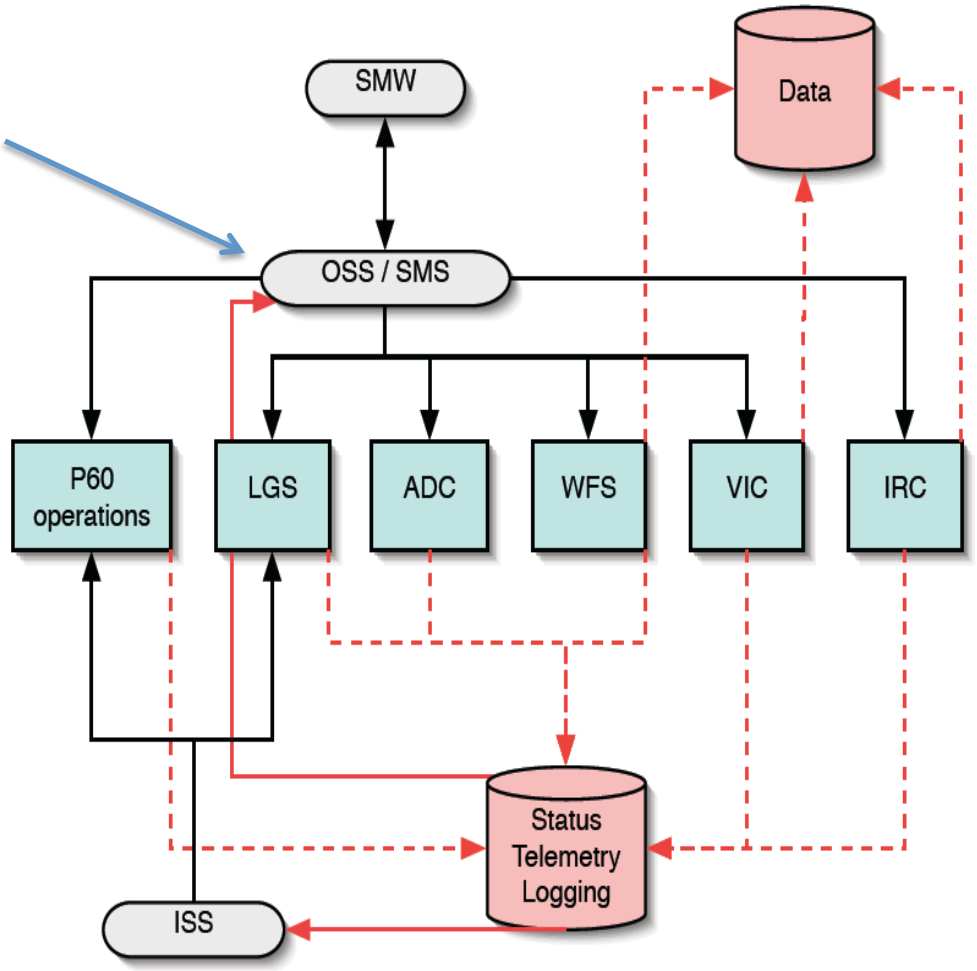
- Written in C++ for Linux
- Lightweight (Single processor)
- Fast (> 3 kHz)
- Reconfigurable (Text files)
- Modular
- Daemonized
- Safety Oriented

Software and Control

Robo Daemon

Sub-system daemons

Individual config files



Client program for daemon testing

Uses same interface

Credits: Reed Riddle

Error Handling

- Internal error handling → Sub-system daemons
- Control daemon → Can kill and restart daemons+hardware
  - NPS on eth+serial
- Worst case → Shutdown

Telemetry + Logs

- Logs from each daemon
- 1 second telemetry
  - High speed for debug/calib
- Web display of telemetry and images
  - Color coded for easy monitoring

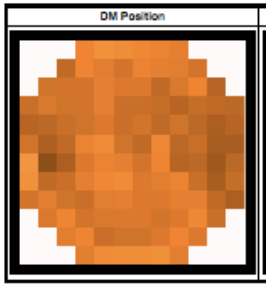
Telemetry

Browser Update Date: Date
Log File Update Date: Date

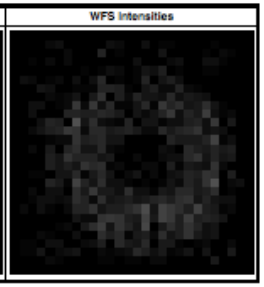
Robo-AO Status Images

Images

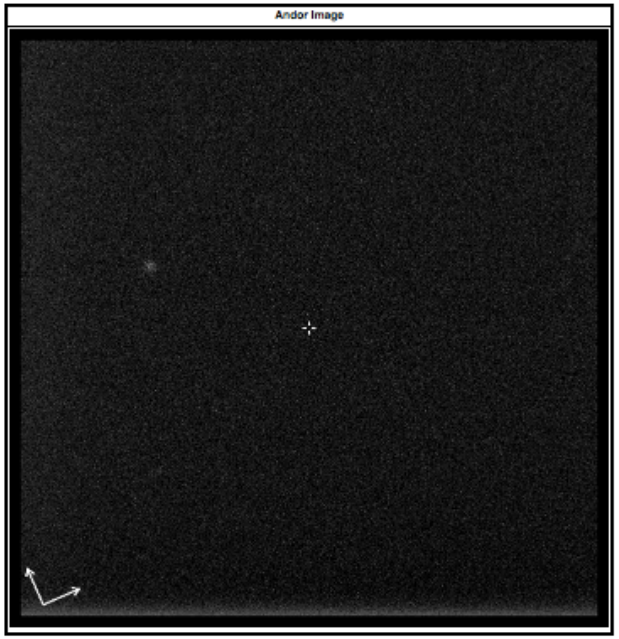
DM Position



WFS Intensities



Andor Image



Browser Update Date: Tue, 04 Sep 2012 05:23:31 GMT
Log File Update Date: Invalid Date

Robo-AO Status

Javascript Error Message: No Valu

Data Tables

Queue Information				
Date	Name	Project	Object	State
Tue, 04 Sep 2012 05:23:59 GMT	SD_NLTT50759	1	30480	AO_BACKGROUND
RA	Dec	Magnitude	Exp	Filter
+21:12:0.5	+18:22:16	15.12	120	FILTER_SLOAN_I

Laser System		Laser Diode			Laser				Chiller			
Date	System	T (ºC)	C (A)	State	P (W)	Sleep	Shutter	Interlock	T (ºC)	Op (s)	Flow	Reservoir
Tue, 04 Sep 2012 05:24:01 GMT	No Fault	17.9	34.2	ON	11.50	AWAKE	OPEN	CLSD	11.1	11.41	FLOWING	OK

AO System	Focus			Average Intensity	Deformable Mirror			
Date	Current Focus (nm)	Average Focus (nm)	Secondary Refocus (mm)	Intensity	Min Value	Median Value	Max Value	r0
Tue, 04 Sep 2012 05:21:14 GMT	223.31	157.77	0.0201	29.7	14178	20266	30808	0.95

AO Loop	DM Loop					TT Loop				
Date	Run Time	Frames	Frame Rate	Skips	Drops	Run Time	Frames	Frame Rate	Skips	Drops
Tue, 04 Sep 2012 05:21:14 GMT	127.999624	152183	1198.22	4	1301	-9999.000000	0	-9999.00	0	0

Tip Tilt	NGS TT Actuator Positions		Laser TT Actuator Positons	
Date	Tip-Tilt 1	Tip-Tilt 2	Tip-Tilt 3	Tip-Tilt 4
Tue, 04 Sep 2012 05:21:13 GMT	32768	32768	17907	55476

ADC		Positions			Motors		Pointing			
Date	Updating	Zenith Cone	Parallactic Angle (°)	Prism Angle (°)	Axis 1 (°)	Axis 2 (°)	RA (Hr)	Dec (°)	HA (Hr)	Zenith Angle (°)
Tue, 04 Sep 2012 05:24:00 GMT	YES	NO	79.75	79.73	0.0	0.5	-9999.99	0.3	YES	YES

VIC	Camera		Fan and Cooler					Detector Settings		
Date	Status Error	Error	Cooler	Current Temp (°C)	Target Temp (°C)	Setpoint	Temp Stable	Fan Mode	Gain	Obs Mode	Amplifier
Tue, 04 Sep 2012 05:24:00 GMT	0	0	ON	-78.598	-80.000	YES	YES	0	300	10	0

	Telescope	Dome	Faults

Logs

```
2012-09-04 05:25:32.001 (ROBOAO_robotic::Control::tcs_send_command): input coordinates to TCS:  RA: +21h01
m35.2s Dec: +00d42m37s Epoch: 2000
2012-09-04 05:25:32.003 (ROBOAO_robotic::Control::point_telescope): loading telescope targets command sent
 sucessfully
2012-09-04 05:25:33.009 (ROBOAO_robotic::Control::point_telescope): new telescope coordinates have loaded
2012-09-04 05:25:33.009 (ROBOAO_robotic::Control::point_telescope): pointing telescope at target coordinat
es
2012-09-04 05:25:33.009 (ROBOAO_robotic::Control::tcs_send_command): pointing telescope at input target
2012-09-04 05:25:33.014 (ROBOAO_robotic::Control::point_telescope): point telescope command sent sucessful
ly
2012-09-04 05:25:33.014 (ROBOAO_robotic::Control::point_telescope): ADC correction has started
2012-09-04 05:25:37.920 (ROBOAO_robotic::Control::point_telescope): waiting for telescope to point...
2012-09-04 05:25:42.826 (ROBOAO_robotic::Control::point_telescope): waiting for telescope to point...
2012-09-04 05:25:47.730 (ROBOAO_robotic::Control::point_telescope): waiting for telescope to point...
2012-09-04 05:25:52.634 (ROBOAO_robotic::Control::point_telescope): waiting for telescope to point...
2012-09-04 05:25:54.038 (ROBOAO_robotic::Control::point_telescope): telescope pointing complete
2012-09-04 05:25:54.038 (ROBOAO_robotic::Control::point_telescope): telescope pointing check. Telescope co
ord: +315:23:45.6 +00:42:37.0008 21.0264 0.71027797  Pointing coord: +21:01:35.2 +00:42:37 21.026445 0.710
2778 4.5649211e-05 1.7881393e-07
2012-09-04 05:25:54.038 (ROBOAO_robotic::Control::point_telescope): telescope successfully pointed, no err
ors found
2012-09-04 05:25:54.038 (robod): telescope successfully pointed at target
2012-09-04 05:25:58.002 (robod): checking LGS closure window, attempt 1
2012-09-04 05:25:58.002 (ROBOAO_robotic::Control::check_lgs_window): LGS window is open until 2012-09-04 0
5:41:07
2012-09-04 05:25:58.002 (robod): LGS window clear
2012-09-04 05:25:58.002 (robod): starting AO system, attempt 1
2012-09-04 05:25:58.002 (ROBOAO_robotic::Control::start_ao_system): starting laser propagation
2012-09-04 05:25:58.003 (ROBOAO_robotic::Control::start_ao_system): start laser propagation command sent
2012-09-04 05:25:58.003 (ROBOAO_robotic::Control::lgs_send_command): firing the LGS laser
2012-09-04 05:25:58.000 (ROBOAO_robotic::Control::start_ao_system): waiting for laser to propagate.....
2012-09-04 05:26:00.001 (ROBOAO_robotic::Control::start_ao_system): waiting for laser to propagate.....
2012-09-04 05:26:01.003 (ROBOAO_robotic::Control::start_ao_system): waiting for laser to propagate.....
2012-09-04 05:26:02.000 (ROBOAO_robotic::Control::start_ao_system): laser started propagating successfully
2012-09-04 05:26:02.001 (ROBOAO_robotic::Control::start_ao_system): taking AO system background
2012-09-04 05:26:02.001 (ROBOAO_robotic::Control::start_ao_system): AO system background command sent
2012-09-04 05:26:02.001 (ROBOAO_robotic::Control::seeing_measurement): setting up VIC seeing measurement
2012-09-04 05:26:02.001 (ROBOAO_robotic::Control::seeing_measurement): VIC parameter setup command sent
2012-09-04 05:26:02.001 (ROBOAO_robotic::Control::vic_send_command): initializing the VIC camera
2012-09-04 05:26:02.001 (ROBOAO_robotic::Control::ao_send_command): command received:  [6013:CONTROL_TAKE_
BACKGROUND]
```

Observing Modes

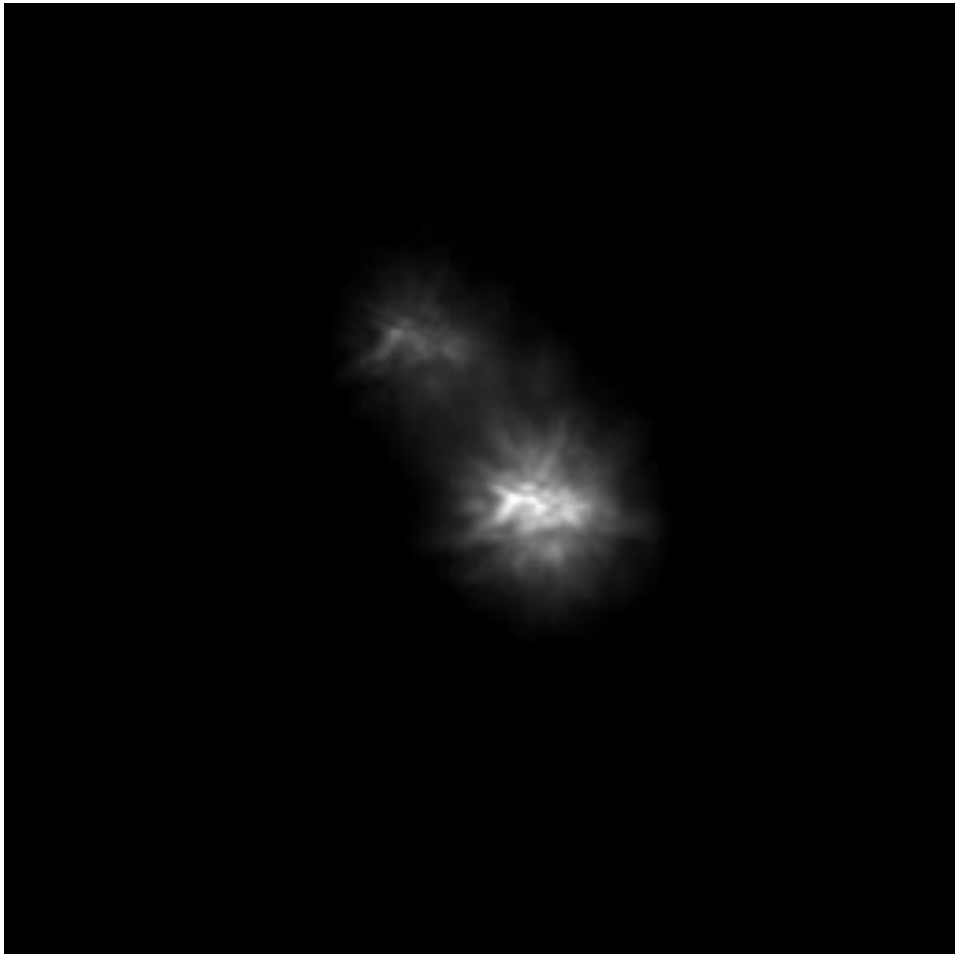
- Fixed set of modes
  - Various gains, frame rates
  - Easier for calibration
- System does biases and flats
  - Need bright flats!
- TBD: Incorporate queue scheduler!

Data Reduction

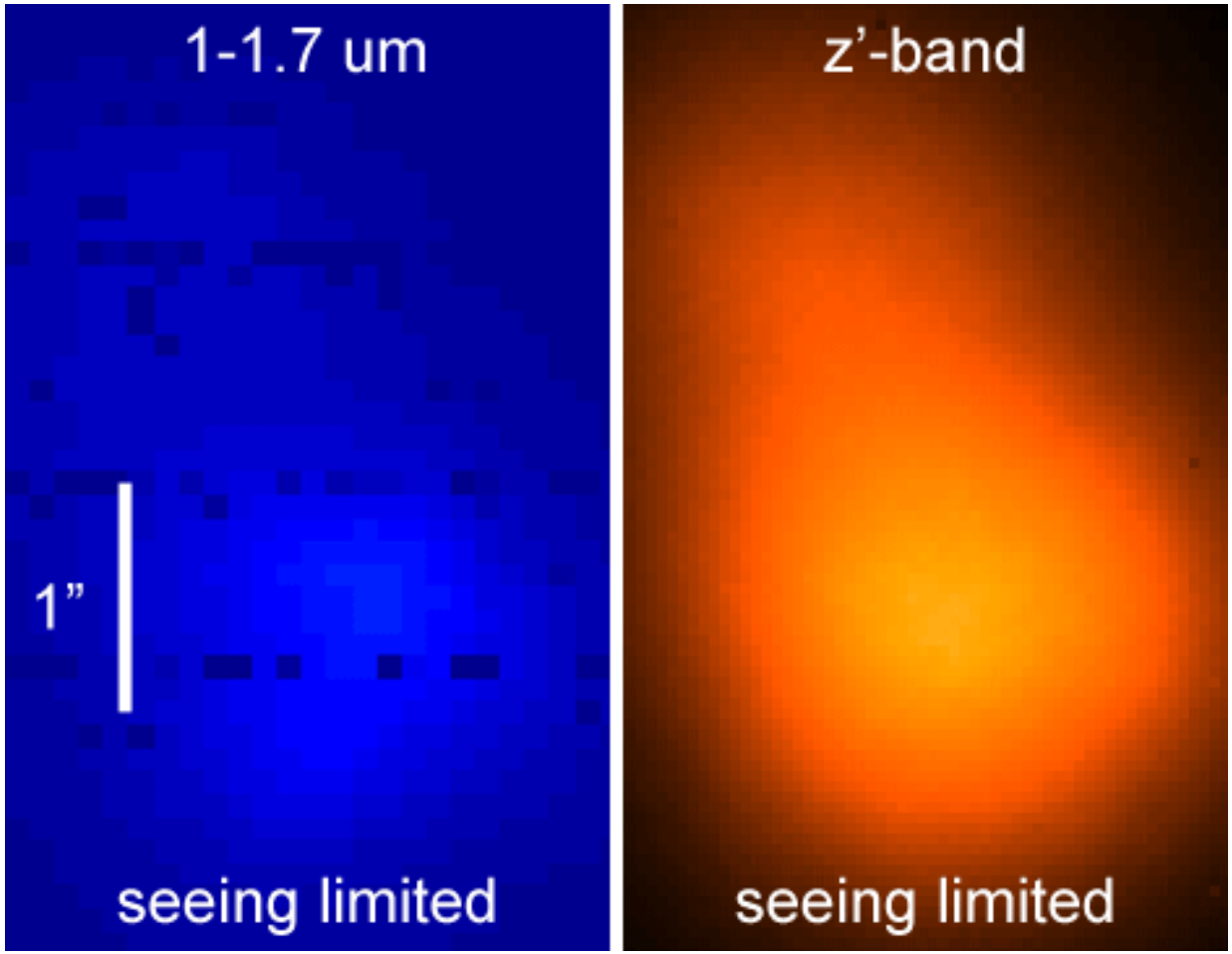
- Quick look pipeline
  - Check data quality, seeing
- Full reduction pipeline
  - Careful shift-and-add for optimal data reduction
- Will change when H2RG included

It works!

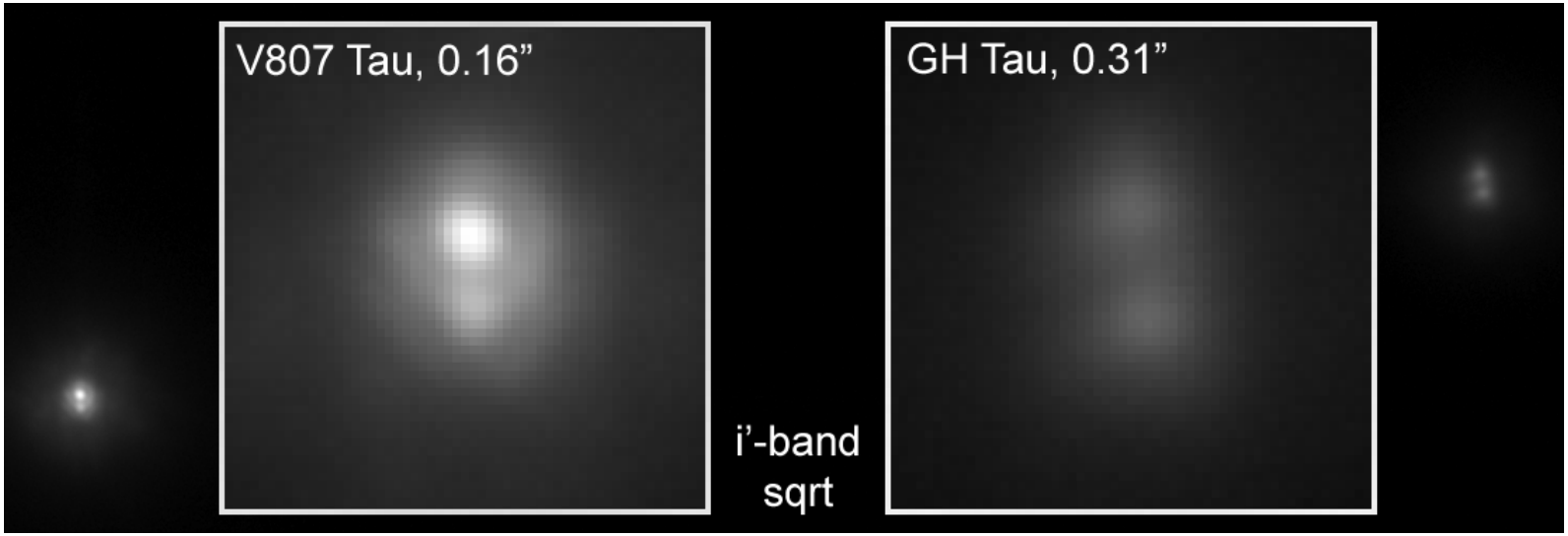
First HO loop closing (Aug 2011)



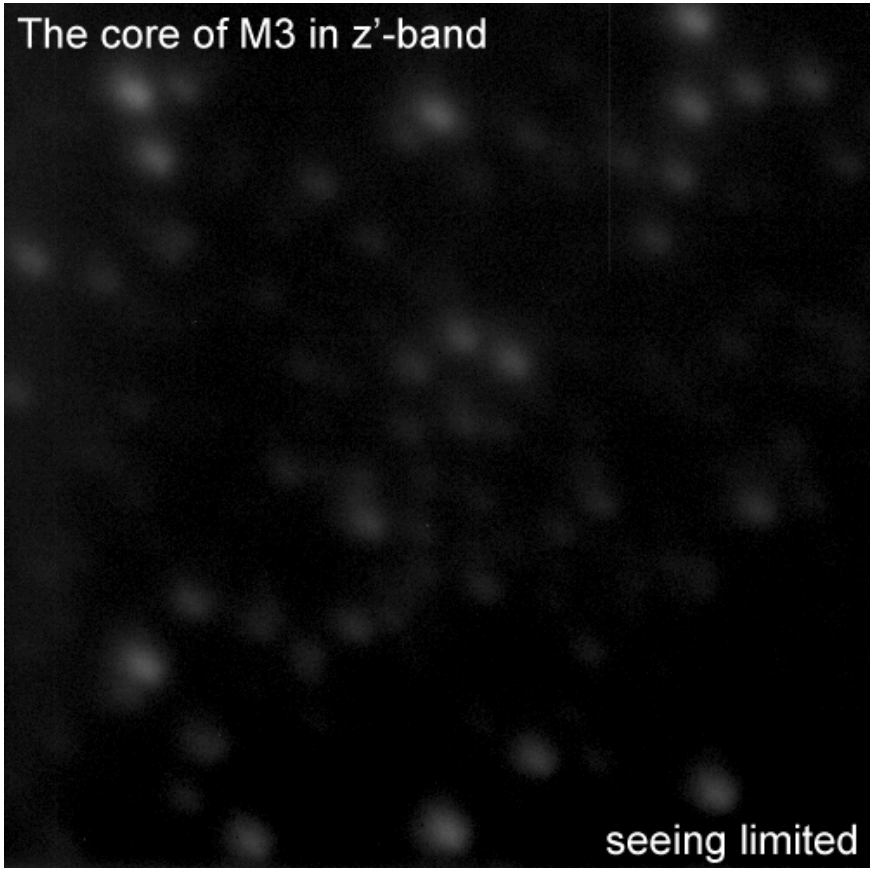
It works!

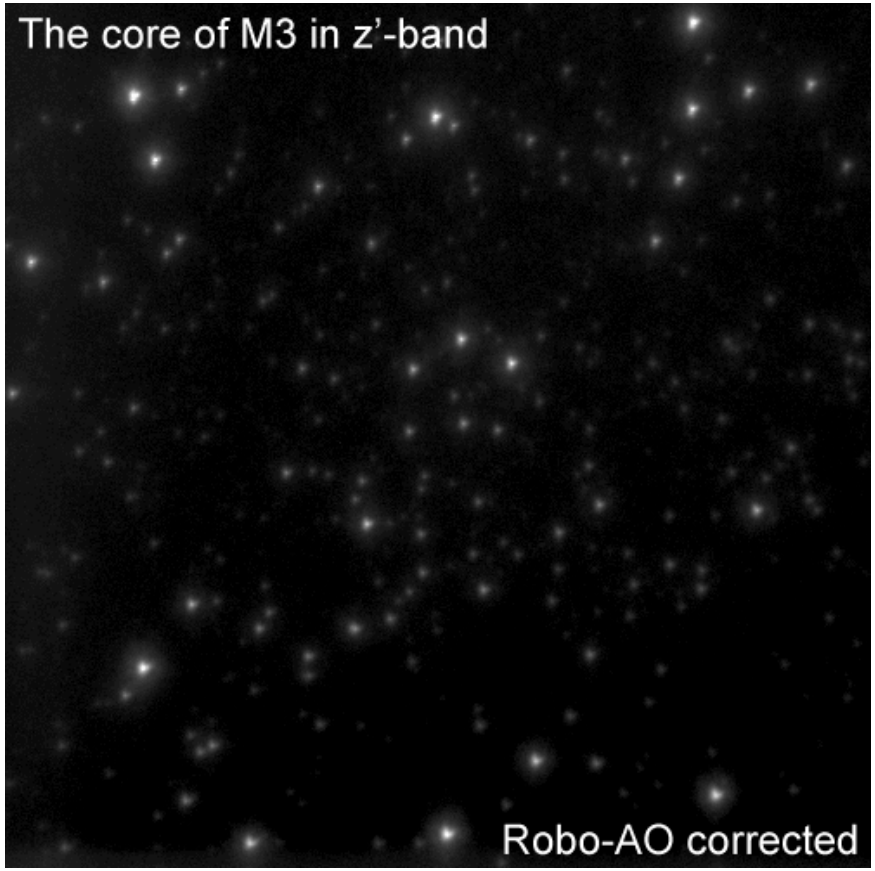


It works!

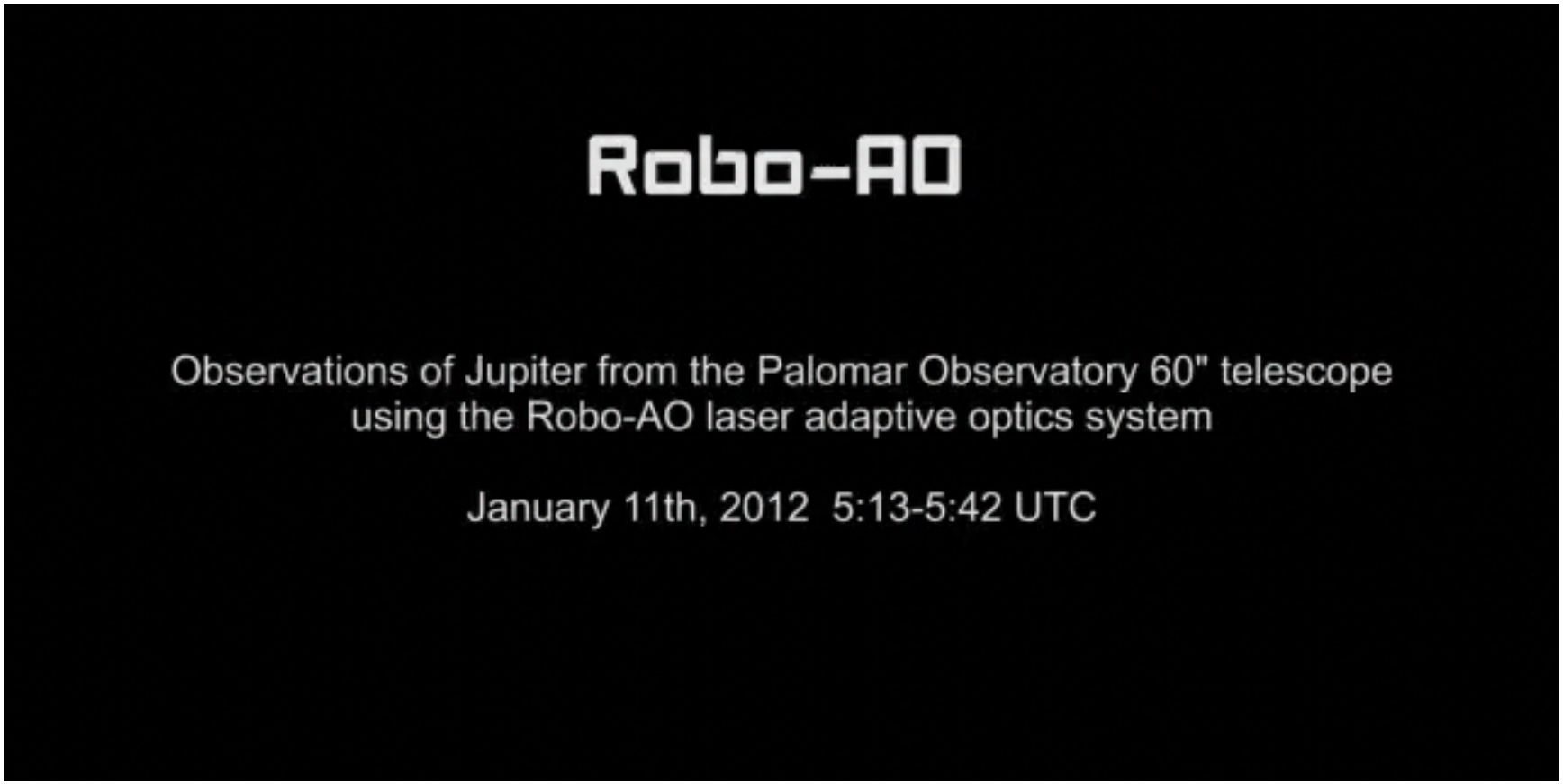


It works!

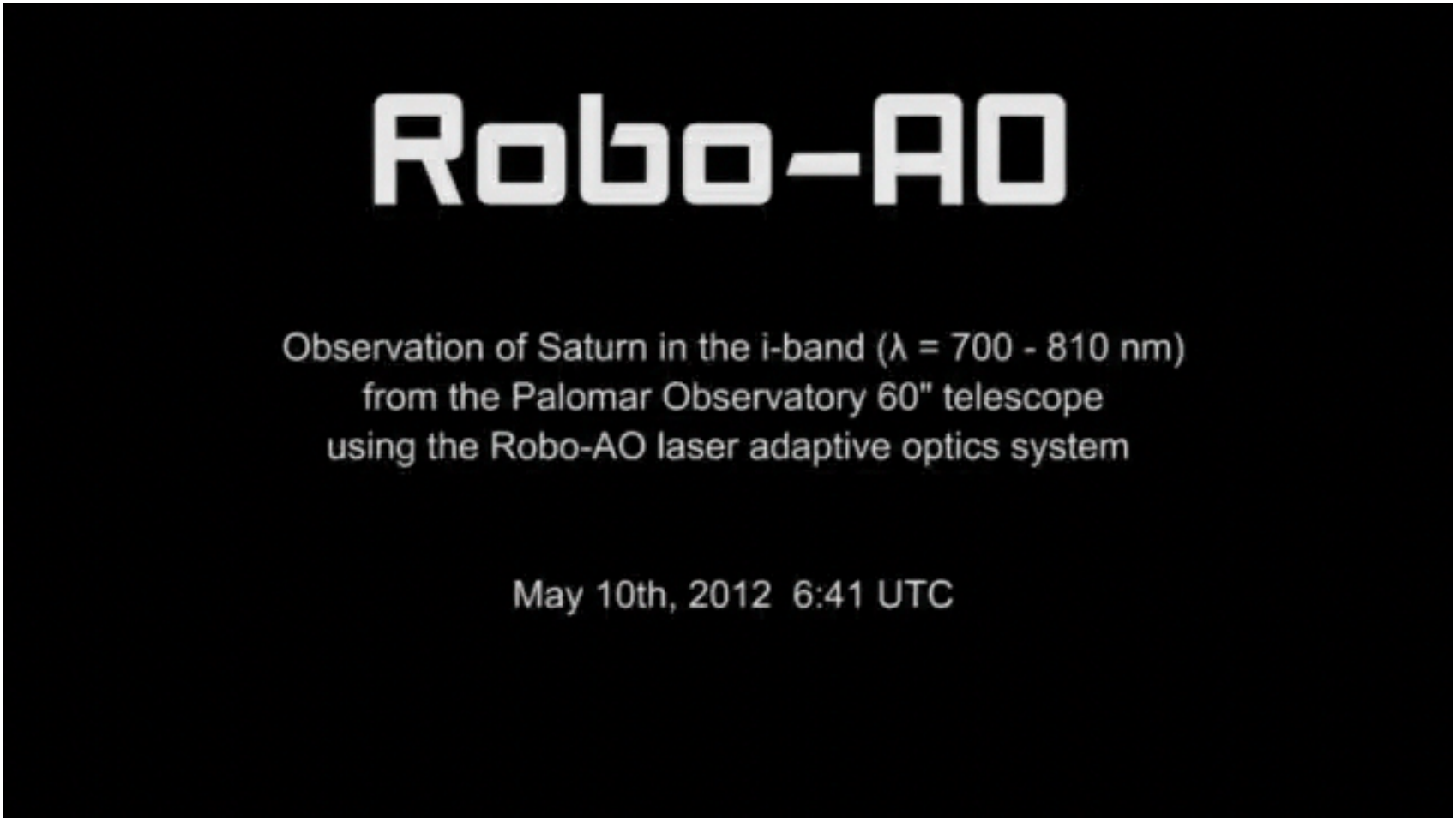

The core of M3 in z'-band
seeing limited


The core of M3 in z'-band
Robo-AO corrected

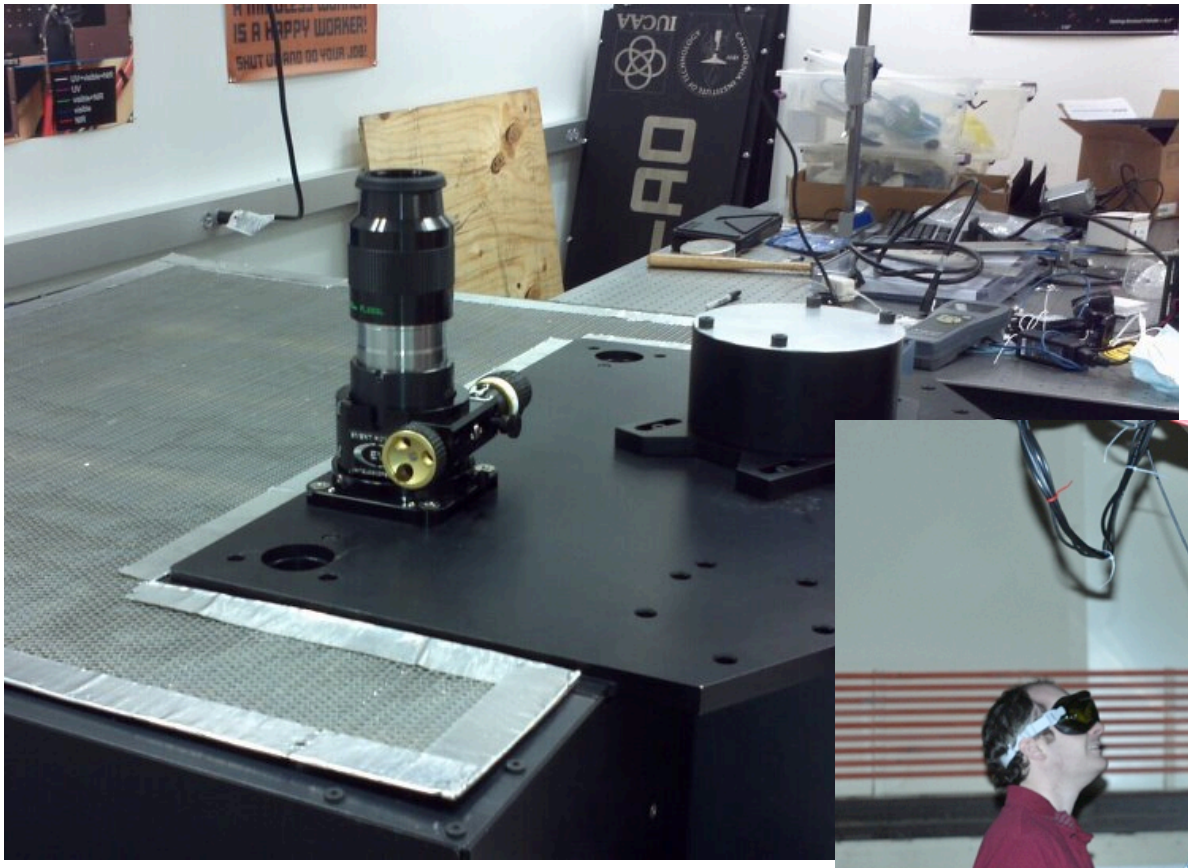
It works!

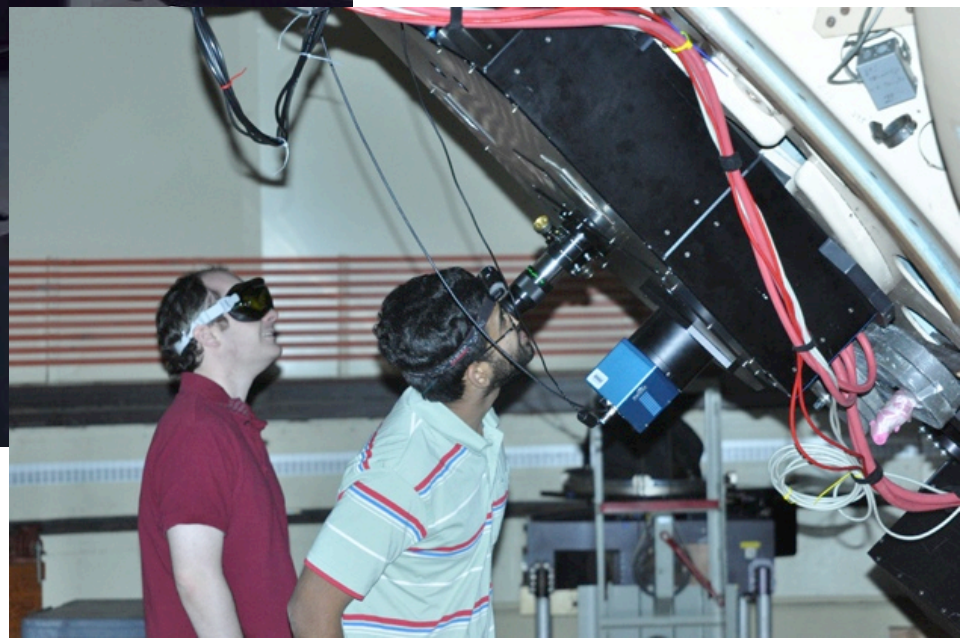

Robo-AO
Observations of Jupiter from the Palomar Observatory 60" telescope
using the Robo-AO laser adaptive optics system
January 11th, 2012 5:13-5:42 UTC

It works!


Robo-AO
Observation of Saturn in the i-band (λ = 700 - 810 nm)
from the Palomar Observatory 60" telescope
using the Robo-AO laser adaptive optics system
May 10th, 2012 6:41 UTC

AO supported eyepiece





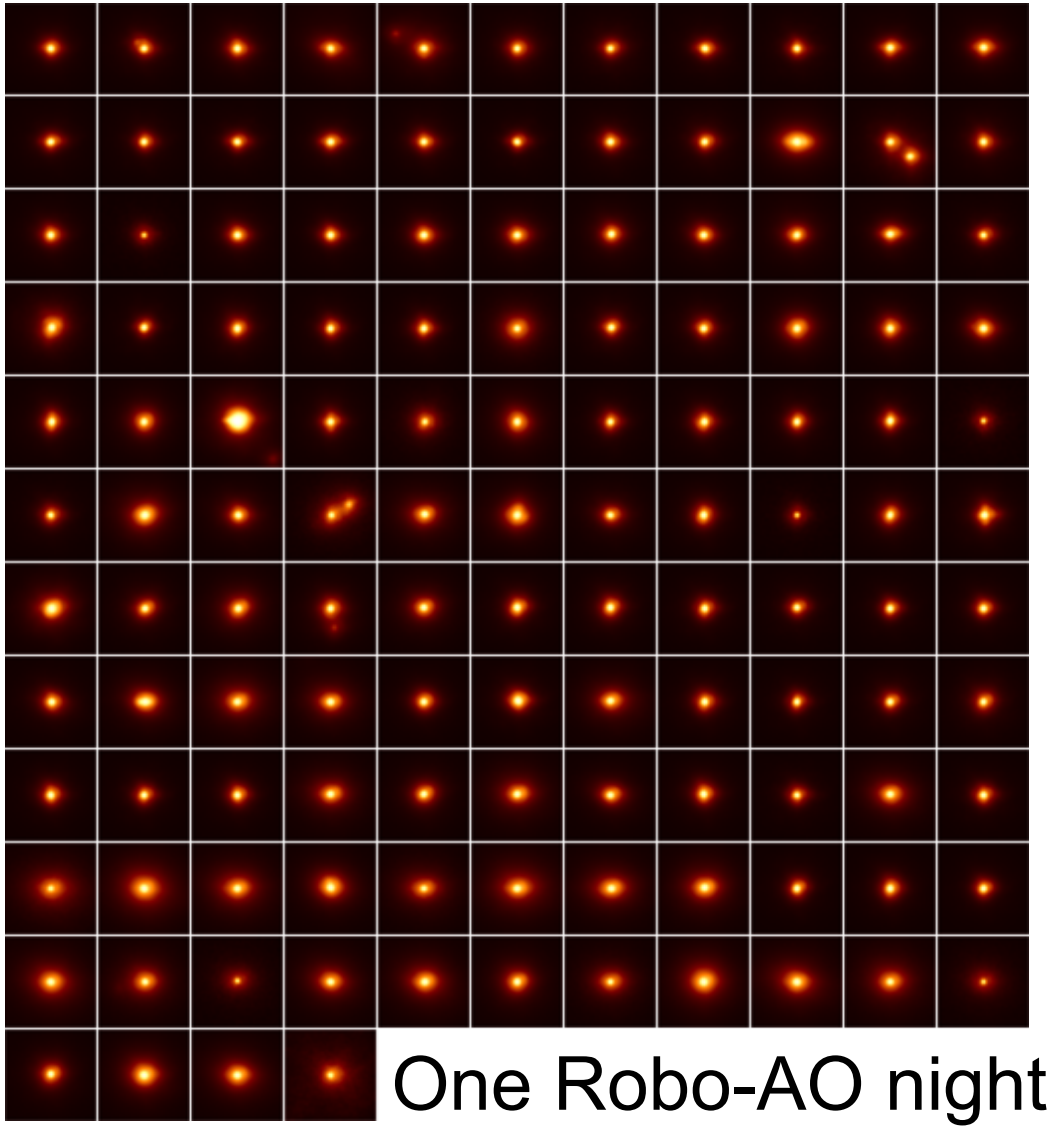
It works!

Over past year, AUTOMATION

From target lists to data frames

No queue scheduling (yet)

It works!



2 arcsec

125 targets!
(old by now)

One Robo-AO night!

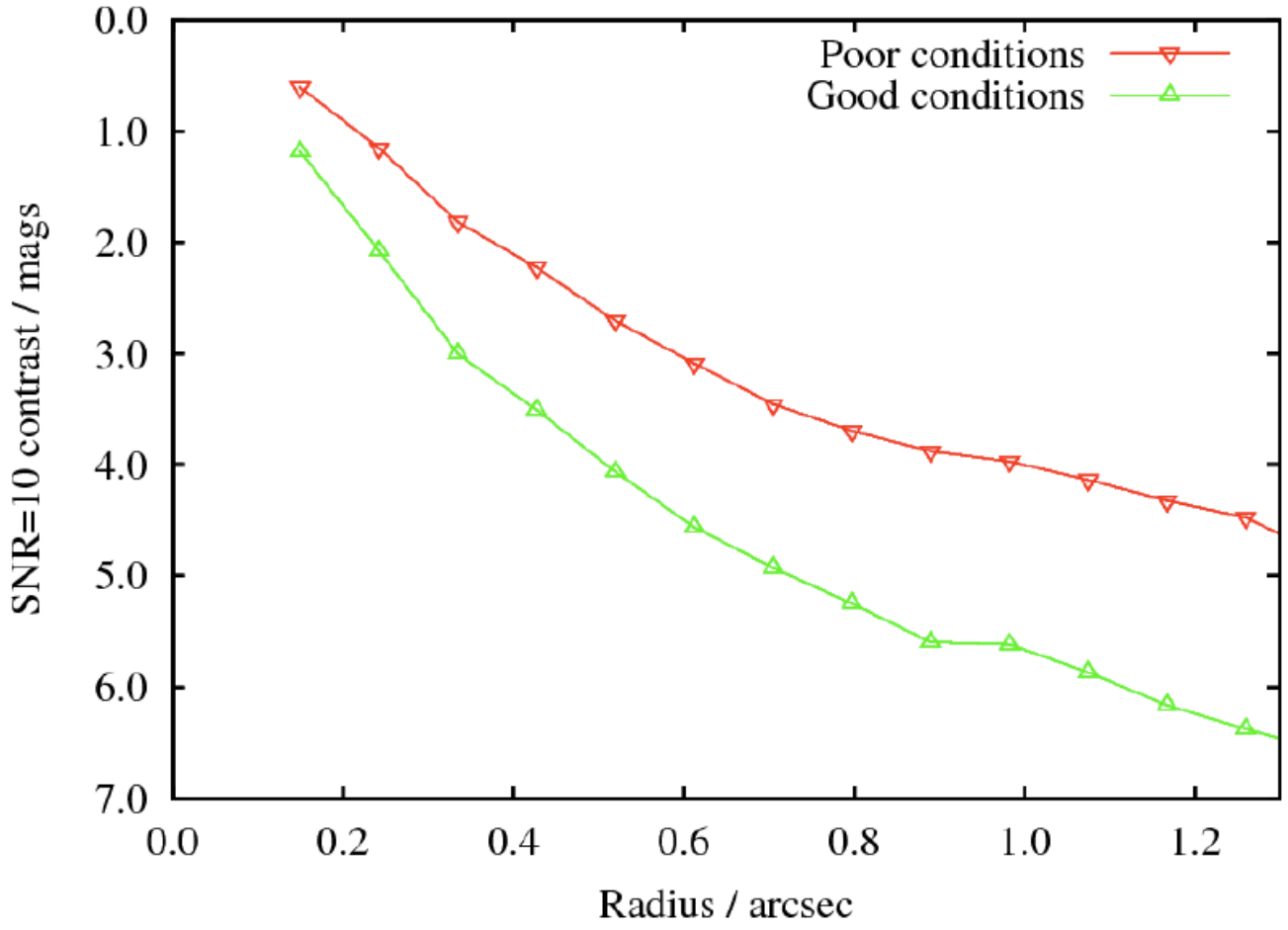
Science with Robo-AO

- Larger AO programs
  - By an order of magnitude!
- High resolution observing in visible
- Very efficient data collection

Robo-AO Binarity Survey

- The largest binarity survey!
  - Looking for brown dwarf companions
  - 2500 targets
  - Volume limited sample
  - Over all spectral types + WDs
  - Single instrument
  - Easier to understand biases

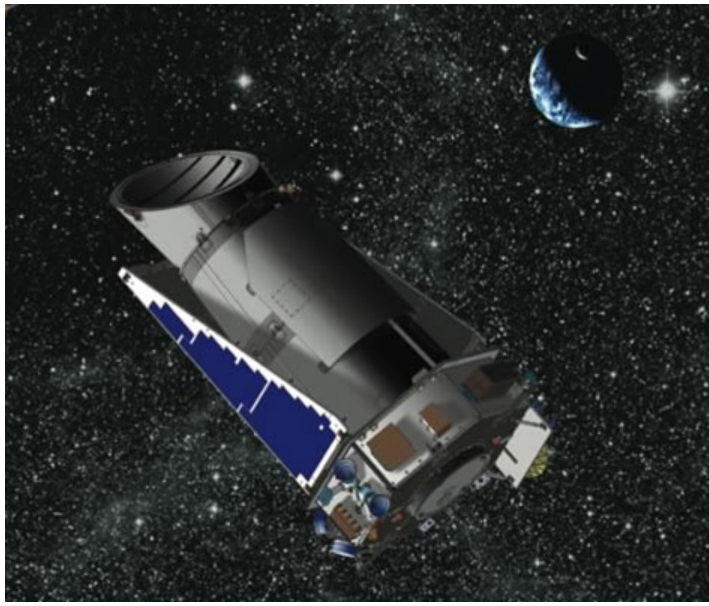
Robo-AO Contrast



Credits: Nicholas Law

Science with Robo-AO

- Kepler Candidate Followup
  - Vetting for blended binaries
  - ~1000 KOIs
  - Looking for false positives



Credits: NASA

Science with Robo-AO

- PTF binaries
  - Testing PSF shape algorithms
    - Can we identify blended binaries by finding slightly different PSFs?
- Lensed Quasars
  - Identifying lenses from SDSS quasars

Current Status

- Science observations underway!
  - 50 nights at Palomar
- H2RG camera being built
  - IUCAA designing dewar + electronics
  - Should be installed in 2013
- Add more capabilities?
  - Fiber fed spectrograph

Robo-AO around the world!

1.5-m at Palomar, USA

2-m Girawali Observatory, INDIA

1-m Table Mountain USA

South Pole??

May be your favorite telescope

Robo-AO Core Team

- Caltech
  - **Christoph Baranec (PI)**
  - Reed Riddle (Software)
  - Shriharsh Tendulkar
  - Richard Dekany
  - COO Staff
- IUCAA
  - **A. N. Ramaprakash (Co-PI)**
  - Mahesh Burse
  - Hillol Das
- Dunlap Institute (Toronto)
  - **Nicholas Law (PS)**

http://www.astro.caltech.edu/Robo-AO

Take home message

- AO on small telescopes is a good idea
- Large AO programs are now feasible
- Small telescopes need innovative instruments