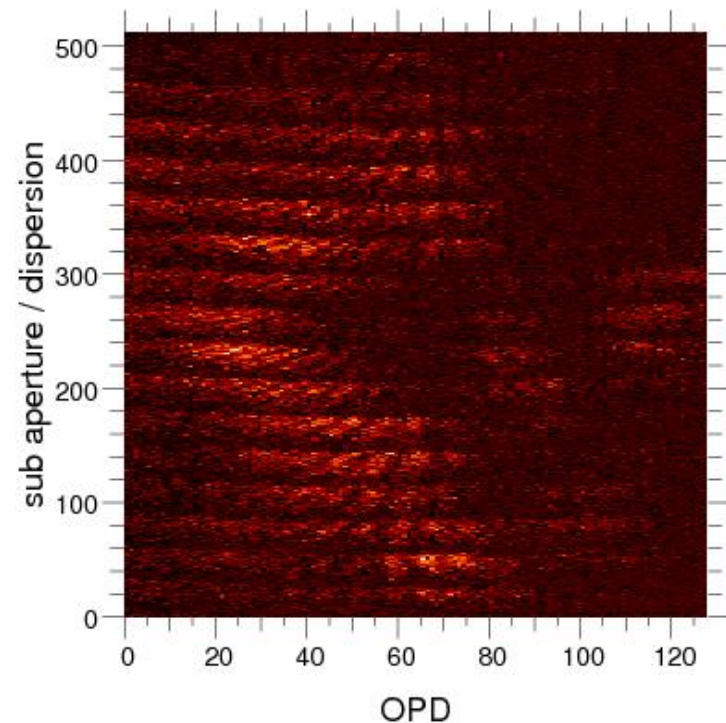




PAVO, SUSI and ROCS: Status and Future Plans

Mike Ireland...

+ Peter Tuthill, Theo ten Brummelaar, Gordon Robertson, Gail Schaefer, Antoine Merand, Daniel Huber, Nathan Buttersworth, Aaron Rizzuto... + thanks to Judit, Nils, etc...





Outline...

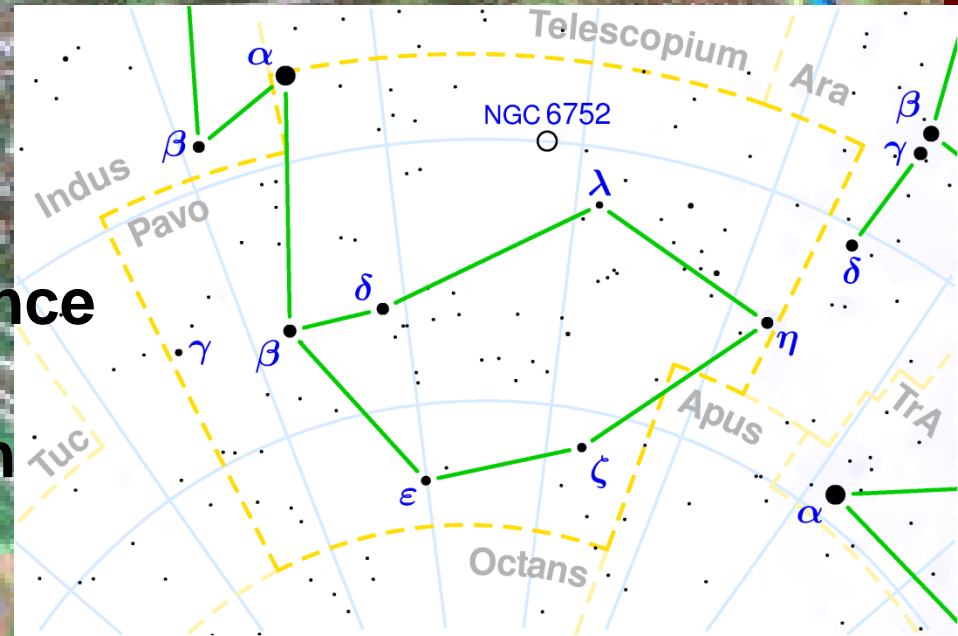
- The PAVO concept (slightly tricky)
- PAVO@CHARA implementation
- Data analysis progress
- Intro to SUSI
- PAVO@SUSI implementation
- Remote observing at SUSI
- Future expectations

PAVO

Precision Astronomical Visible Observations ... or a peacock ... or a turkey

Goal at CHARA is to **beat VEGA** by:

- Factor of 2 in sensitivity.
- Factor of 2 in accuracy.
- Factor of 2 in observing cadence for same S/N.
(but no high spectral resolution mode)





Timeline...

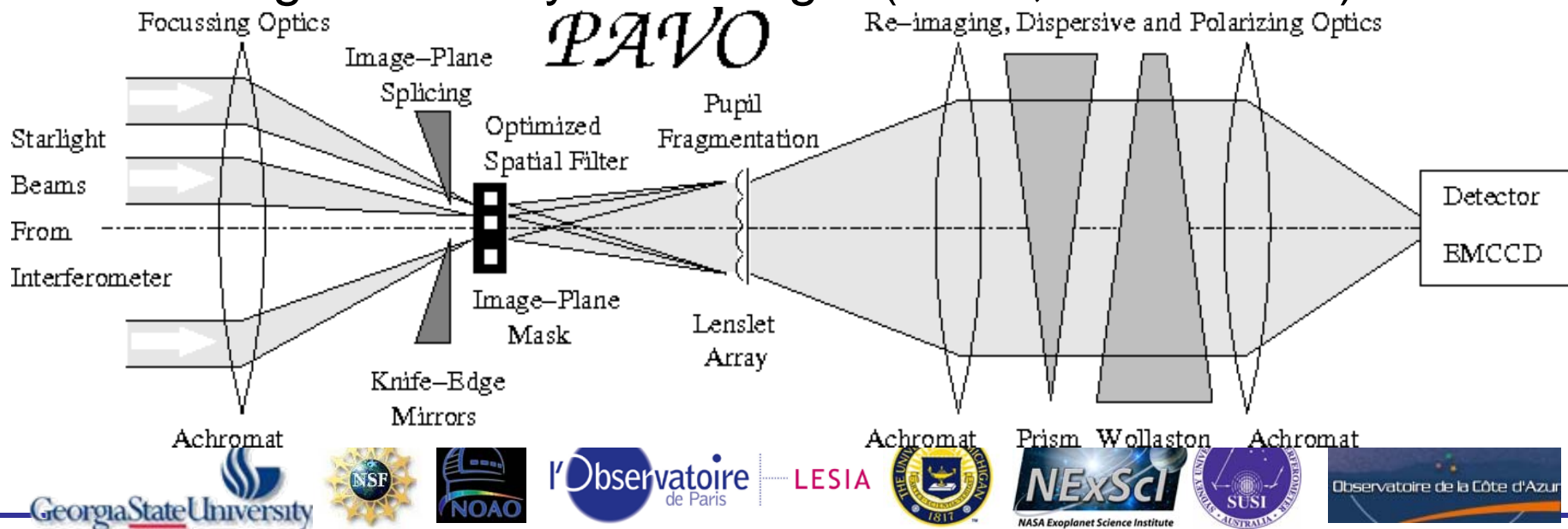
- Jan 2007: Concept for ARC proposal
- May 2007: Hal and Theo agreed to channel Keck vis combiner money to PAVO prior to ARC announcement
- August 2007-Jan 2008: Construction
- March-July 2008: Commissioning
- Aug-Dec 2008: Shared risk science



PAVO Optical Concept

Quick Intro:

- 1) The PAVO beam-combiner places 2 (SUSI) or 3 (CHARA) star images beside each other.
- 2) The images pass through a mask, which acts as a spatial filter
- 3) Fringes are formed in a pupil-plane
- 4) An IFU turns these fringes into a data cube, with an image of the fringes at every wavelength ($R \sim 50$, 620-950nm)





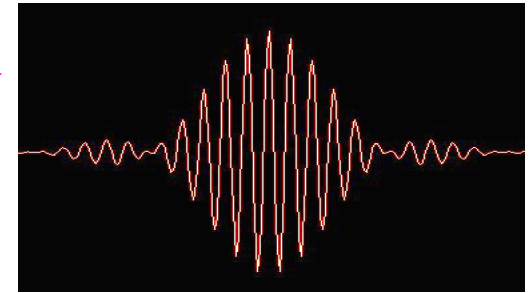
PAVO: Precision Astronomical Visible Observations

Output 1

Output 2

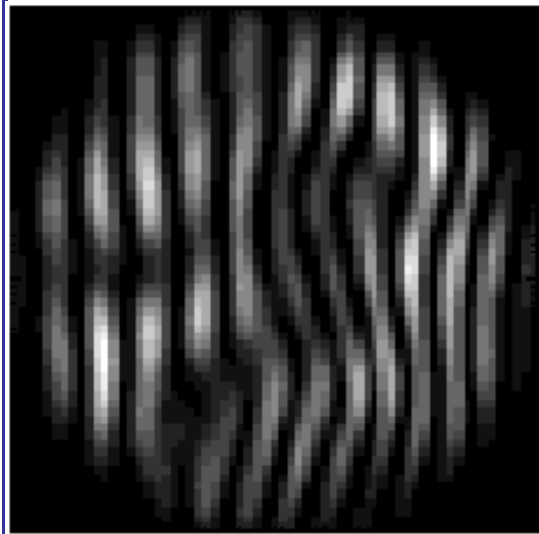


Difference Signal

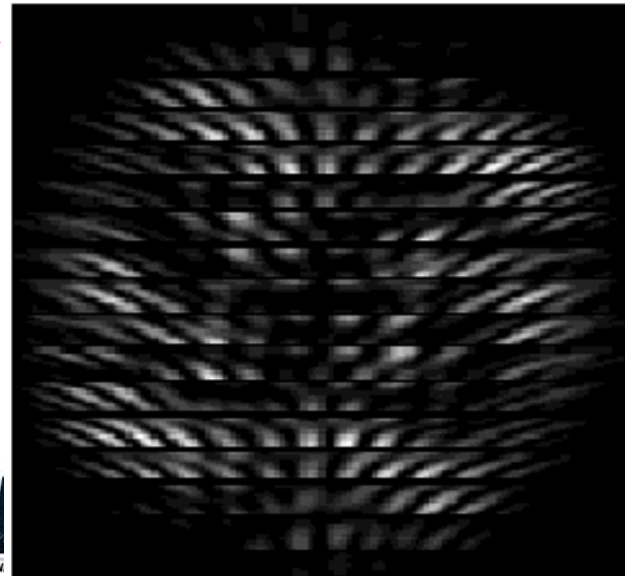


- SUSI/CHARA Classic... Full pupil summed in a two “pixels”, temporal modulation.
- PAVO: 120 (SUSI) and 6000 (CHARA) pixels over the pupil, spatial modulation.
- Spectral dispersion enables group-delay tracking.

Pupil fringes at single wavelength



Broad-band Fringes after IFU



Integral Field Unit
 CHARA: 16 lenslets
 Think of a data *cube*

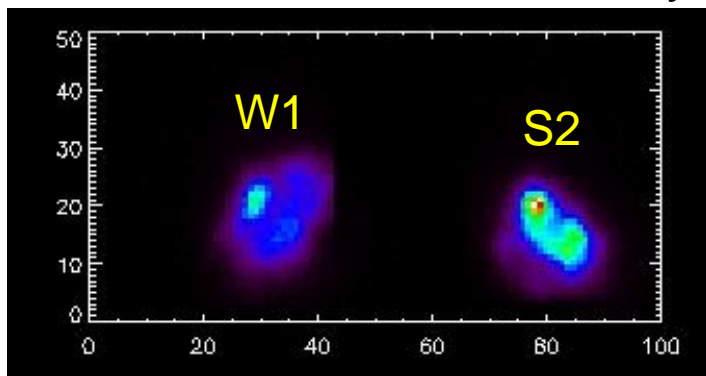


Notes: Spatial-filtering 1

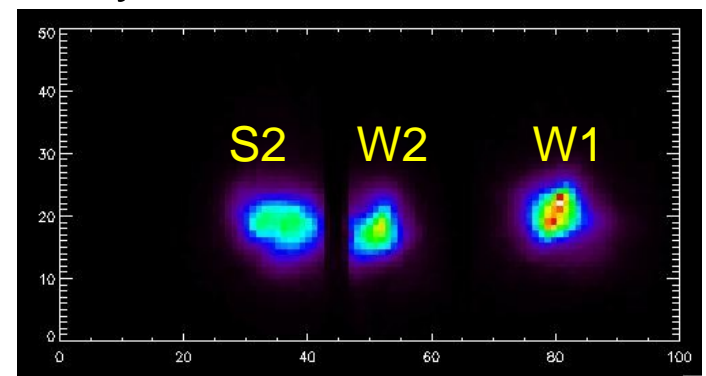
- The image-plane spatial filter is a pinhole spatial-filter, that should allow >50% of the starlight through in ~1.2" seeing (neglecting aberrations).



- Side comment: In the presence of aberrations, the left half of the pupil might make it through one hole, and the right half through another. Then there is no overlap and zero visibility. So the aberrations affect reliability as well as sensitivity.



1.2" mask
hole to scale





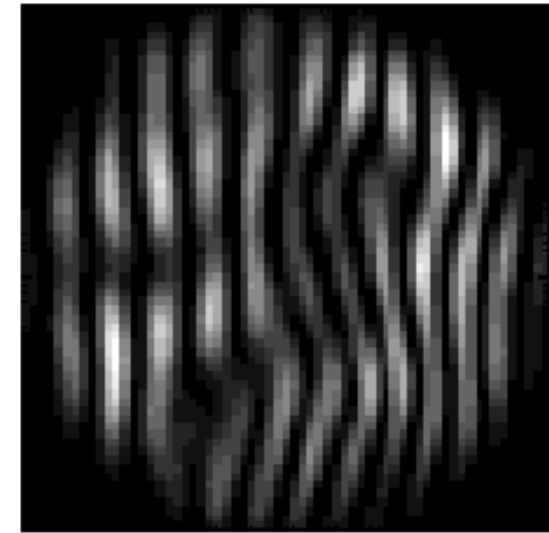
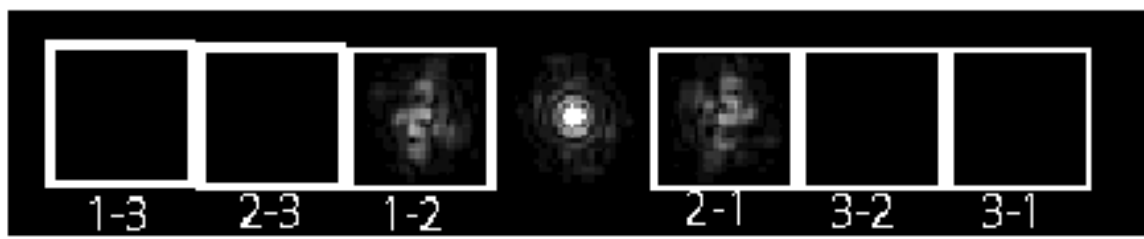
Notes: Spatial-Filtering 2

- 1) Phase aberrations across the pupil occur at all spatial frequencies.
- 2) By band-limiting the flux in the image-plane (i.e. passing the light pass through a mask), phase aberrations can only occur at low spatial frequencies.
- 3) The effect of finite sampling in the pupil-plane then becomes an analytic correction to the fringe visibility

V^2 is completely insensitive to phase across the (spatially-filtered) pupil

$$A_{\text{cor}}(x', y') = A(x, y) / \text{sinc}\left(\frac{\pi x' S_x}{\lambda D}\right) / \text{sinc}\left(\frac{\pi y' S_y}{\lambda D}\right).$$

2D Optical FFT



$$A(x', y') = \int F(x, y) \exp(2\pi i \frac{xx' + yy'}{\lambda D}) dx dy$$



LESIA





Notes: Pupil-plane Fringes

- *Saying all this another way...* Seeing and aberrations will prevent fringes from being straight, but as long as 2 pupils are evenly illuminated, the instantaneous fringe visibility should be 1.
- As well as band-limiting the fringes, the spatial-filter causes non-uniform intensity, requiring moderately frequent photometry measurements.

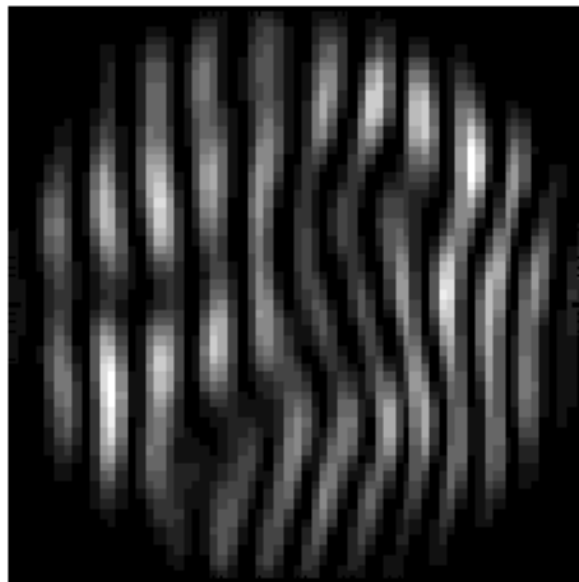
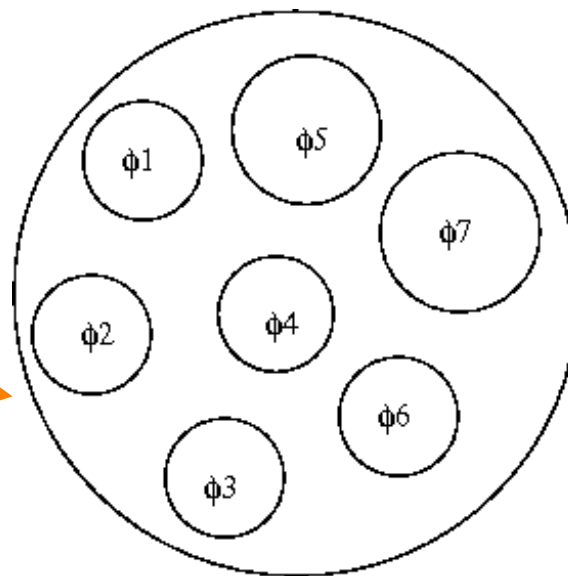


Image or Pupil-plane?

The coherent “sub-apertures” which have fringes on them could be in an image-plane, a pupil plane or something in-between. The choice of a pupil-plane was chosen because we have no photometric taps, and intensity should be more stable in a pupil-plane.

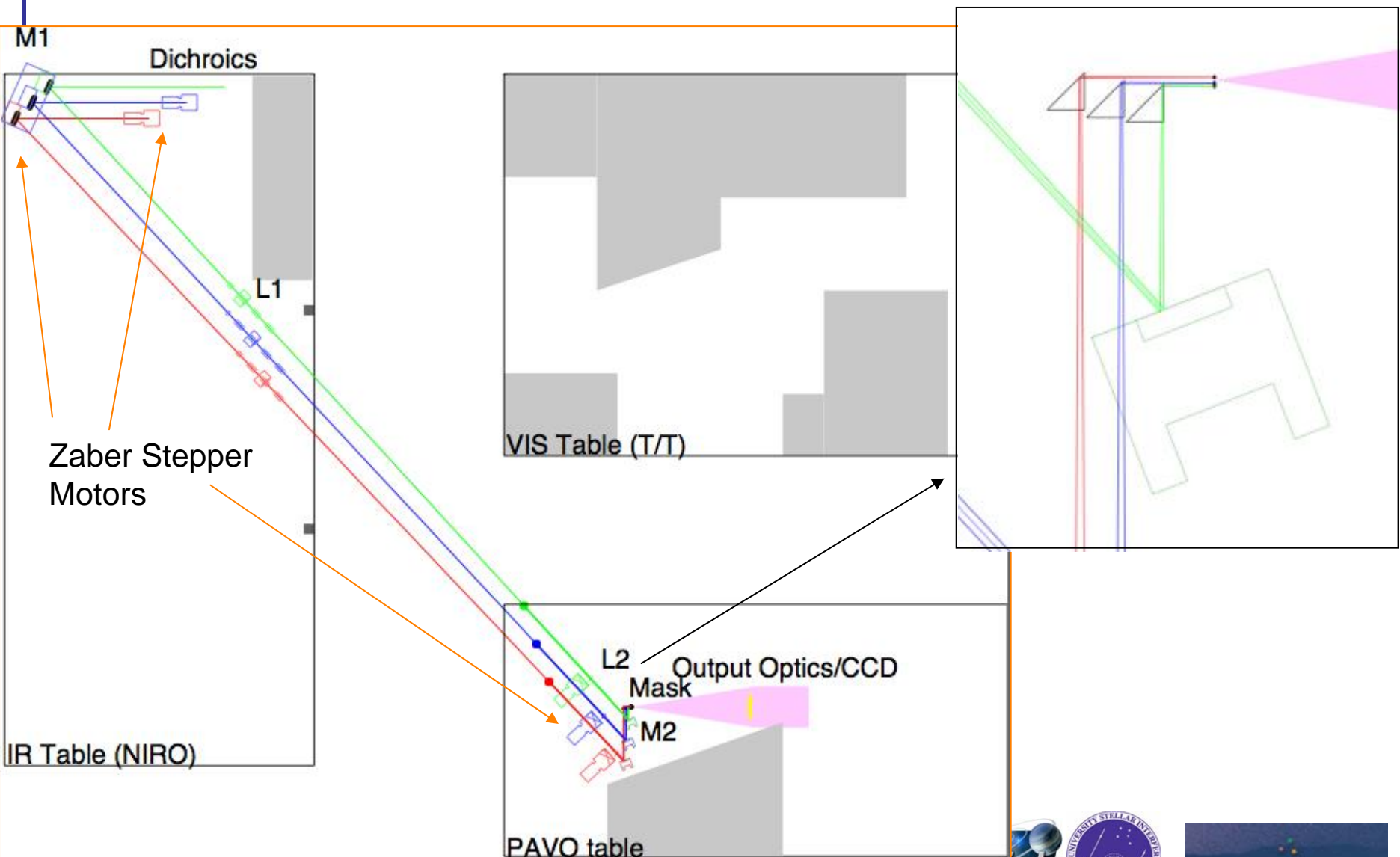
“Sub-apertures” can be made in the image or pupil planes.



System response (point source V^2 etc...) is a weighted average of a function of intensity...
... so we want intensity to be stable

$$V_{sys}^2 = \frac{1}{N_{subap}} \sum_{pupil} \frac{4I_1 I_2}{(I_1 + I_2)^2}$$

Optics at CHARA



IR Table (NIRO)

VIS Table (T/T)

PAVO table

Output Optics/CCD

Zaber Stepper Motors

Dichroics

M1

L1

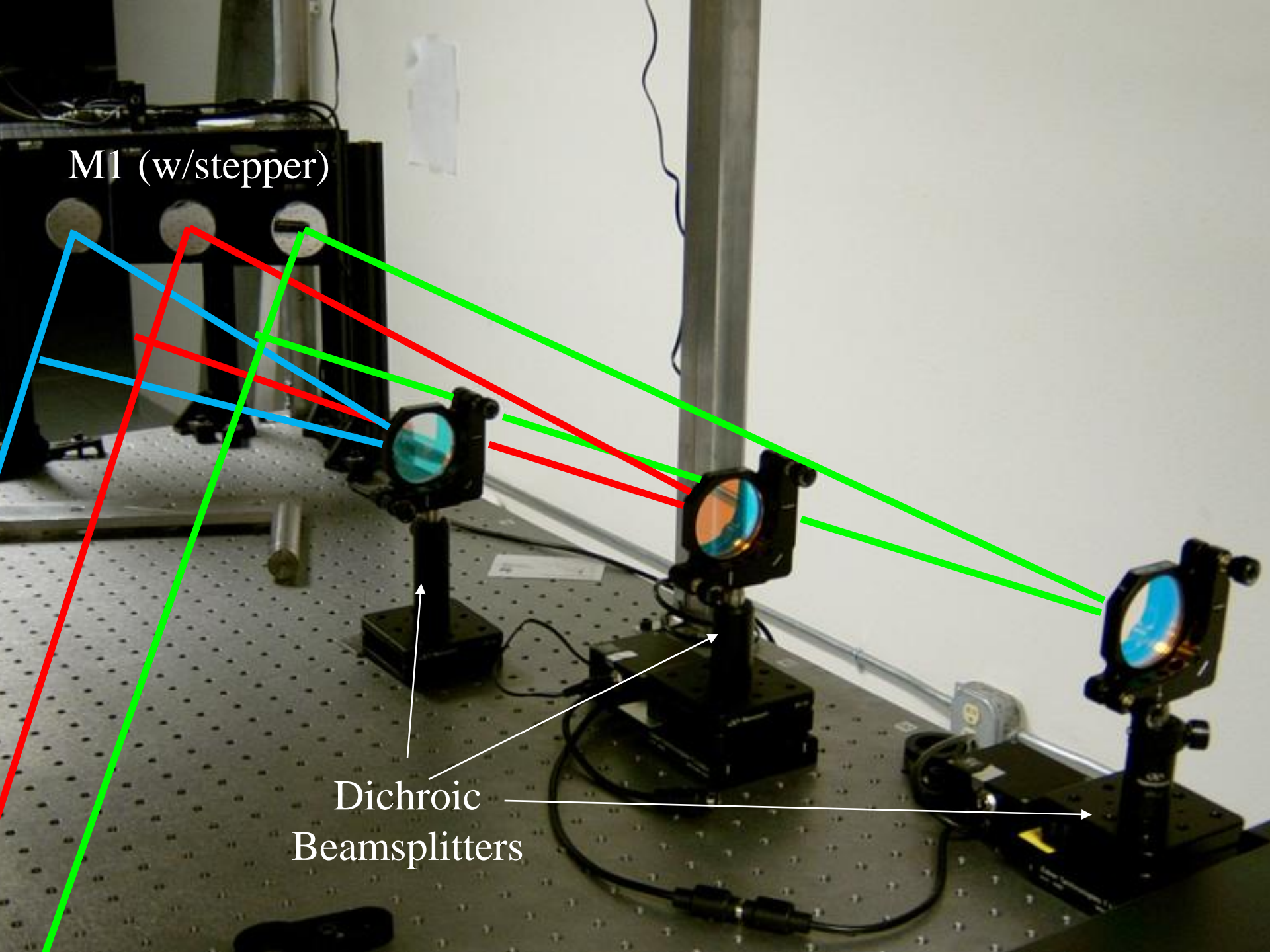
L2

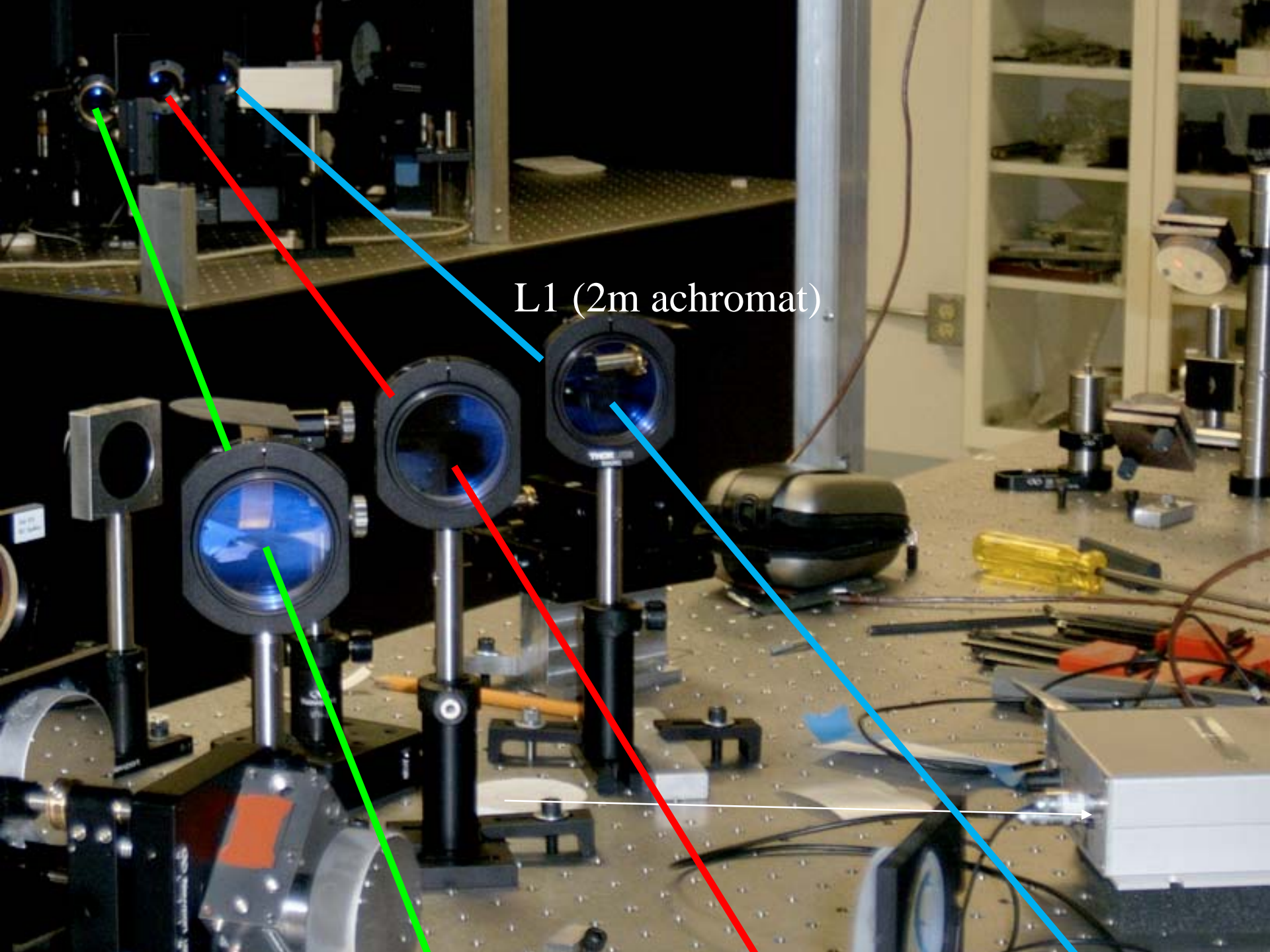
Mask

M2

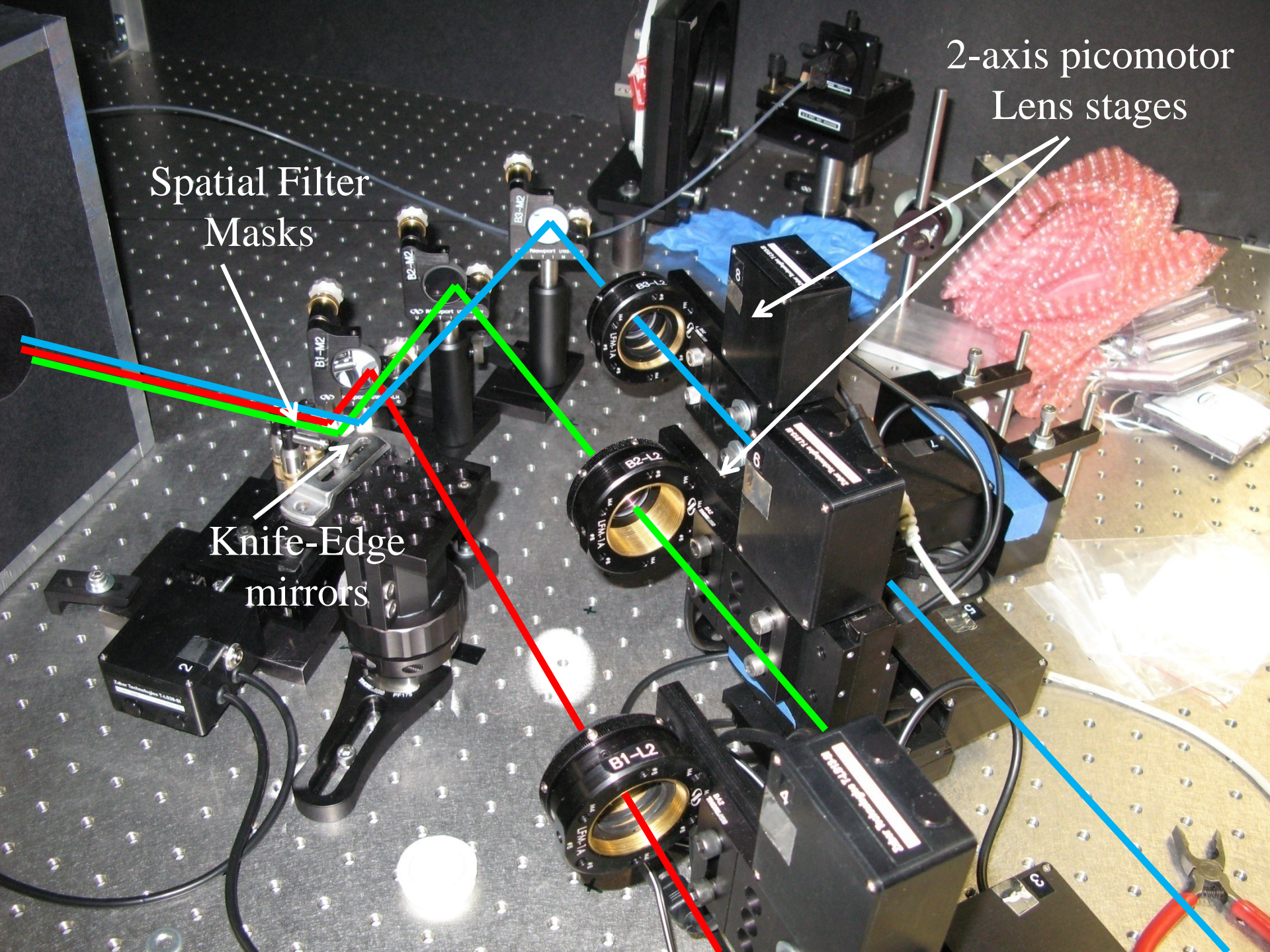
M1 (w/stepper)

Dichroic
Beamsplitters





L1 (2m achromat)



Spatial Filter
Masks

Knife-Edge
mirrors

2-axis picomotor
Lens stages

B1-L2

B2-L2

B3-L2

B1-M2

B2-M2

B3-M2

2

6

4

5

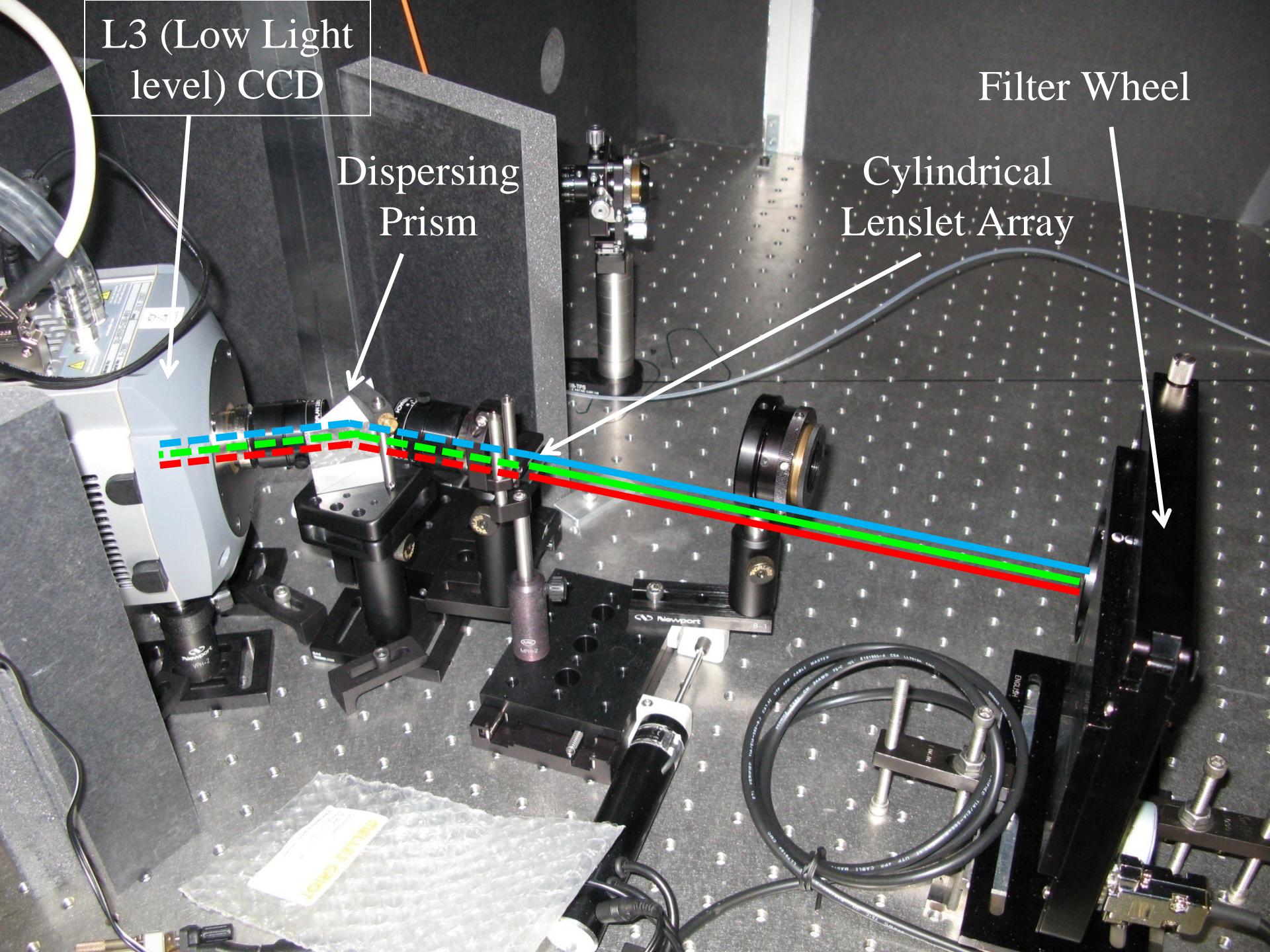
3

L3 (Low Light level) CCD

Filter Wheel

Dispersing Prism

Cylindrical Lenslet Array





PAVO Software@ CHARA



W2 FIND **VO ZABER ENGINEERING** **IRIS** **PAVO**

WAZOO - SECONDARY

CAL TIME: 21:33 CHARA TIME: 04:33 SIDEREAL TIME: 10:00 HOUR ANGLE-00:32

BRATOR 1	FIND IRC	WHEN	7_Hya		
118680	IRC	HR	3454	HD	74280 SAO 117050
CLEAR RA: 08 43 13.4752 DEC: +03 23 55.184 Vmag: 4.27 Kmag: 0.00 Type: B3V AZ/EL: 214.3/54.3 39.57					
OBJECT	FIND IRC	WHEN	sig_Leo		
141959	IRC	HR	4386	HD	98664 SAO 118804
CLEAR RA: 11 21 08.1943 DEC: +06 01 45.558 Vmag: 4.04 Kmag: 0.00 Type: B9.5Vs AZ/EL: 141.9/56.1					
BRATOR 2	FIND IRC	WHEN	>> rho_Leo <<		
135914	IRC	HR	4133	HD	91316 SAO 118355
CLEAR RA: 10 32 48.6719 DEC: +09 18 23.708 Vmag: 3.84 Kmag: 0.00 Type: B1Ib AZ/EL: 161.4/63.9 12.52					
CHECK STAR FIND IRC WHEN NOT SET					
NUM	IRC	HR	HD	SAO	
CLEAR					
JOB QUEUE: 0 START JOB QUEUE STOP JOB QUEUE CLEAR JOB QUEUE					
Tiptilt (mS)	XXXX	Center (m)	0.000	Range (m)	0.010 REF AUTO 0.0
PAVO SKIP LOW SNR BYPASS FILTER TARGET MEM BL SOL Acq: None Init Tpoint					
CONFIG	SCOPES	K BAND	FB LONG	1000Hz/2x2	200 Hz Frq NORM MODE
IN	OUT	FIND	SYNC GPS	SYNC ME	STAR ACQUIRED TRACK SOCKET SET DISPLAY
SERVO MOD SIN r0 (cm) Seeing Snd					
ON	NO	7.5	1.27	ON	FRINGE RECORD DITHER RECORD SCAN
ON	NO	3.4	2.47	ON	accepted connection from s2.chara-array.org
ON	NO	2.6	3.05	ON	accepted connection from zoot.chara-array.org
OFF	NO	0.0	0.00	OFF	accepted connection from s2.chara-array.org
ON	NO	5.5	1.64	ON	accepted connection from zoot.chara-array.org
ON	NO	6.2	1.48	ON	accepted connection from s2.chara-array.org
= 0.08" r0 = 9.7cm Seeing 1.02"					
= 0.12" r0 = 3.3cm Seeing 2.53"					
= 0.11" r0 = 2.1cm Seeing 3.69"					
Tiptilt: S2 Detector RMS = 1.06" r0 = 0.0cm Seeing 0.00"					
Detector RMS = 0.10" r0 = 5.4cm Seeing 1.68"					
Detector RMS = 0.09" r0 = 4.9cm Seeing 1.81"					
COPE E1 4.2 accepted connection from s2.chara-array.org					
COPE E1 4.2 accepted connection from zoot.chara-array.org					
COPE E1 4.2 accepted connection from s2.chara-array.org					
COPE E1 4.2 accepted connection from zoot.chara-array.org					
Detector RMS = 0.07" r0 = 9.7cm Seeing 1.03"					
Detector RMS = 0.12" r0 = 3.4cm Seeing 2.44"					
Detector RMS = 0.11" r0 = 4.3cm Seeing 2.00"					
Detector RMS = 1.04" r0 = 0.0cm Seeing 0.00"					
Detector RMS = 0.11" r0 = 5.7cm Seeing 1.60"					
Detector RMS = 0.09" r0 = 4.8cm Seeing 1.83"					
TILT 1.2 accepted connection from irimage.chara-array.org					
COPE E1 4.2 accepted connection from zoot.chara-array.org					

STATUS STOW RESET TILT S2

Group Delay DFT, Baseline 2

M5 OPEN M5 CLOSE CLOCK LPT AUTO MODE VERBOSE PING REOPEN END

FIND OPEN FIND CLOSE REMOTE DISPLAY

HEAT ON HEAT OFF PING REOPEN

OK QUIT

Beam Size: CLOSE BEAM INC STATUS PING REOPEN QUIT

GO/STOP SAVE SEARCH SHUTTER BACK FORE MOVE: B3-Image UP BIGGER LEFT RIGHT step size: 100 DOWN SMALLER X1[14]= -23930 X2[7]= 36659 Y1[13]= -38700 Y2[8]= 47690 B1 B2 B3 TARGETS OG 590 DISPLAY NO DISPLAY IMAGE PUPIL ENG MASK OUT STATUS PLOTS REOPEN QUIT

Socket Manager Reports

Bl	GD	S/N	Tint	V*2	V*2C	V*2S	V*2CS	Disp	Cnt	Tel	State	Pos	Vel	TL	S
M1E2	3.2	7.2	220	1.988	0.035	0.006	-0.118	0.5	541	M1	FIX	0	0.0	0.0	0
E2M2	-0.9	4.8	200	1.905	0.016	0.008	-0.102	0.1	541	E2	AON	14558	-6.3	217	
M1M2	2.3	8.3	281	2.001	0.059	0.008	0.001	1.1	541	M2	AON	3392	-5.3	59	

YOU NEED TO RESTART THE PR

Type RETURN to continue.

(wazoo:1021) cd [2]- Done /control/modules/pavo (wd now: ~)

[3]+ Done /control/modules/pavo (wd now: ~)

(wazoo:1022) cd control/cl (wazoo:1023) gimp

PAVO 1.0

Local Tm: 21:33 Detector T: -68.9A Status: run EM Gain: 150 Max: 338 Flux: 5.32e+05 Binned: 1x4 Exp Time (ms): 9.7 Error: Debug: 0.90N Late: 344 Size: 512x128 Count: 548, 548/ 800 Saving: ON Fillnum: 3006 Shutter: OPEN W: -0.13 0.30 CP: 19.4 1.5 -6.1 -25.2 2.3

Current menu : MAIN F1 Get help Previous menu : None F2 Run the auto list Menu Depth : 0 F3 Background control menu F4 Socket control menu F5 Standard Control menu F6 Utilities Menu F7 Quit system

Help <> Help <BACKSPACE> Previous menu <> MAIN menu

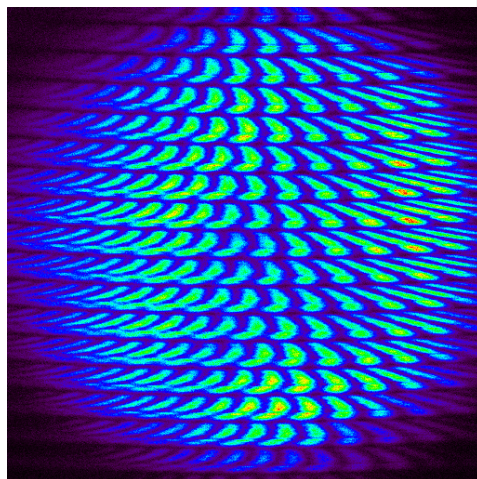
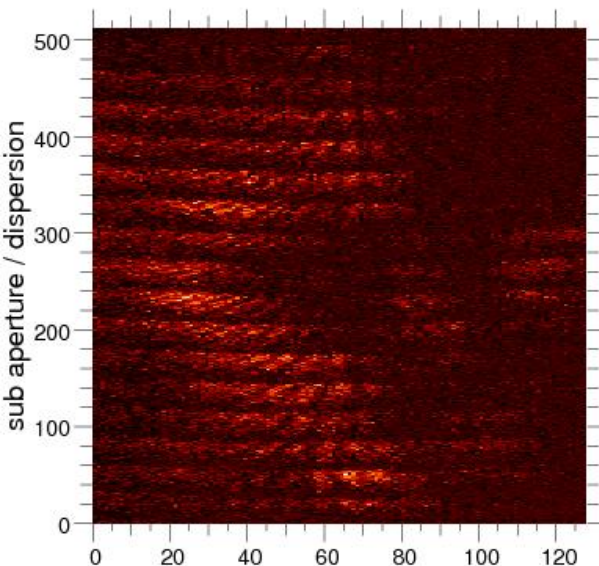
DPLE Command is later!

NAME ople_2 Machine ople.chara-array PID 15210 Commands 2001 Data 2101 Messages 2201 Restart CLEAR

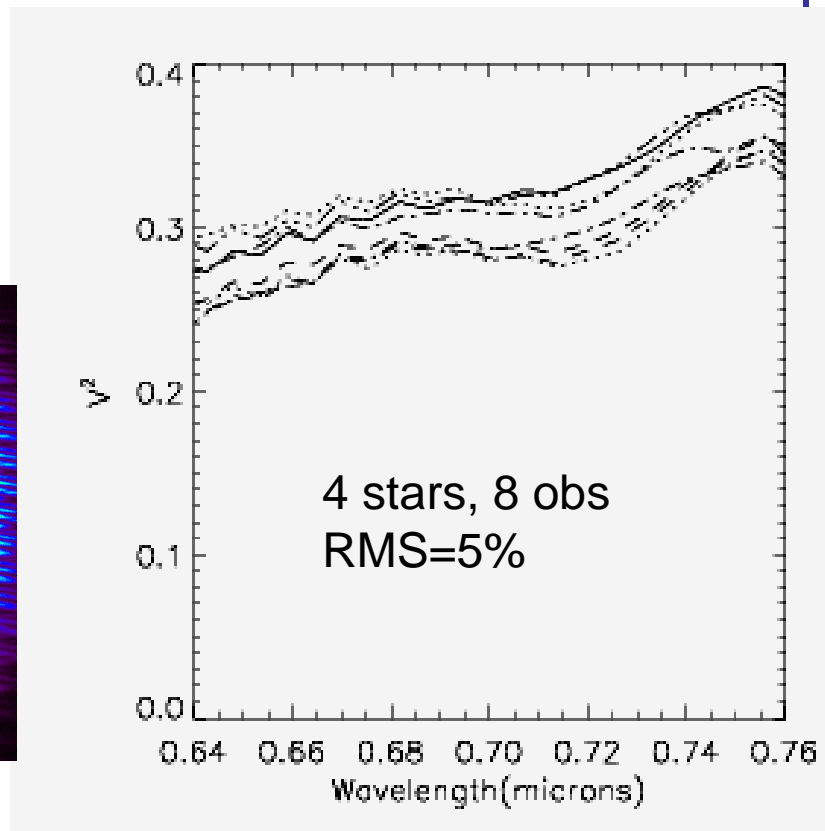
Commissioning 2008

- PAVO@CHARA has tracked 3-baseline fringes at R=8.2 so far (few micron RMS, ~10 sec typical fringe lock, ~1 Hz correction bandwidth).
- On track for R=9 (excellent conditions) with PAVO improvements only, or R=10 with improved CHARA image quality.
- R=7 is the limit for median conditions, and sensitivity goes as $N \cdot V^2$, so e.g. 2nd lobe work has a typical R=2 or worse limit.

10ms on-sky (lam Uma)



Lab Fringes



Raw V2 (no t0 correction)



Data Analysis Pipeline

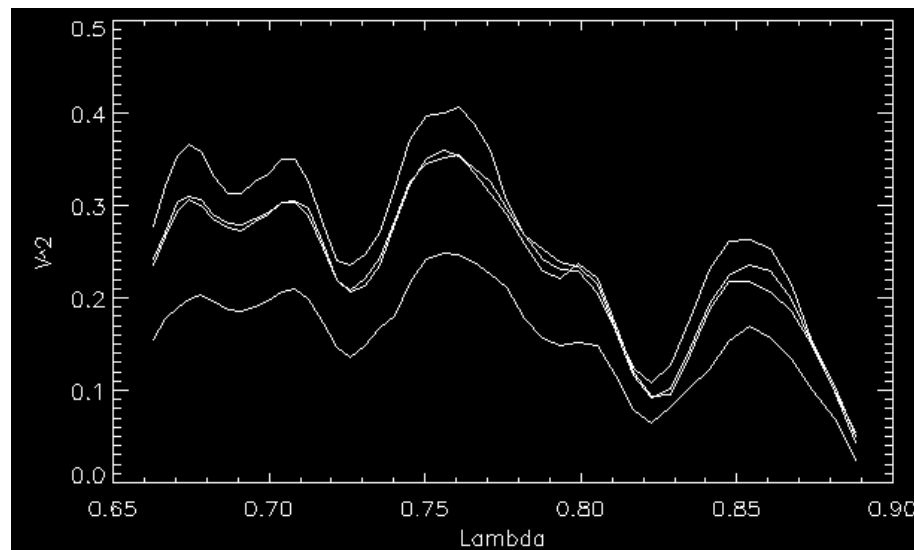
- Language: Initially (e.g. SPIE) written in *yorick*. This had problems with debugging, so we've moved to *IDL*.
- Contributors: Daniel Huber, Nathan Buttersworth and Aaron Rizzuto, Peter Tuthill and me.
- Issues: Foreground subtraction, Speed, Complexity, Data Size (>1 TB... compressed)
- Release Date: Now in CVS – expect a usable version with minimal documentation by April 4.



V²: Single Baseline

- 3-Methods for foreground-subtraction:
 - Get bias from unused baselines.
 - Get bias from power spectrum in-between baselines.
 - Use foreground files to find gain, i.e. $\text{bias} = \text{gain} * \text{flux}$
- Even with good foreground subtraction, there are calibration issues.

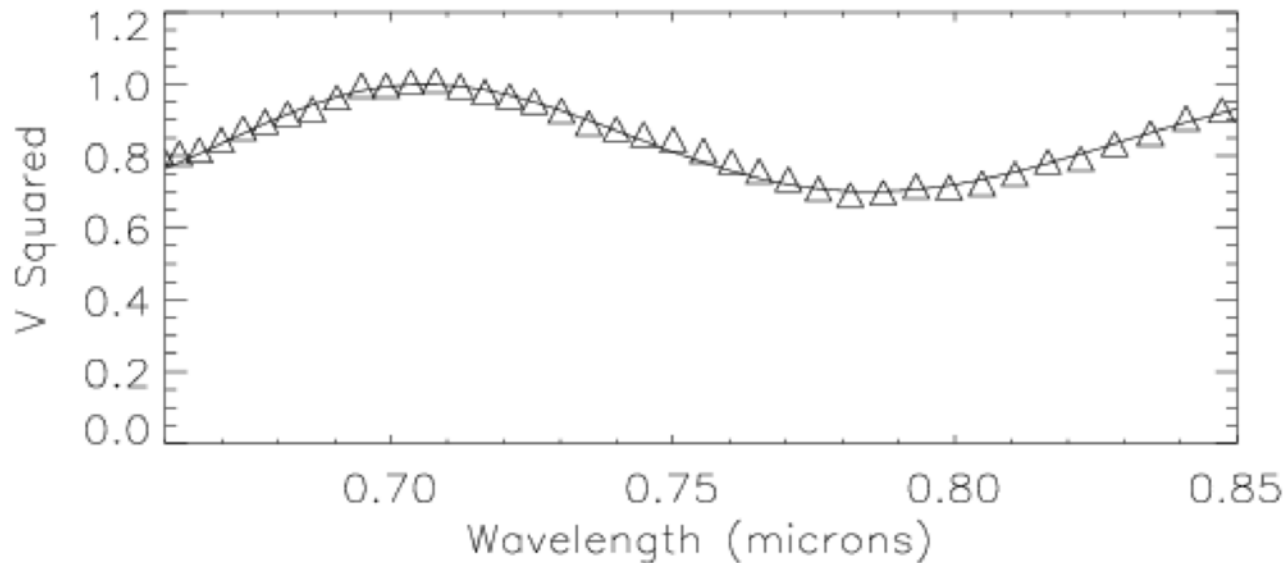
(~half the data doesn't show these effects)



HD 187340, HD 175305, HD 196502, HD 201908



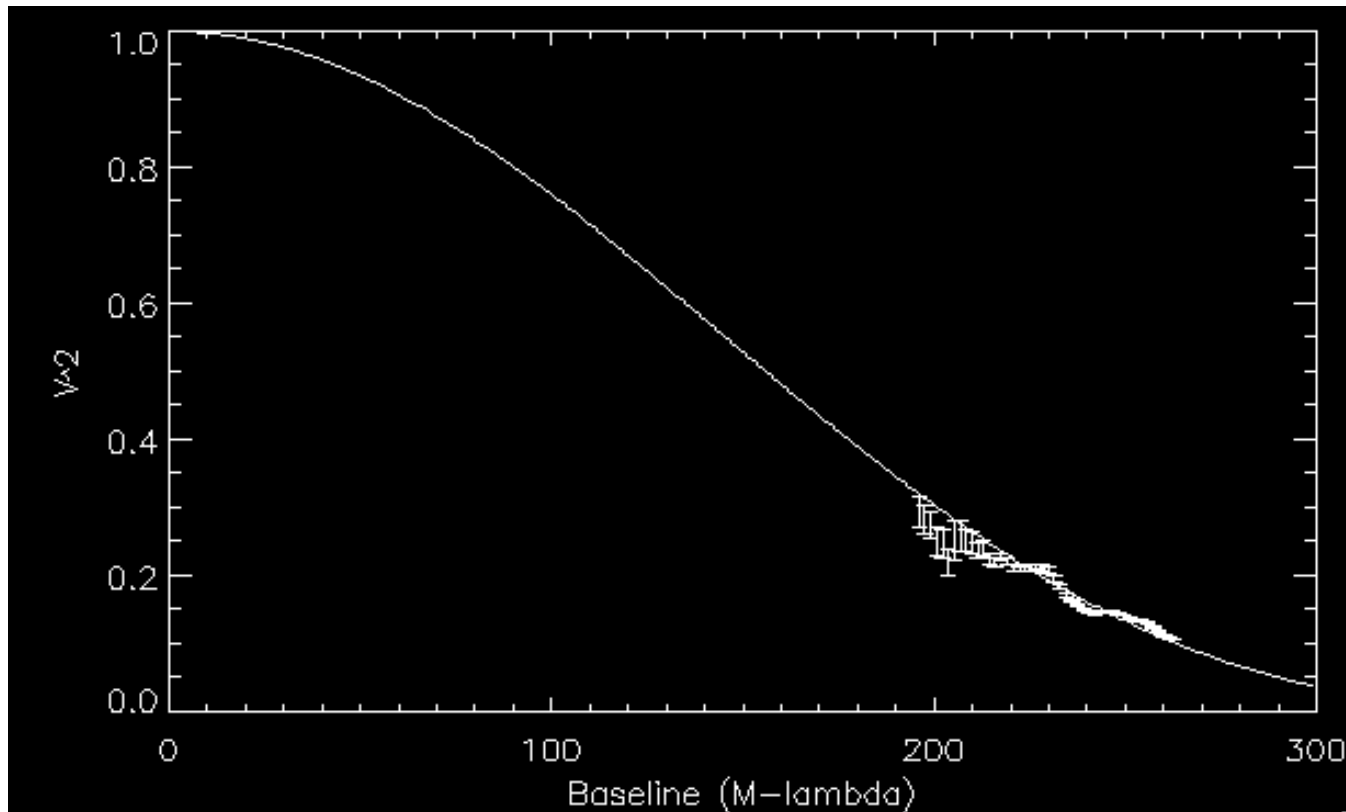
Example V^2 Science



4 minutes (including overheads) on the binary HD 28294 (76 Tau, HIP 20873, vB 68), a Hyades binary that had not been previously resolved. Calibration at the percent level. This binary was resolved on S1S2, has a projected separation of 24 mas (error <0.2 mas) and a contrast ratio of 2.6 magnitudes.



Example V^2 Science

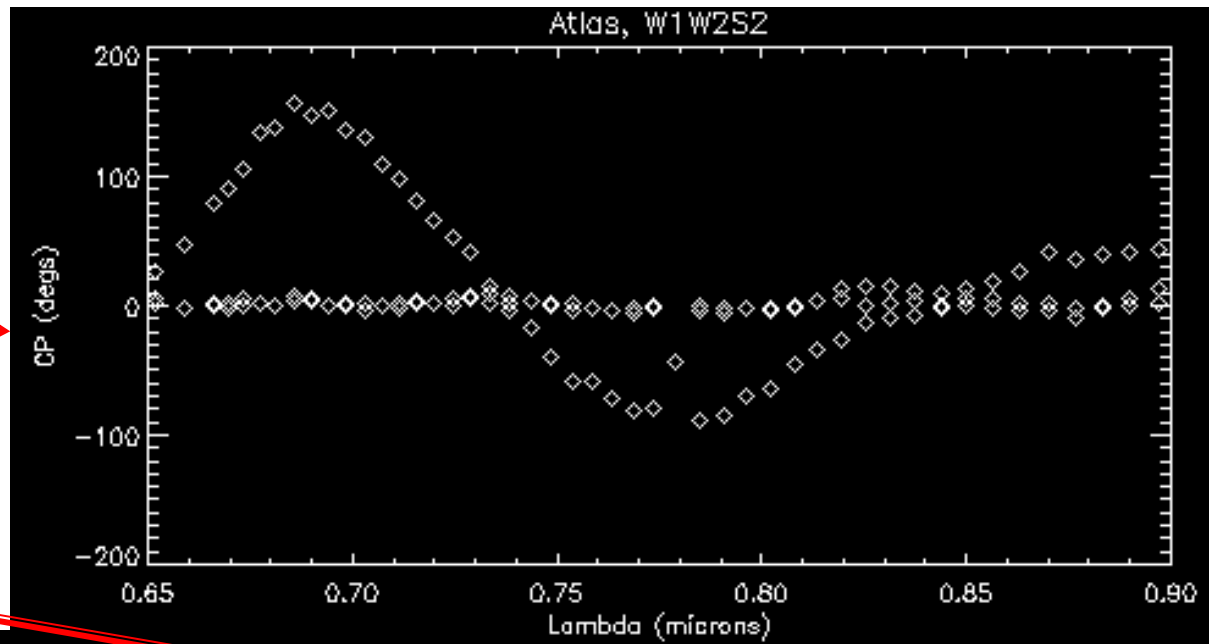


Eps Ori calibrated with HD 35299. 0.68 ± 0.005 mas diameter.
We are systematically analyzing all single-baseline data for 2008...



Preliminary Closure-Phases...

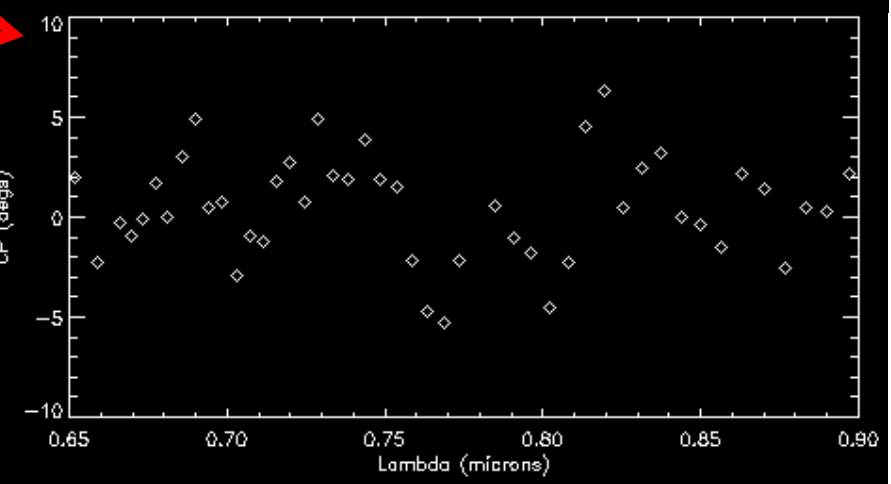
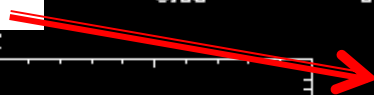
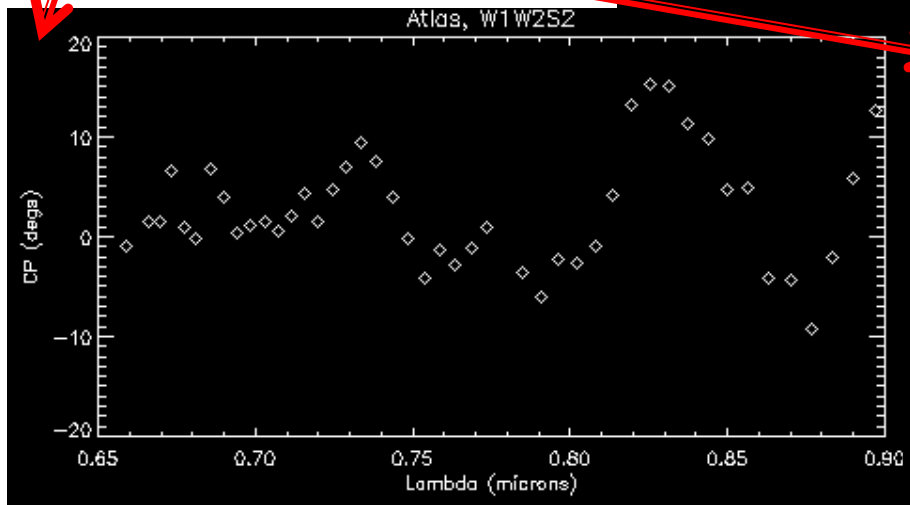
Atlas (SB2 in Pleiades)
+ 2 Cals: obviously
huge Closure-phase
signal



Electra, Cal 1 (binary?)



Cal 2, R=5.5

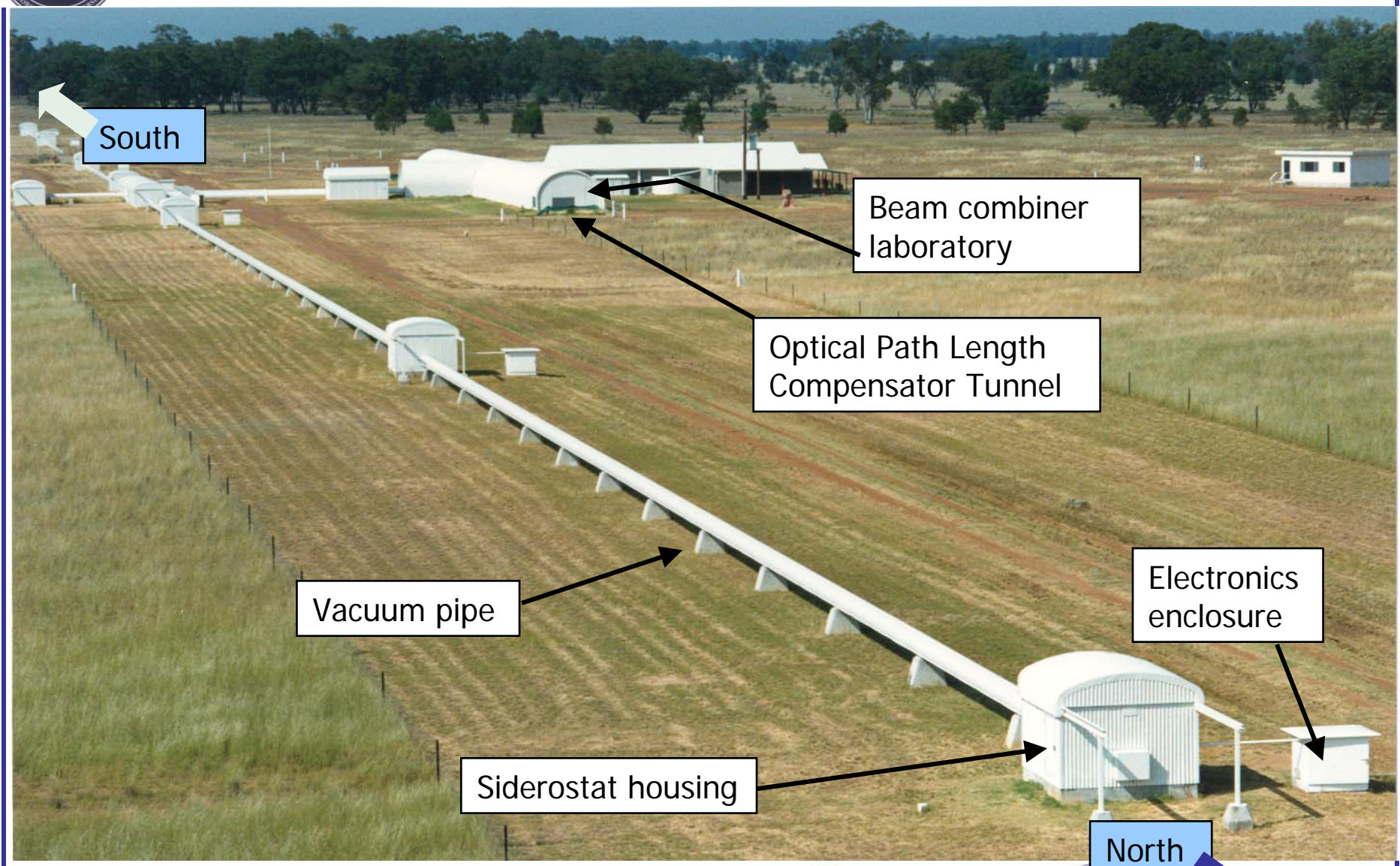


LESIA





SUSI – overall view



LESIA





SUSI – main specifications

Latitude: $-30^{\circ} 19' 20''$

Baselines (North-South): 5, 10, 15, 20, 30, 40, 55, 80, 110, 160 ... 640 m

Siderostat diameter 20 cm; beam diameter 14 cm in vacuum pipe; 4.7 cm after Beam Reducing Telescope

Piezo-actuated tip-tilt mirrors

Optical Path Length Compensator

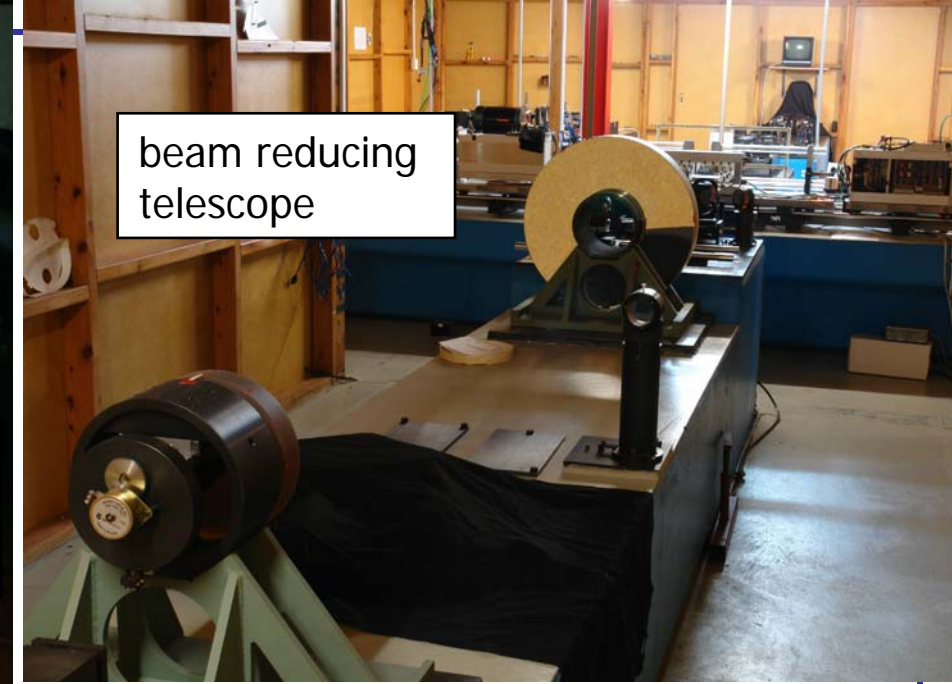
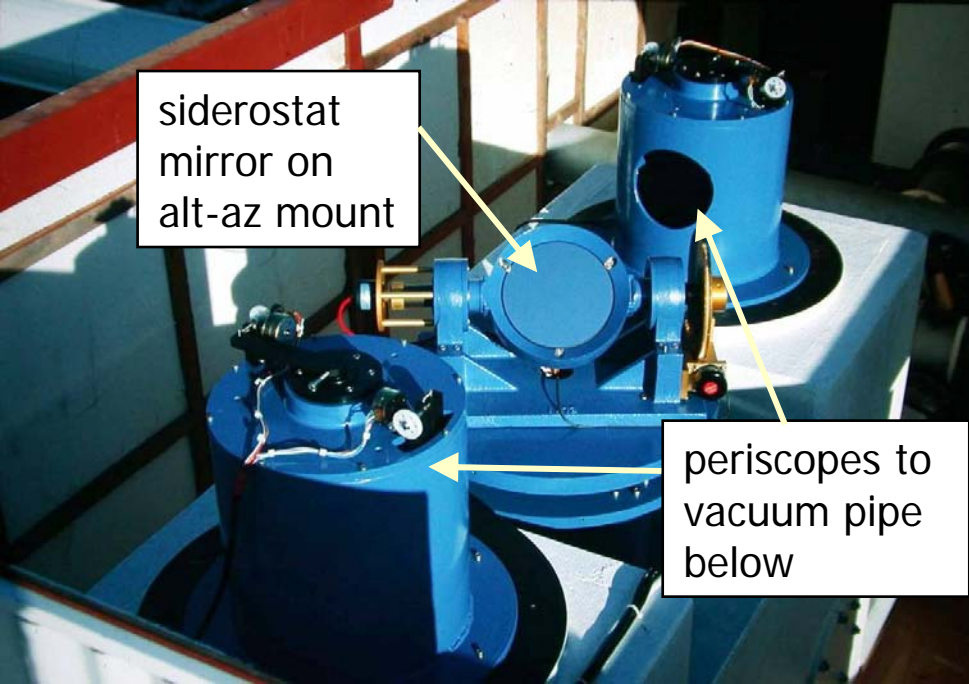
Longitudinal Dispersion Corrector

Beam combiners:

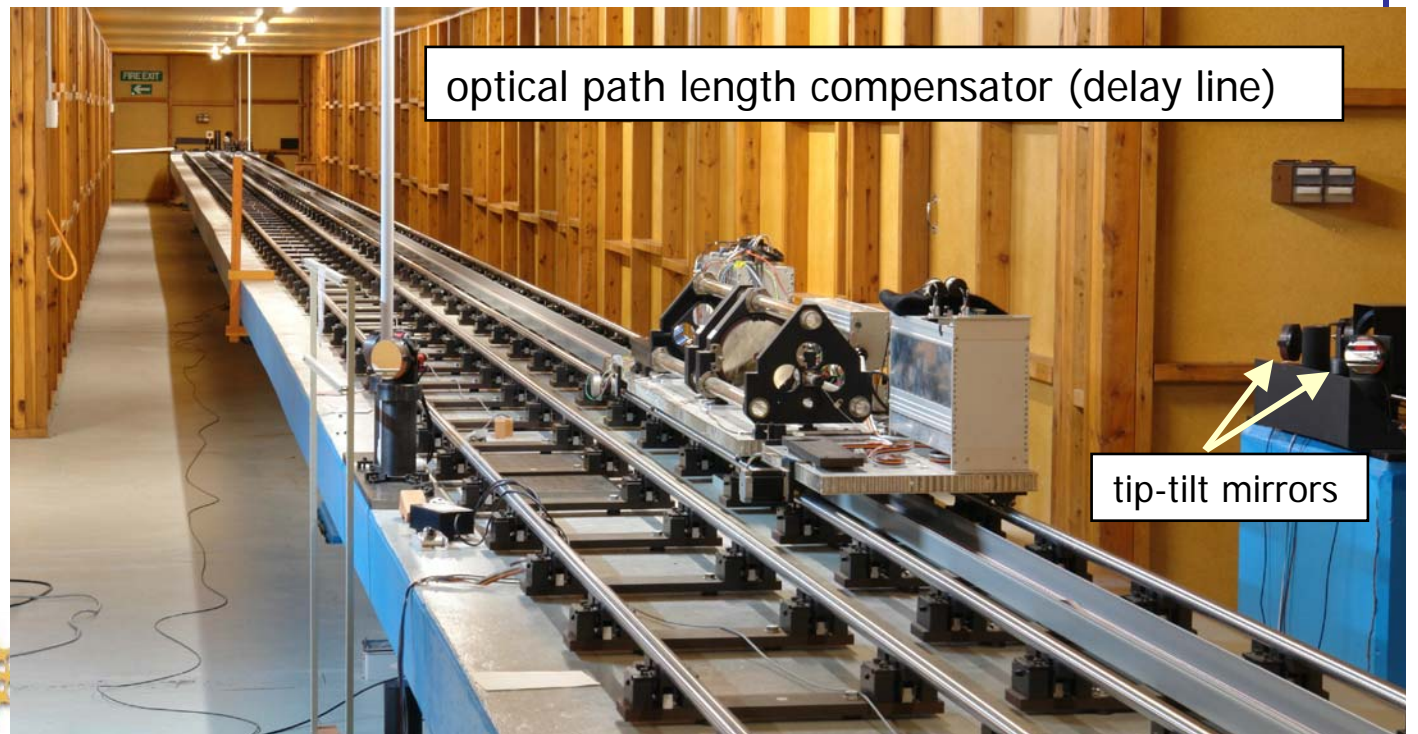
Blue Table (to 2006)

Red Table (to 2009)

PAVO (from 2009)

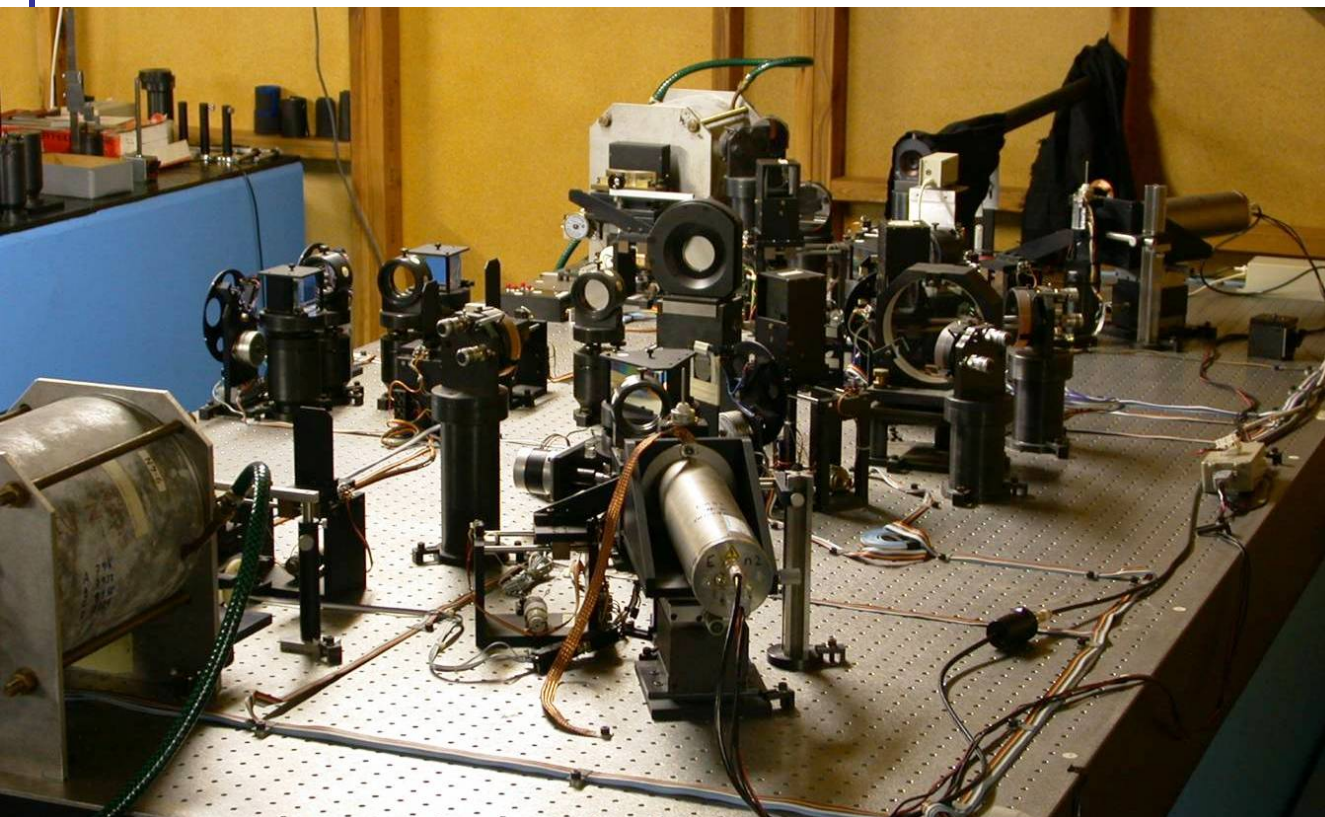


SUSI optical train





Blue table beam combiner



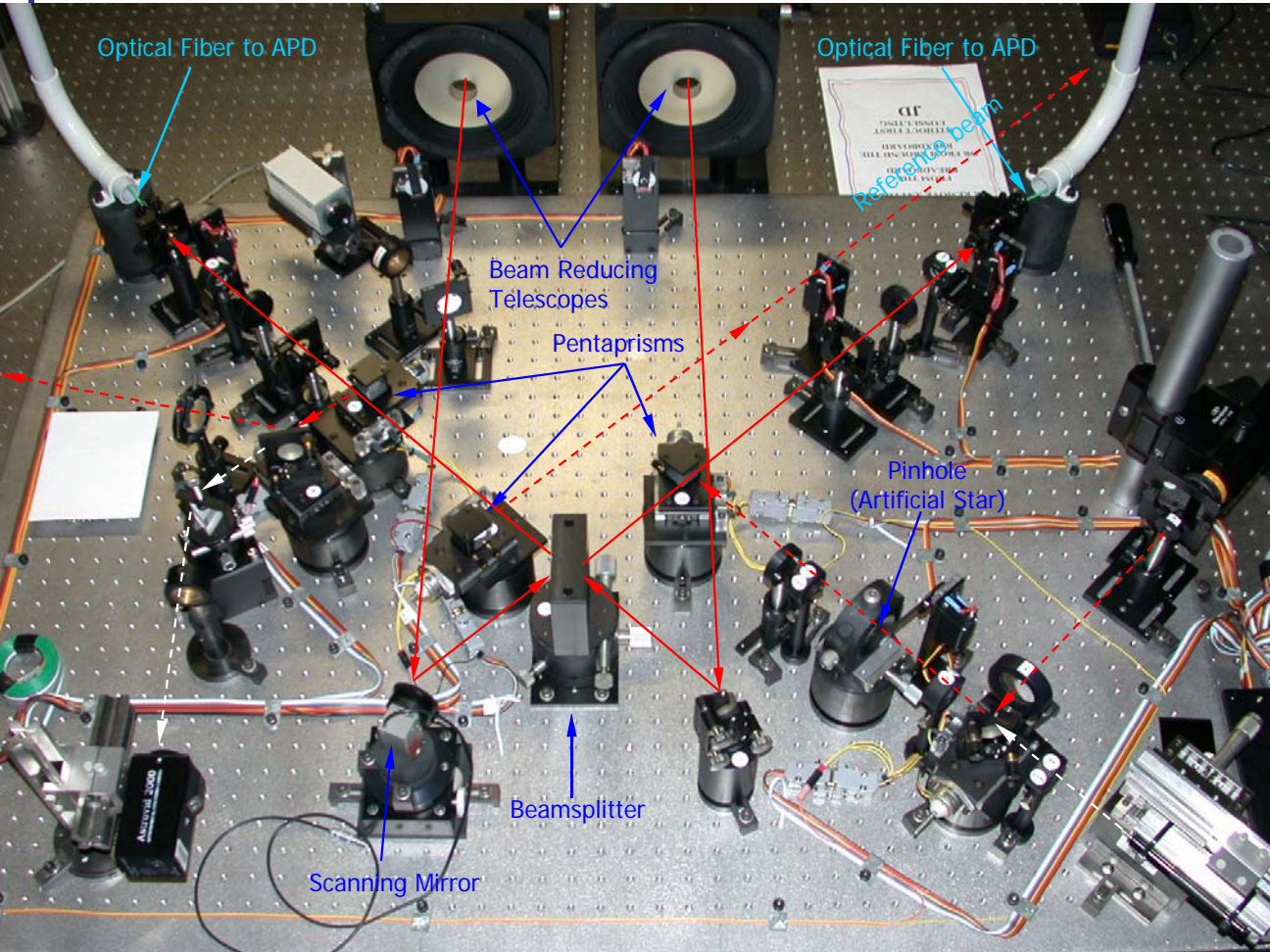
- 1991 to 2006
- Photomultiplier tube detectors
- quad cell PMT tip-tilt detectors
- λ 430 – 520 nm
- $\Delta\lambda$ 1 - 4nm
- $B_{\text{limit}} \sim 2.5$

Programs
Early-type stars
Emission lines
Early-type binaries





Red table beam combiner



- 2004 to 2008
- piezo-scanning system
- APD detectors
- tip-tilt on CCD
- λ 500 – 950 nm
- $\Delta\lambda$ 5% - 20% e.g. 80 nm at 700 nm
- $R_{\text{limit}} \sim 5.0$

Programs
 Late-type stars
 Binaries
 Cepheids

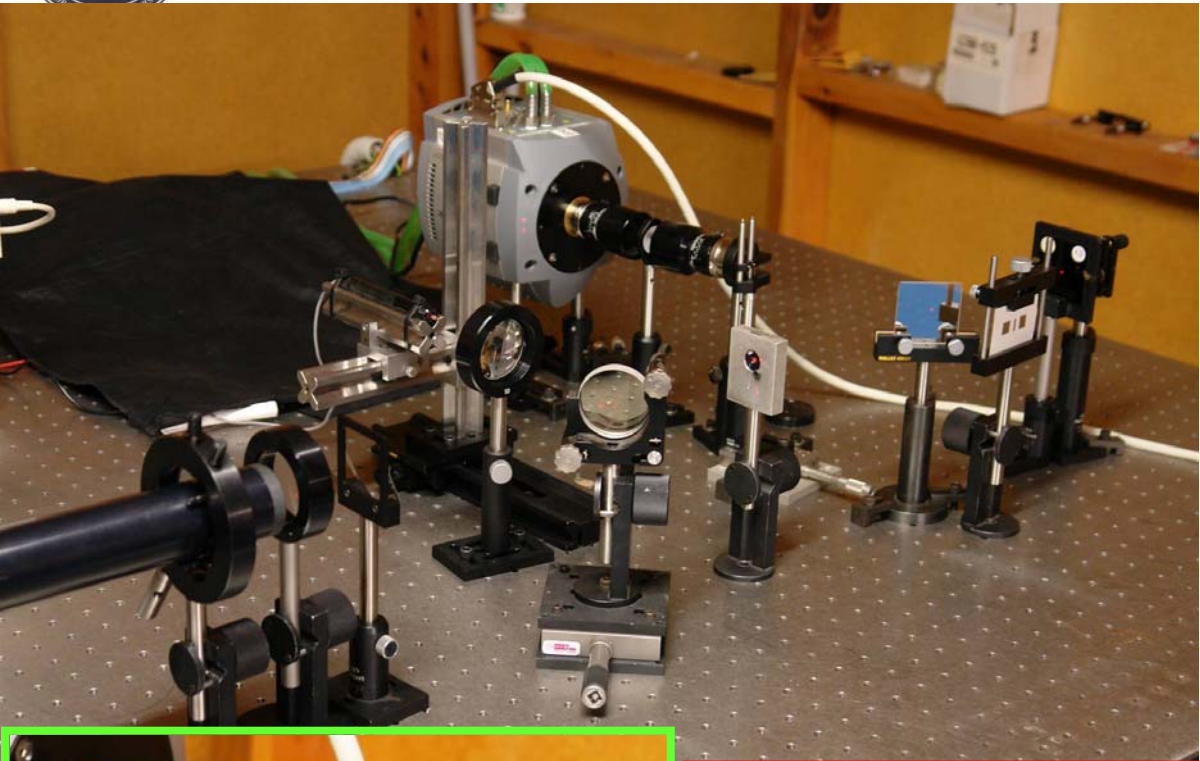


LESIA





PAVO beam combiner – preliminary setup



- spectrally dispersed system using L3 CCD
- λ 520 - 800 nm in ~20 channels
- pupil segmentation into 16 slices
- optimised spatial filtering
- tip-tilt uses $\lambda < 520$ nm, to *same* CCD
- limit R ~ 6.5
- 800-950nm for astrometry



Programs
 Binaries; low mass ratio
 diverse stellar types

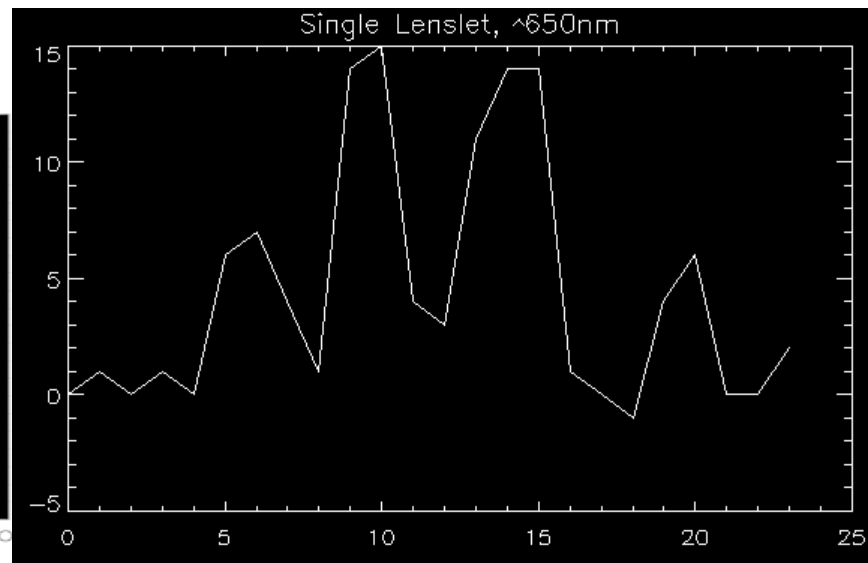
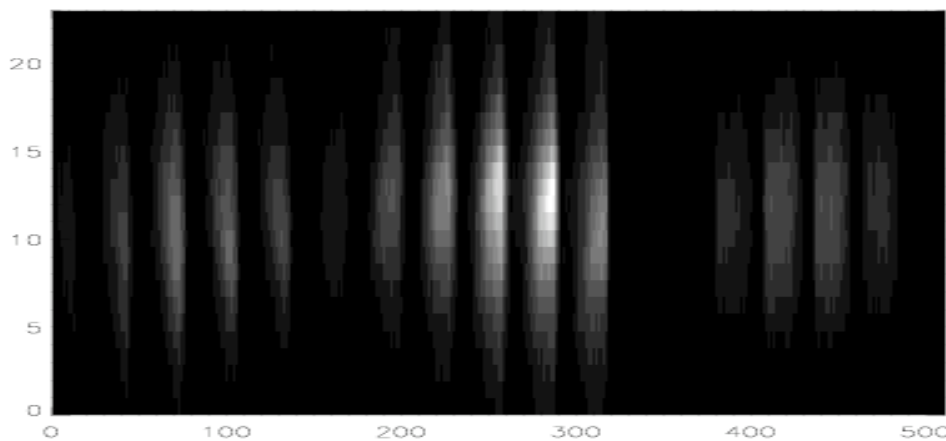


Progress...

- First PAVO@SUSI fringes in November 2008 (6 years after Red Table)
- Since then – the Longitudinal Dispersion Corrector has failed and is being upgraded (Bill Tango lead)
- Throughput/focus issues have been diagnosed and largely fixed. Replacement for 40m lenses over coming 2 months.

Cut through fringes

South North Fringes





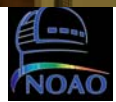
Remote Observing...

- SUSI is 7 hours drive from Sydney, or ~3 hours travel if you fly.
- With such a small team – regular travel to SUSI is unrealistic and we are aiming for remote obs. From Sydney until ~midnight, and from GSU (or anywhere else?) after this...
- Hardware changes: a new acquisition system computer+software, a bunch of computerized sensors (like the path compensator home sensor), motors for siderostat roofs, remote sky and weather monitoring...
- On-site support: We have a contract with the co-located radio telescope staff (Mike Hill) to help with weekly alignment, pumping down vacuum and minor bugshooting.



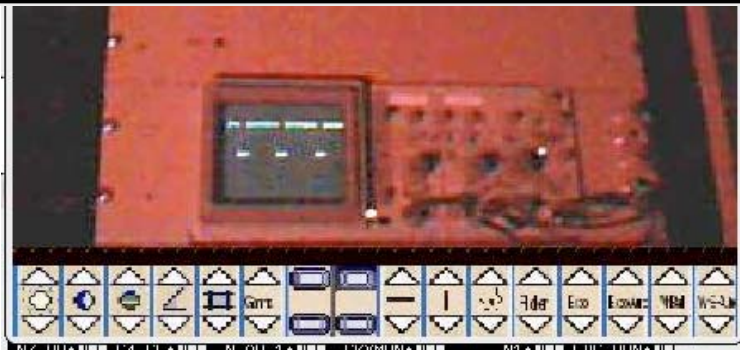
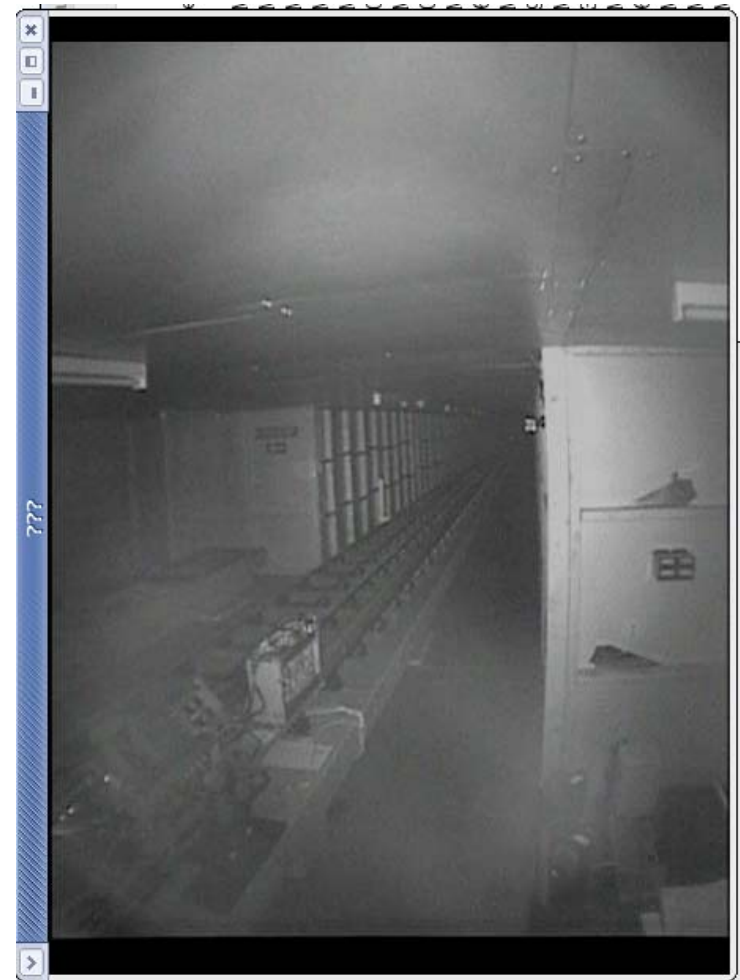
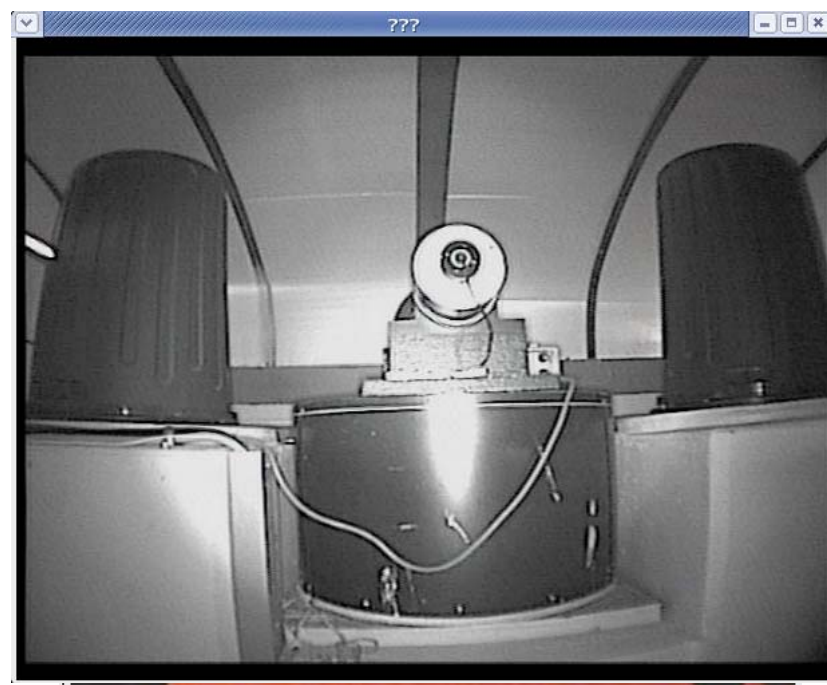
Remote Observing...

The Remote Observing Center Sydney (ROCS) At at various stages of completion...



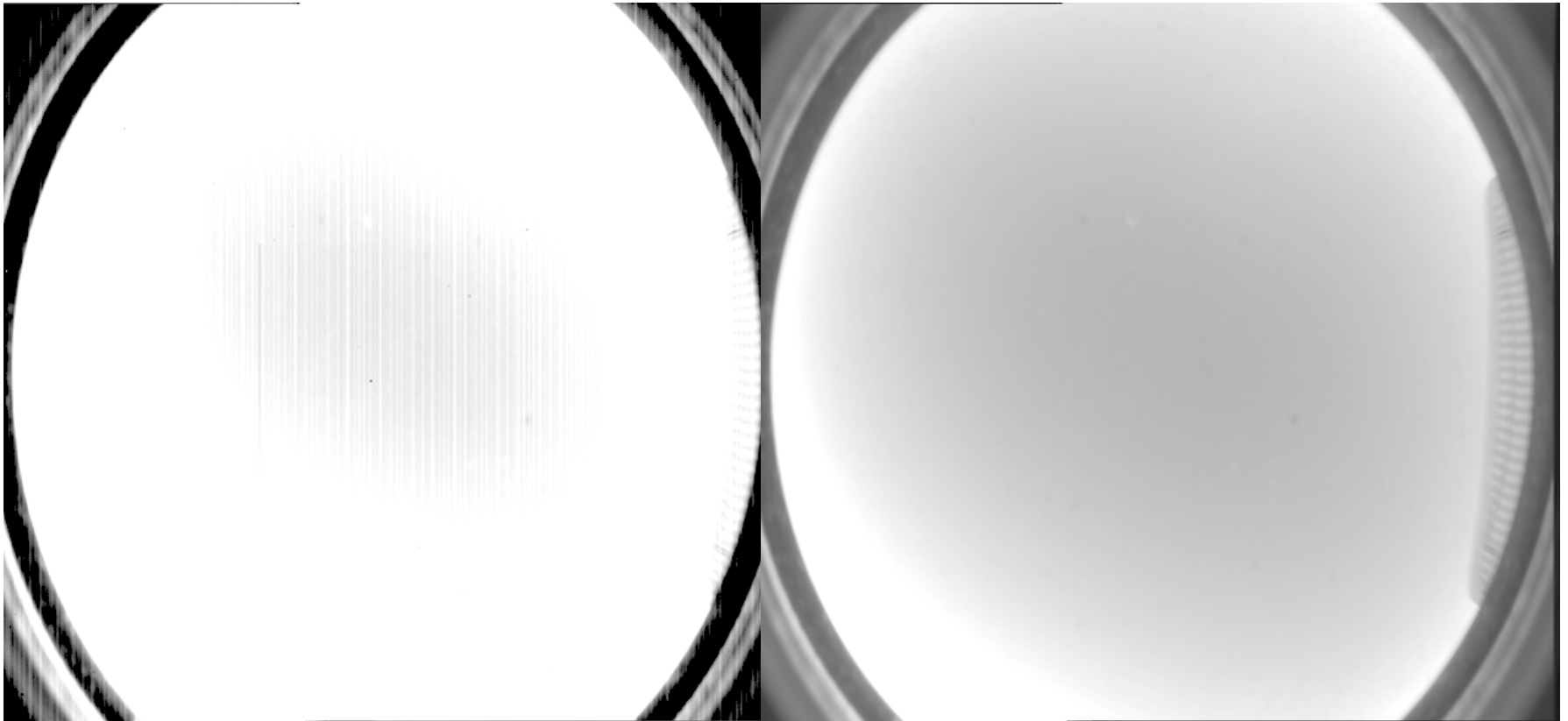


Security Cameras/Webcams





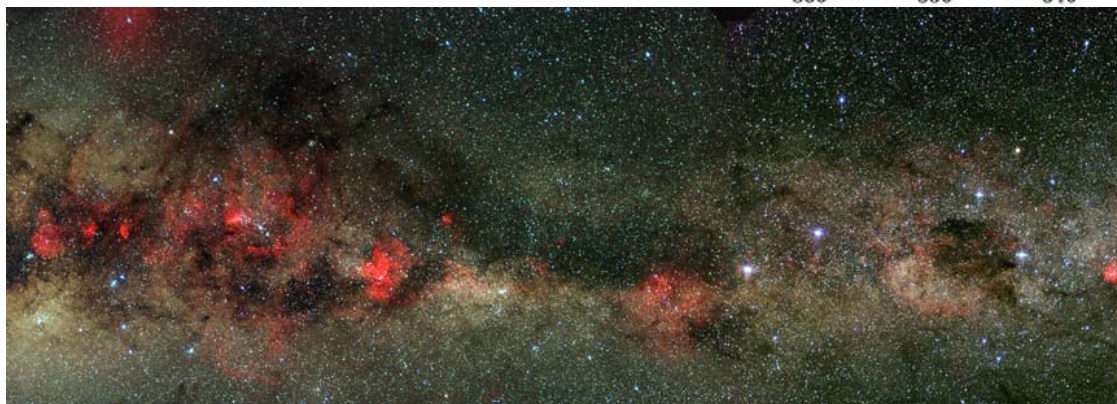
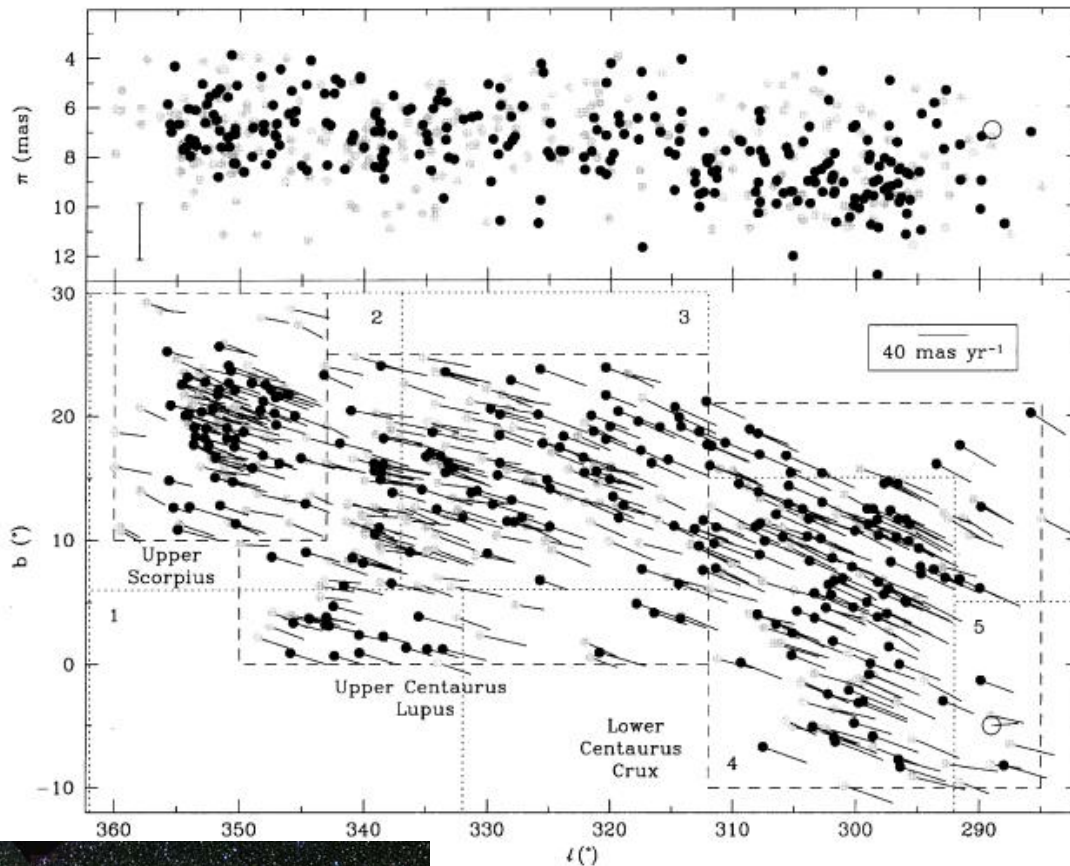
Sky Monitoring





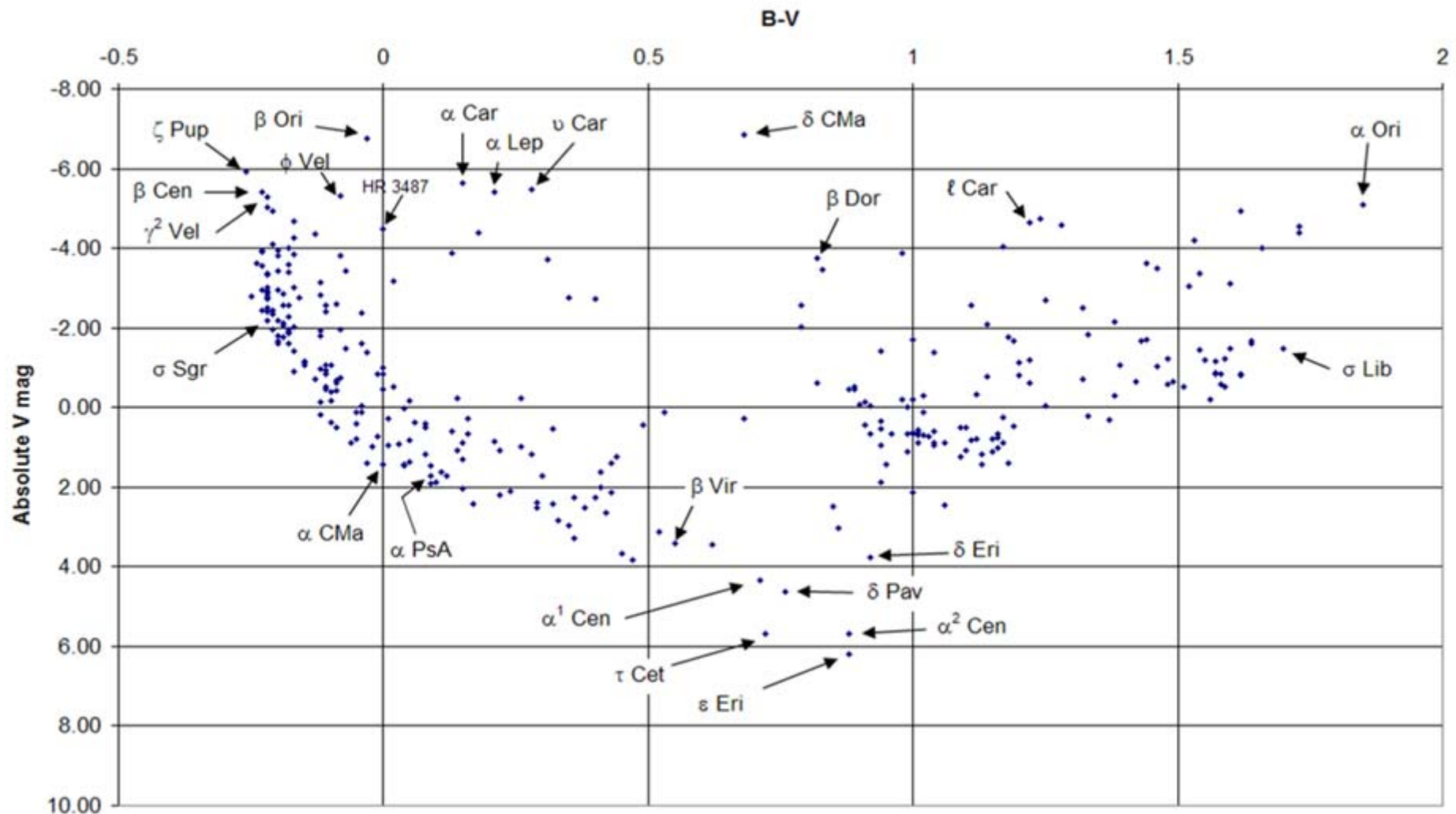
Science - Sco-Cen

PAVO@SUSI Primary
Science Goal: A survey of
and for intermediate and
high mass binary stars in
in the Sco-Cen OB
association.





HR Diagram for southern bright stars – plenty of stellar astrophysics waiting!



V < 4, δ < +15°, Parallax error (older Hipparcos) < 31%



LESIA





Future Plans...

- Early April: Release the preliminary PAVO@CHARA pipeline.
- May/June: First PAVO@SUSI remote observations.
- July: Submission of first PAVO paper.
- August: Call for PAVO@SUSI proposals.
- *Long-term PAVO@CHARA upgrades...*
 - Hardware: None. The lenslet array is still not AR coated (8% loss) and there is no polarimetry mode.
 - Software: Plenty: Aberration removal in software, better weighting, vis/IR simultaneous operation...