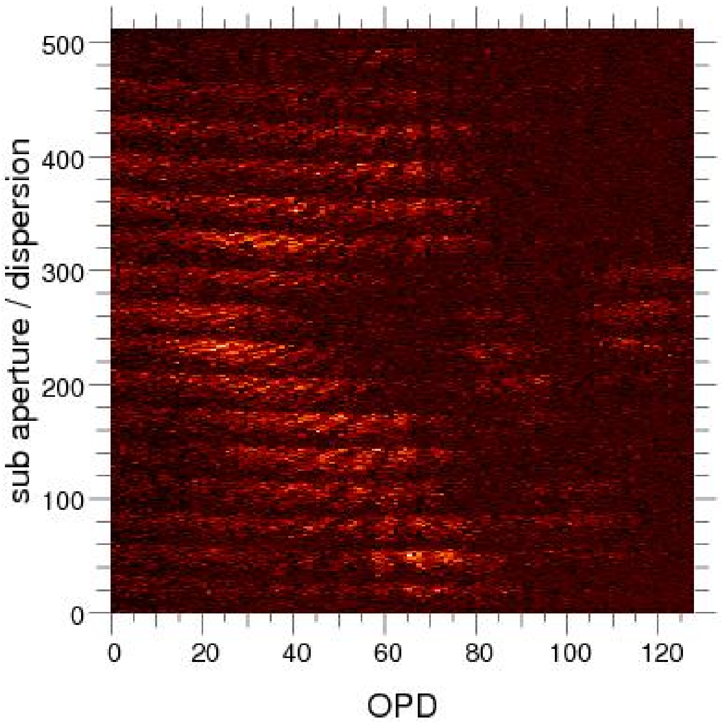
PAVO, SUSI and ROCS: Status and Future Plans

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...

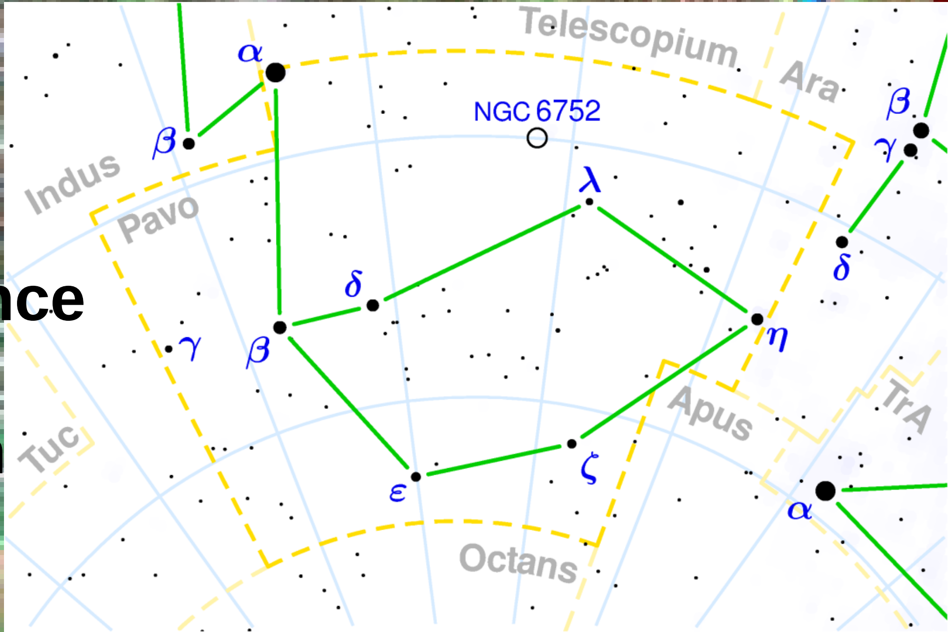
- The PAVO concept (slightly tricky)
- PAVO@CHARA implementation
- Data analysis progress
- Intro to SUSI
- PAVO@SUSI implementation
- Remote observing at SUSI
- Future expectations

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)



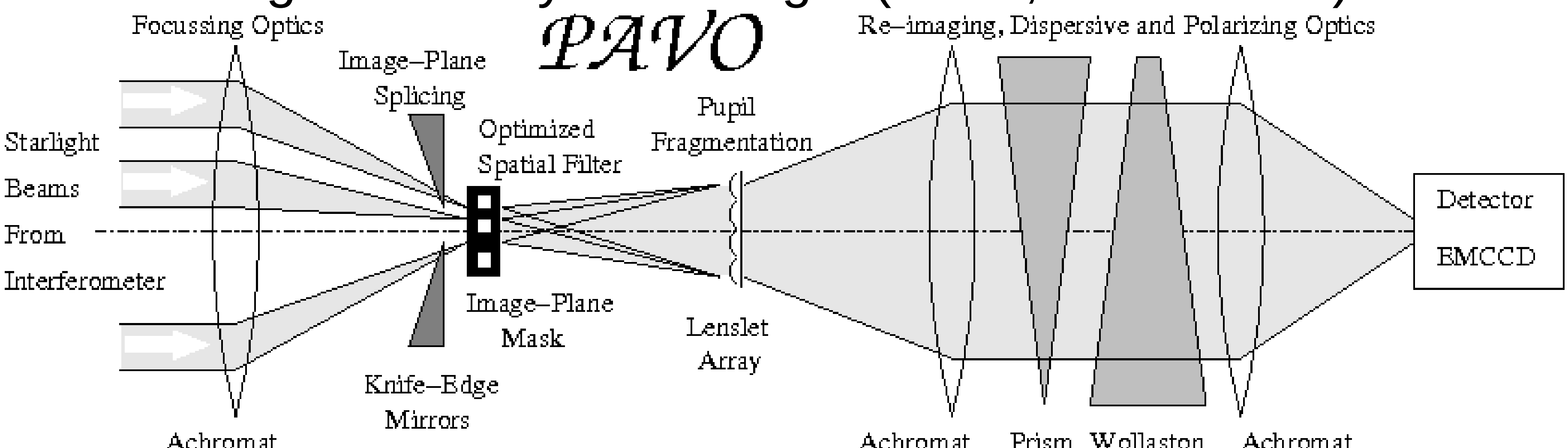
Timeline...

- 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

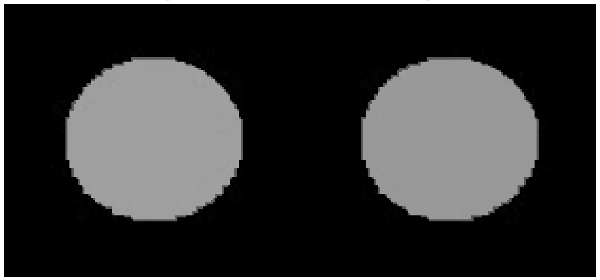
Quick Intro:

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~50, 620-950nm)

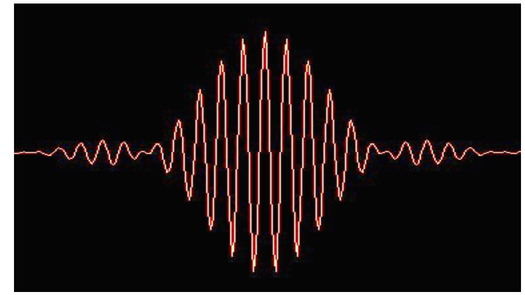


PAVO: Precision Astronomical Visible Observations

Output 1 Output 2

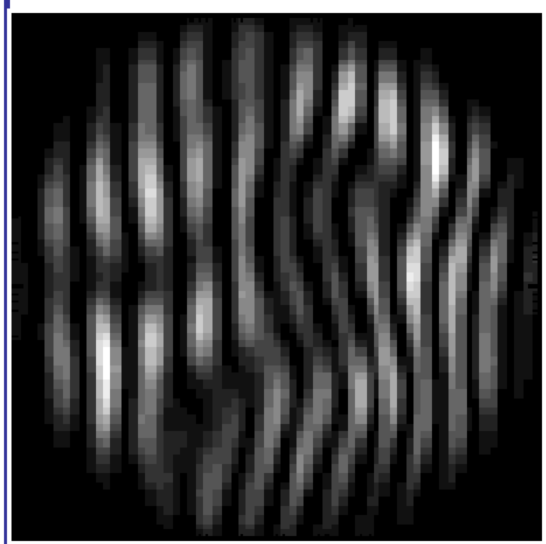


Difference Signal



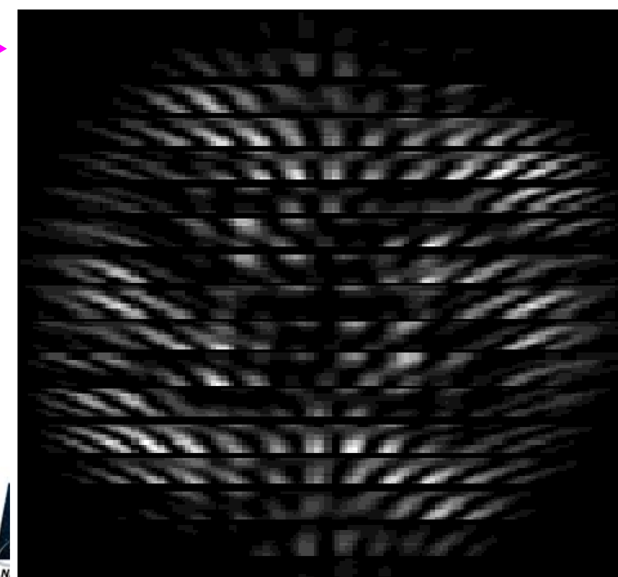
- SUSI/CHARA Classic… Full pupil summed in a two “pixels”, temporal modulation.
- PAVO: 120 (SUSI) and 6000 (CHARA) pixels over the pupil, spatial modulation.
- Spectral dispersion enables group-delay tracking.

Pupil fringes at single wavelength



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

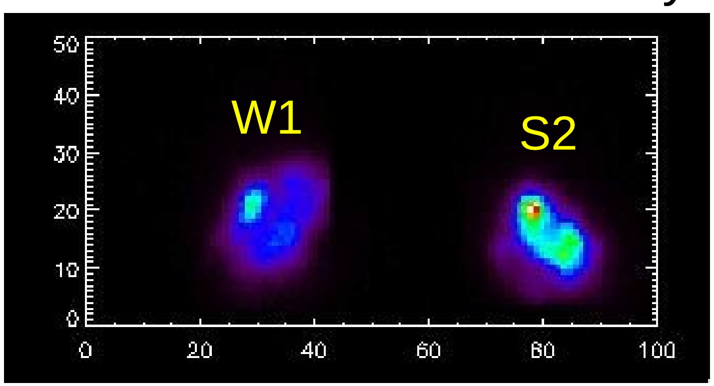
Broad-band Fringes after IFU



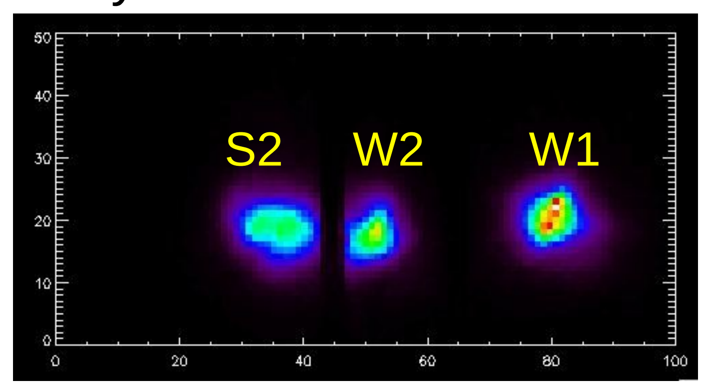
Notes: Spatial-filtering 1

- 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



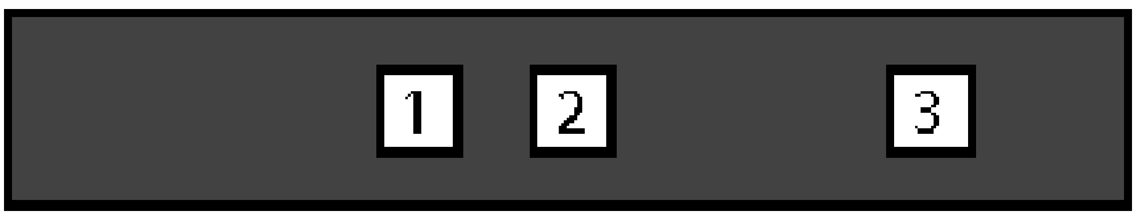
Notes: Spatial-Filtering 2

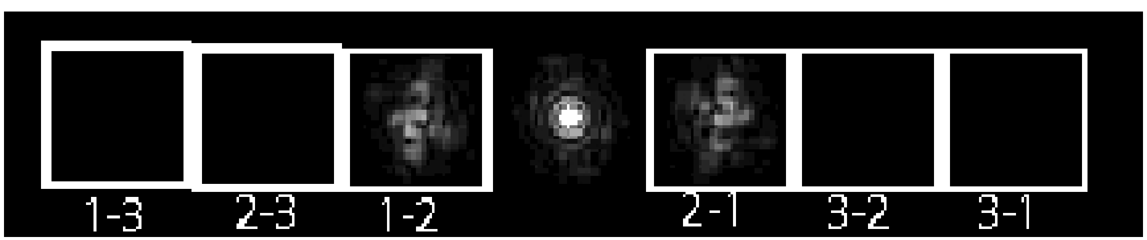
1) Phase aberrations across the pupil occur at all spatial frequencies.
2) By band-limiting the flux in the image-plane (i.e. passing the light pass through a mask), phase aberrations can only occur at low spatial frequencies.
3) The effect of finite sampling in the pupil-plane then becomes an analytic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

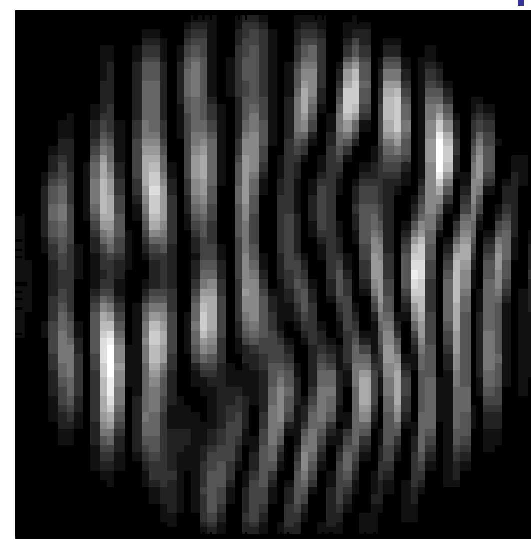
V^2 is completely insensitive to phase across the (spatially-filtered) pupil

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

2D Optical FFT







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

2D Digital FFT

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.

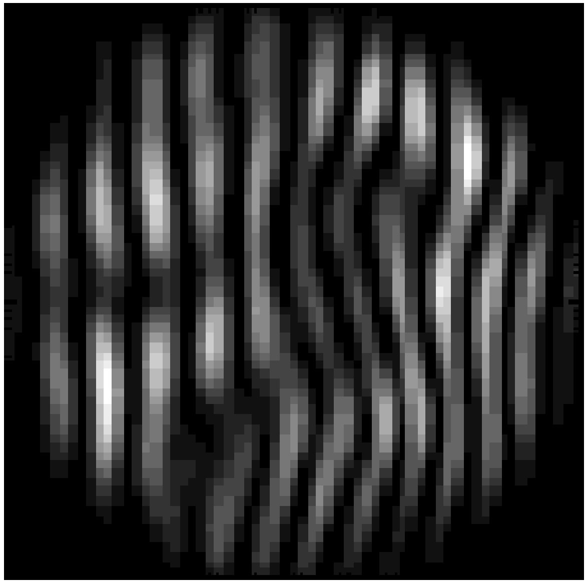
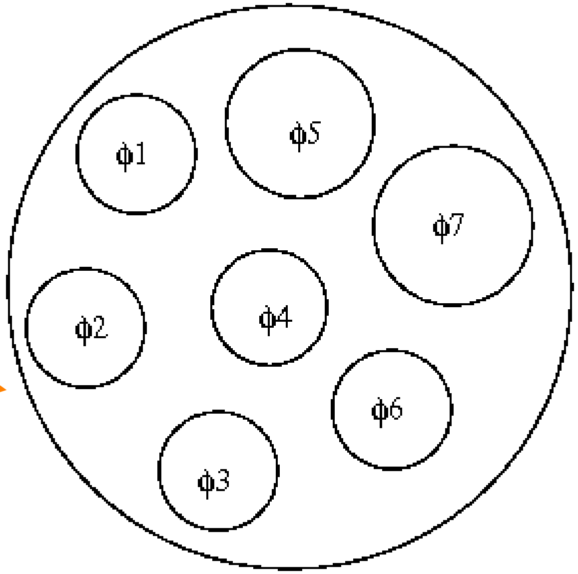


Image or Pupil-plane?

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.

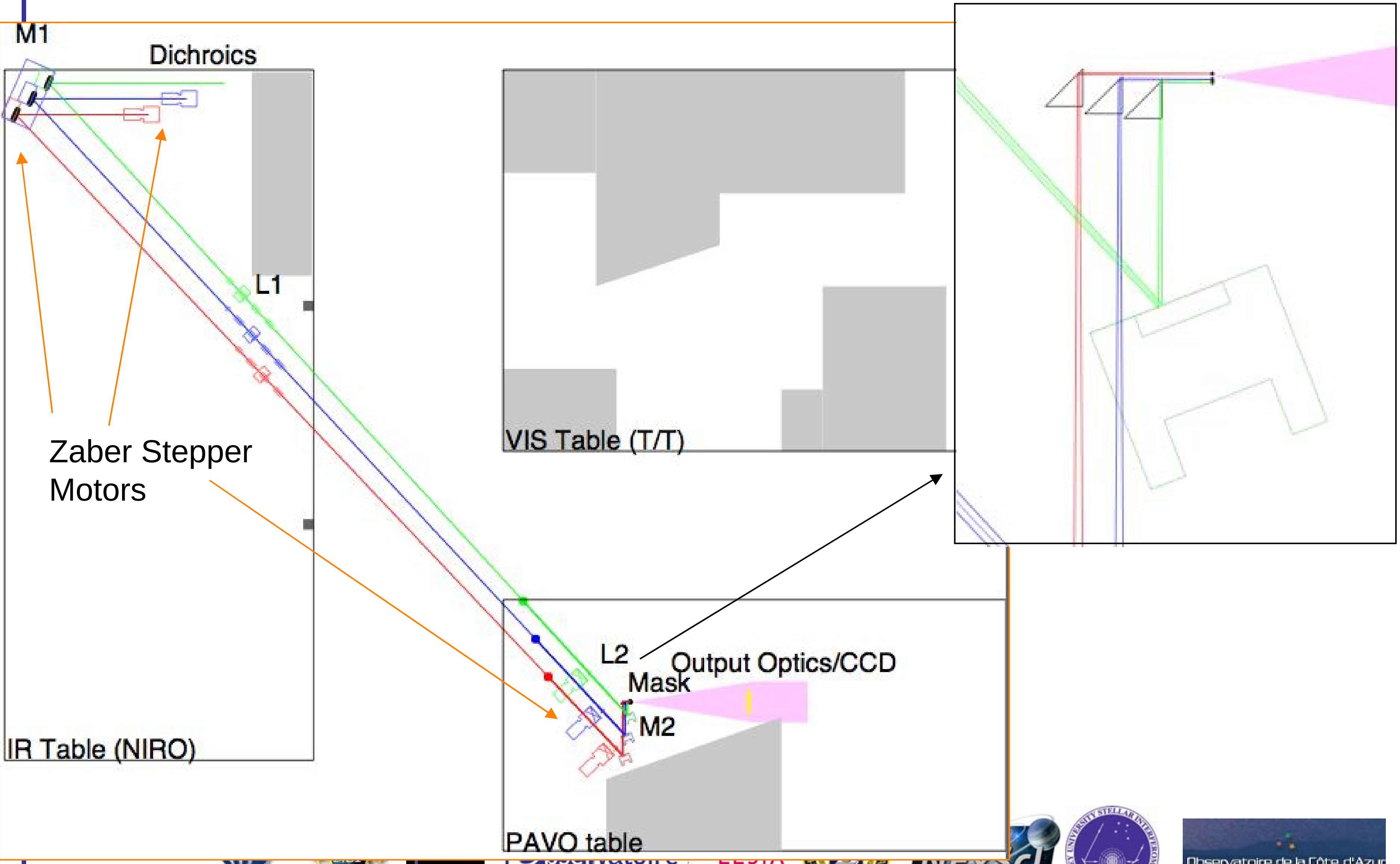
"Sub-apertures" can be made in the image or pupil planes.

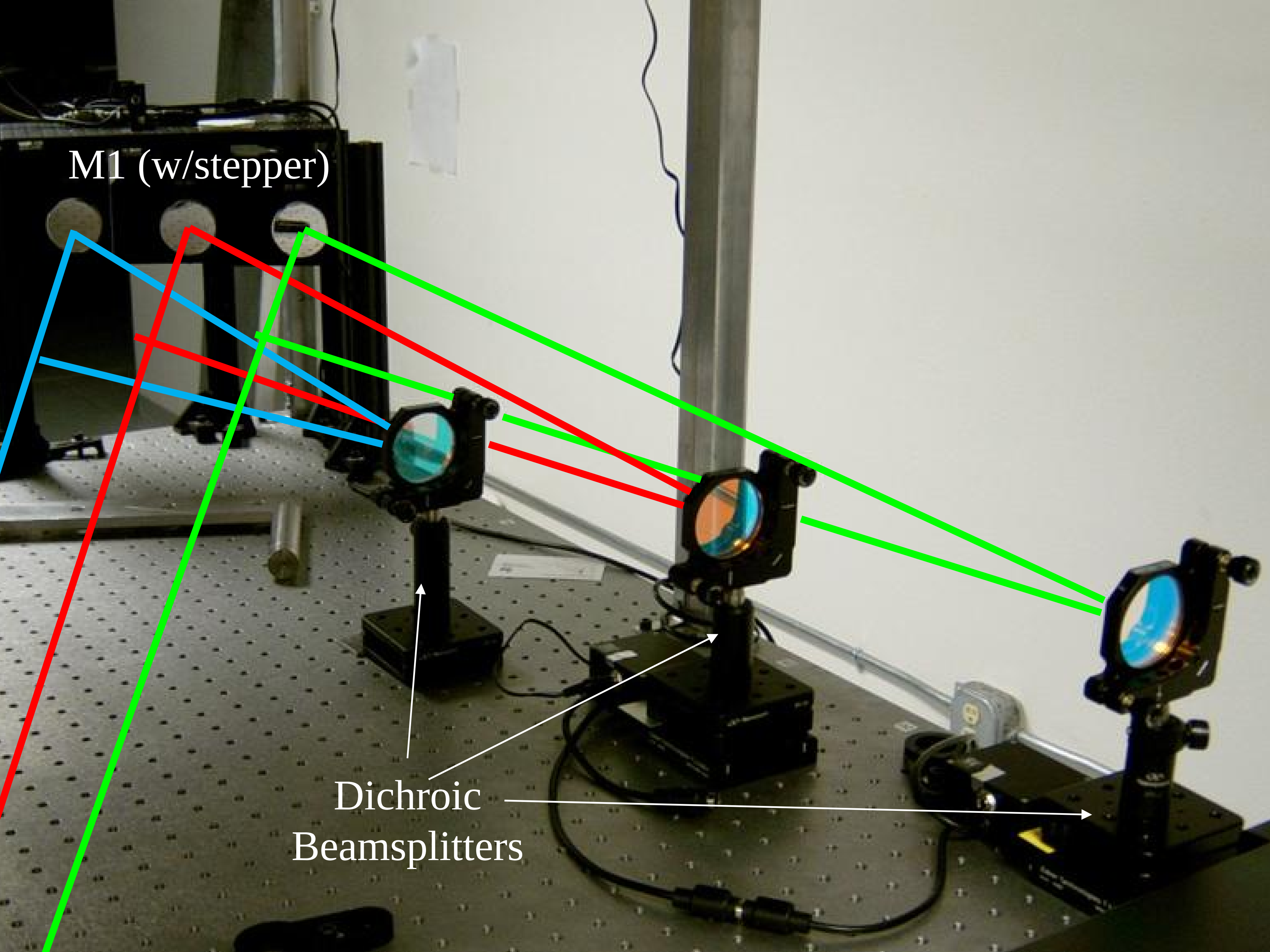


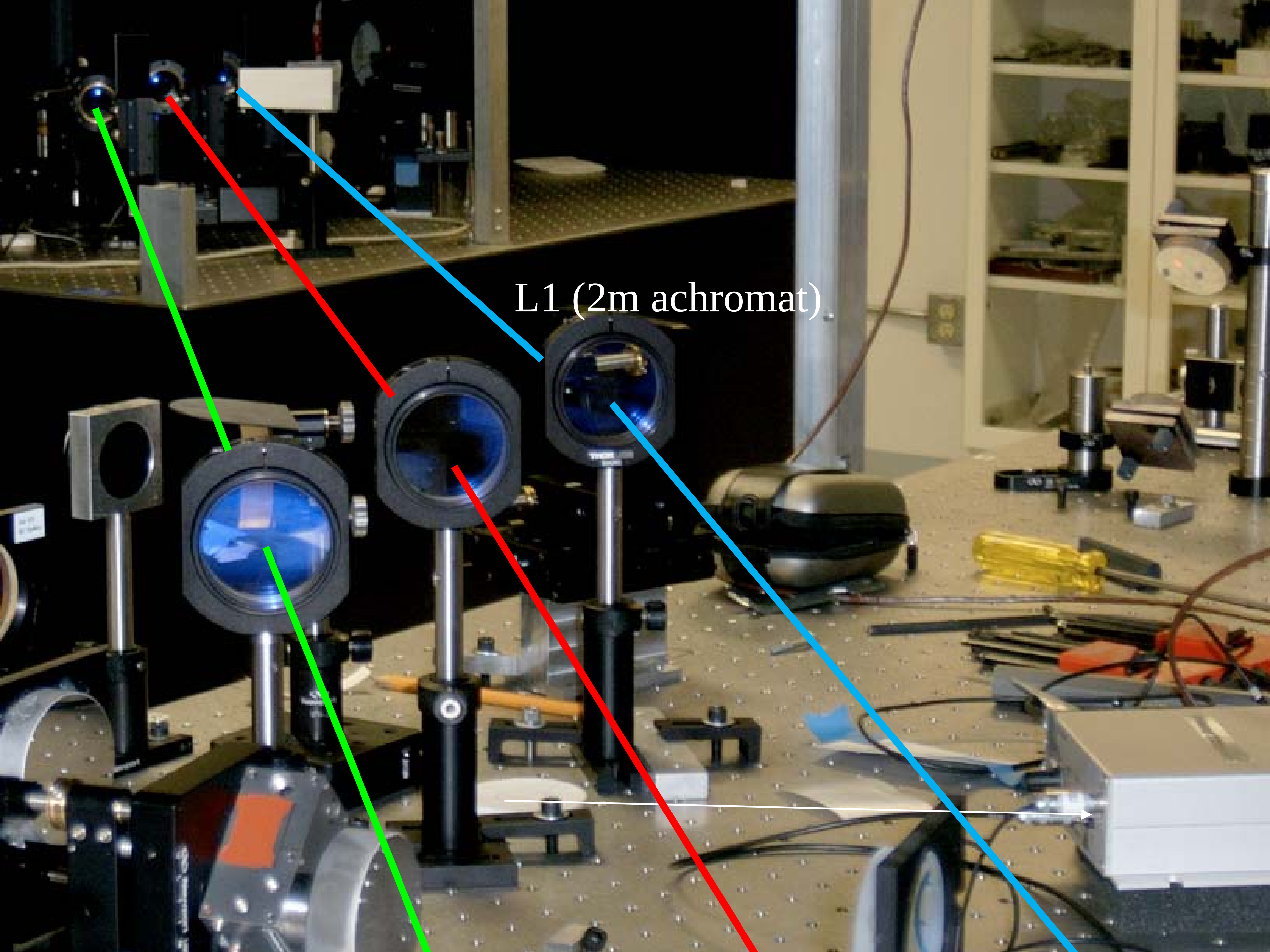
System response (point source V^2 etc…) is a weighted average of a function of intensity… … so we want intensity to be stable

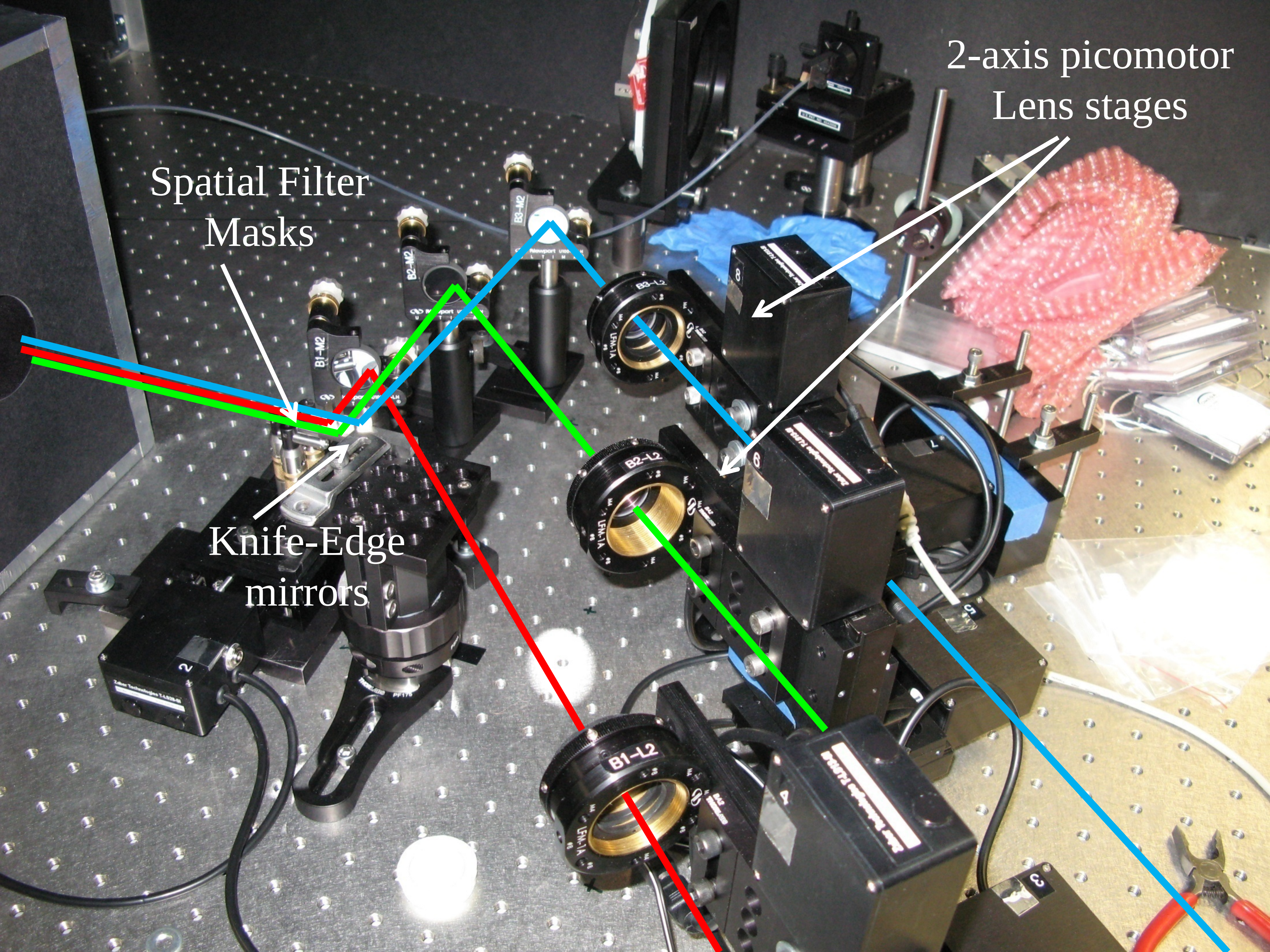
$$V_{sys}^2 = \frac{1}{N_{subap}} \sum_{pupil} \frac{4 I_1 I_2}{(I_1 + I_2)^2}$$

Optics at CHARA

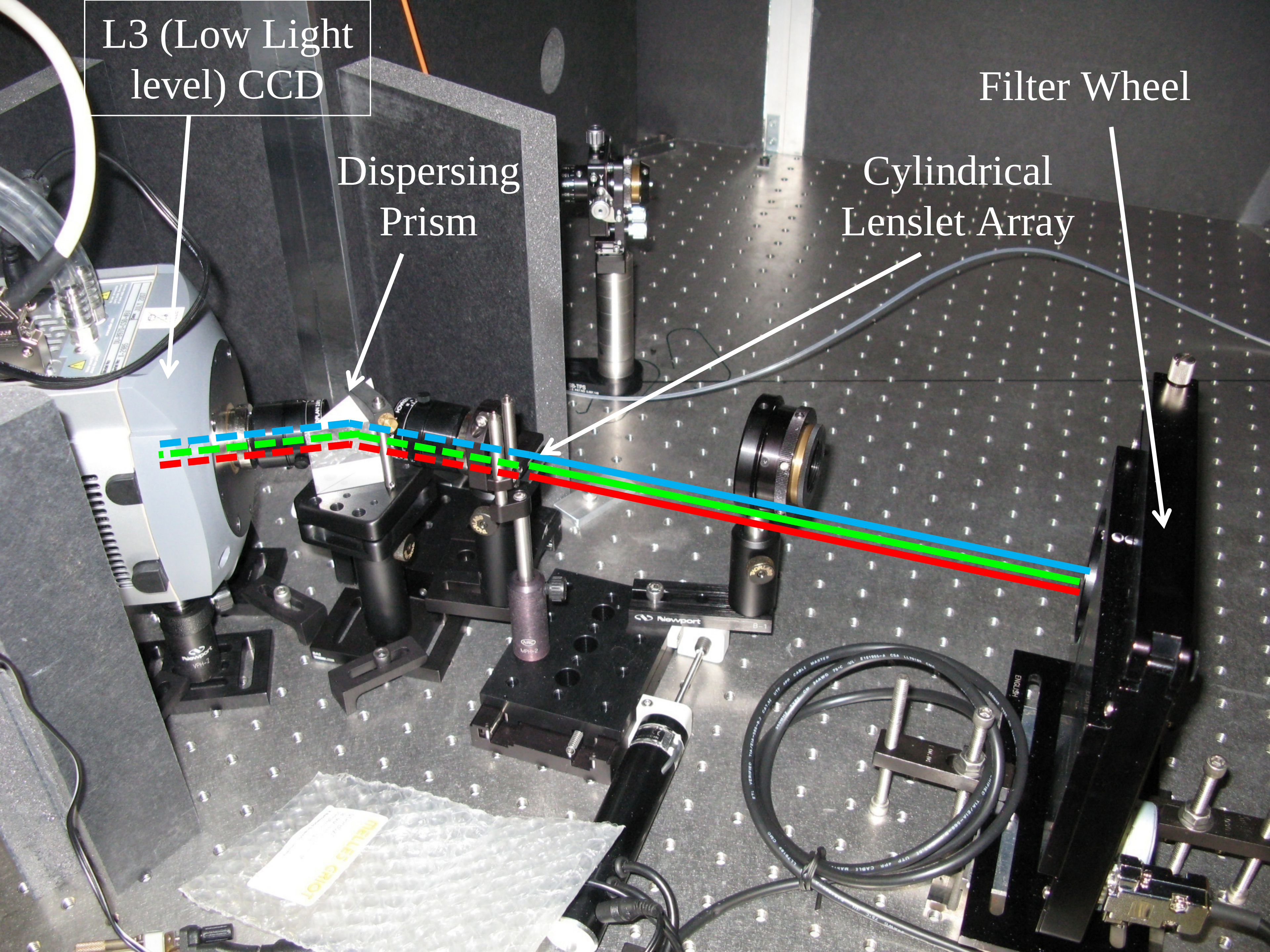



M1 (w/stepper)
Dichroic
Beamsplitters

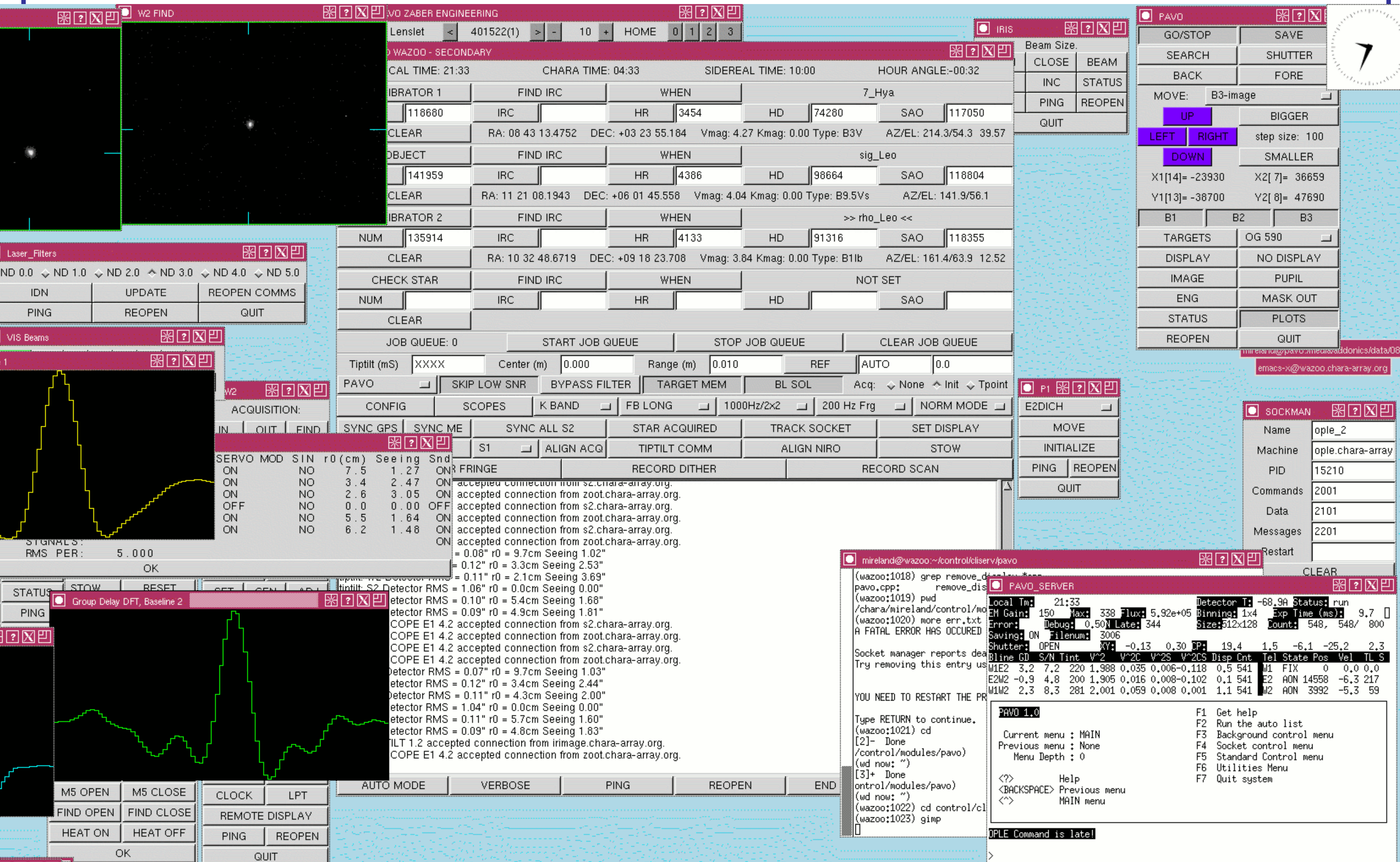

L1 (2m achromat)



2-axis picomotor
Lens stages
Spatial Filter
Masks
Knife-Edge
mirrors
B1-M2
B2-M2
B3-M2
B3-L2
B2-L2
B1-L2


L3 (Low Light level) CCD
Dispersing Prism
Cylindrical Lenslet Array
Filter Wheel

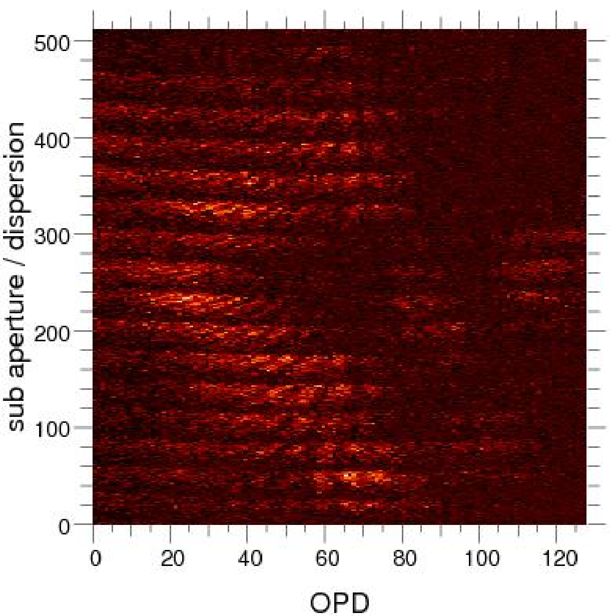
PAVO Software@ CHARA

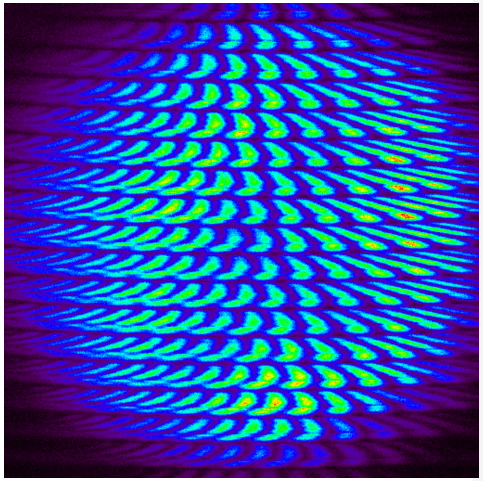


Commissioning 2008

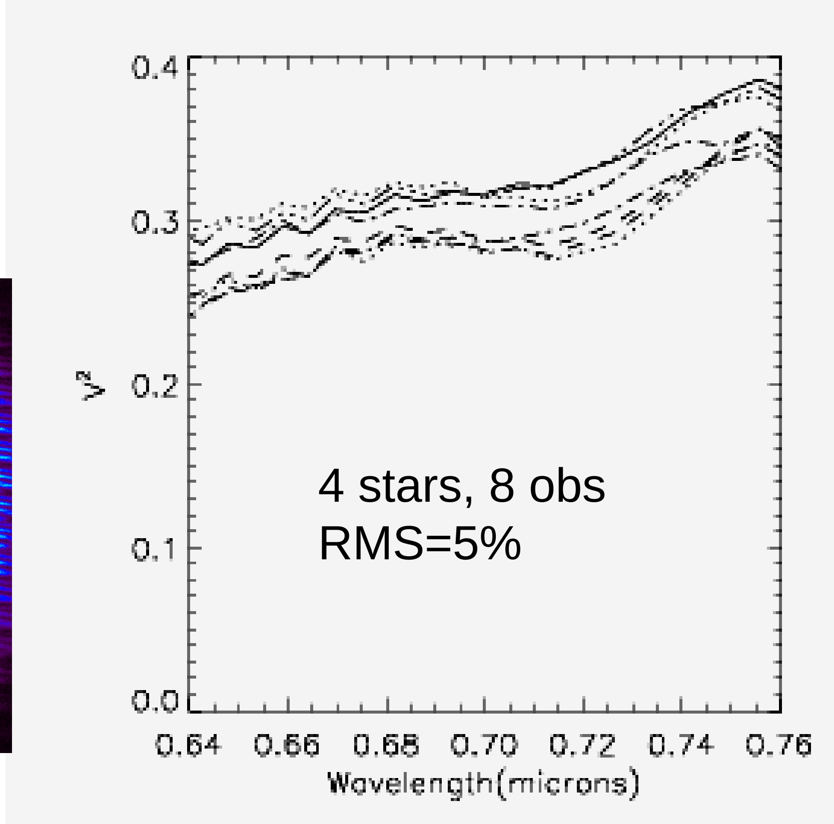
• PAVO@CHARA has tracked 3-baseline fringes at R=8.2 so far (few micron RMS, ~10 sec typical fringe lock, ~1 Hz correction bandwidth).
• On track for R=9 (excellent conditions) with PAVO improvements only, or R=10 with improved CHARA image quality.
• R=7 is the limit for median conditions, and sensitivity goes as N*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)

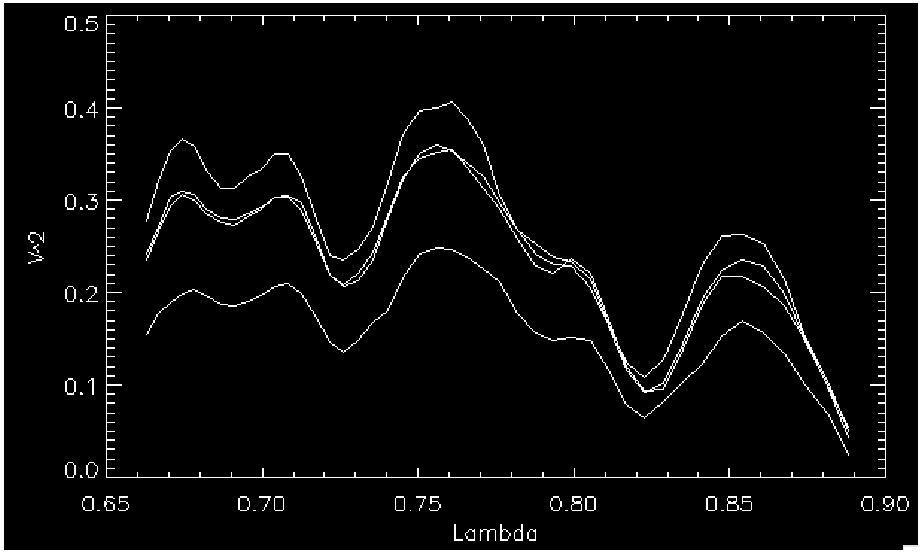
Data Analysis Pipeline

- 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.

V^2: Single Baseline

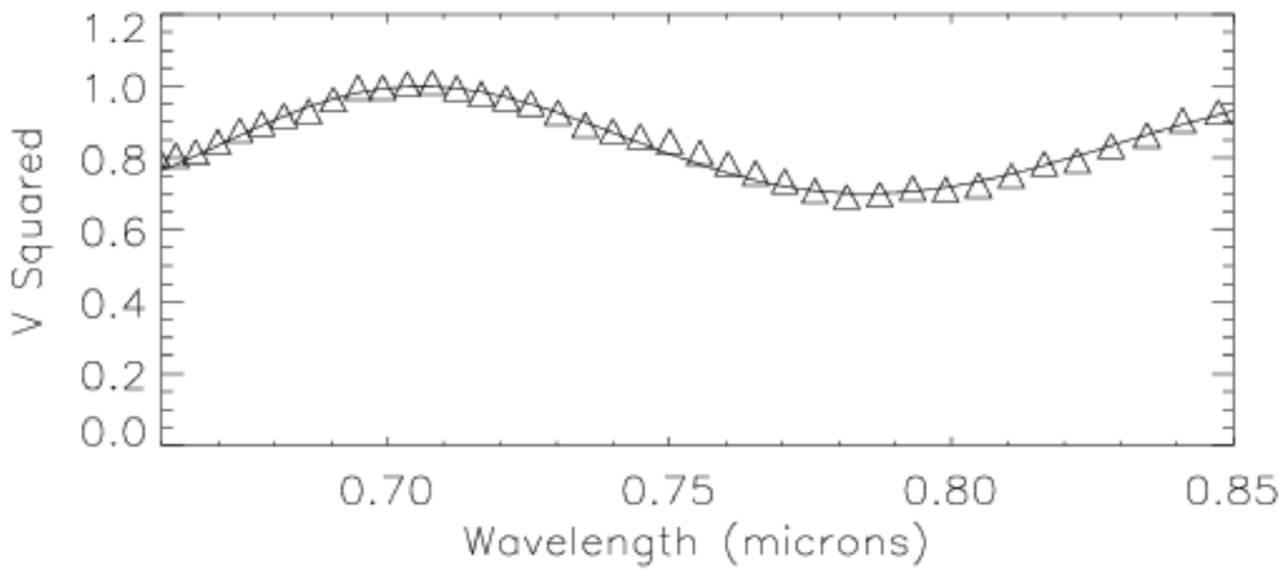
- 3-Methods for foreground-subtraction:
  - Get bias from unused baselines.
  - Get bias from power spectrum in-between baselines.
  - Use foreground files to find gain, i.e. bias = gain*flux
- Even with good foreground subtraction, there are calibration issues.

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



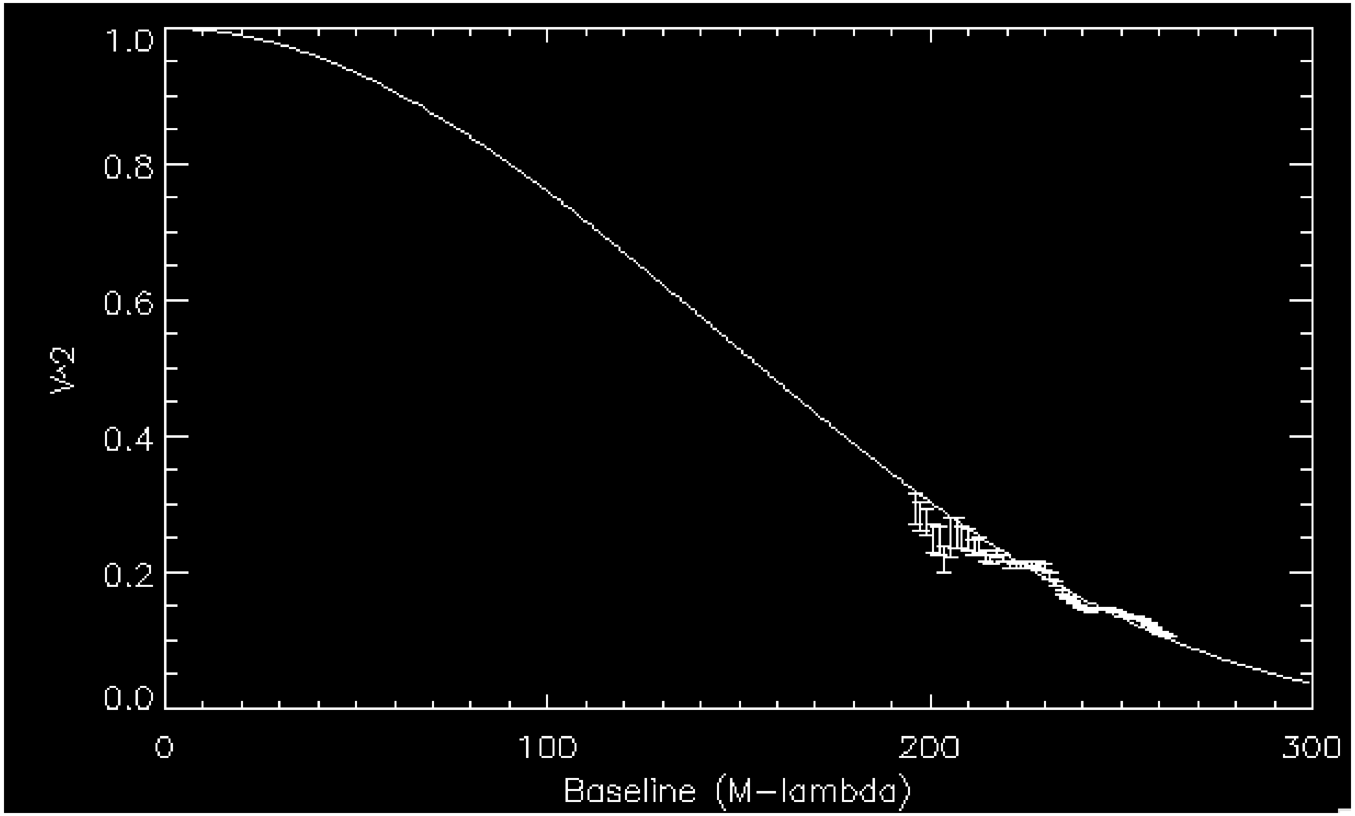
HD 187340, HD 175305, HD 196502, HD 201908

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.

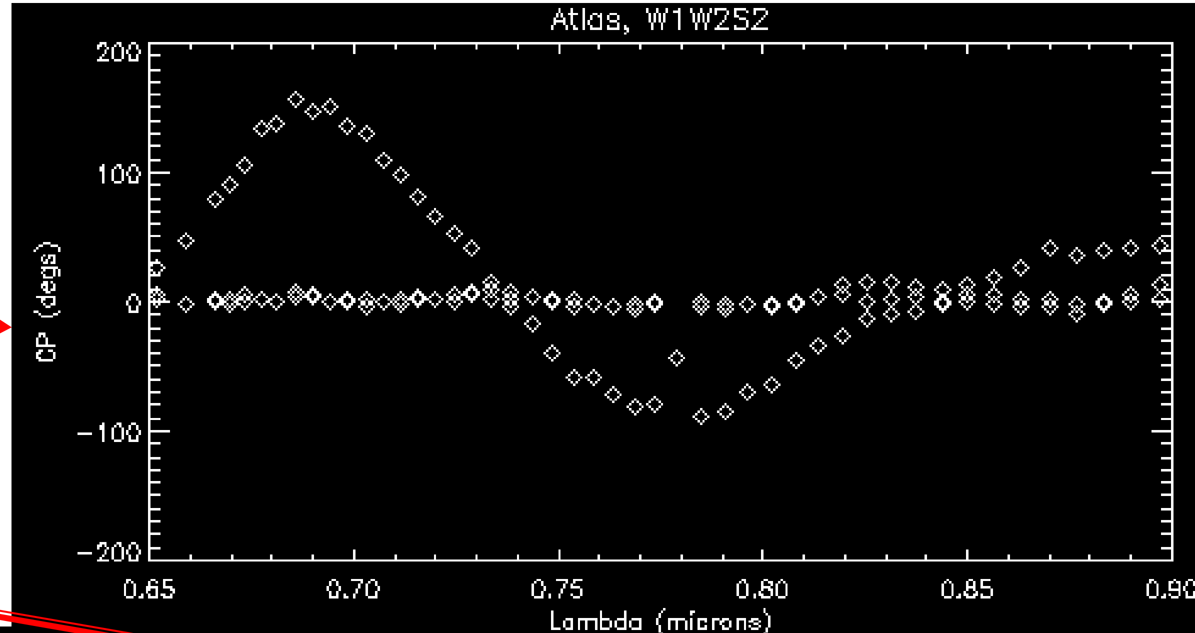
Example V^2 Science



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

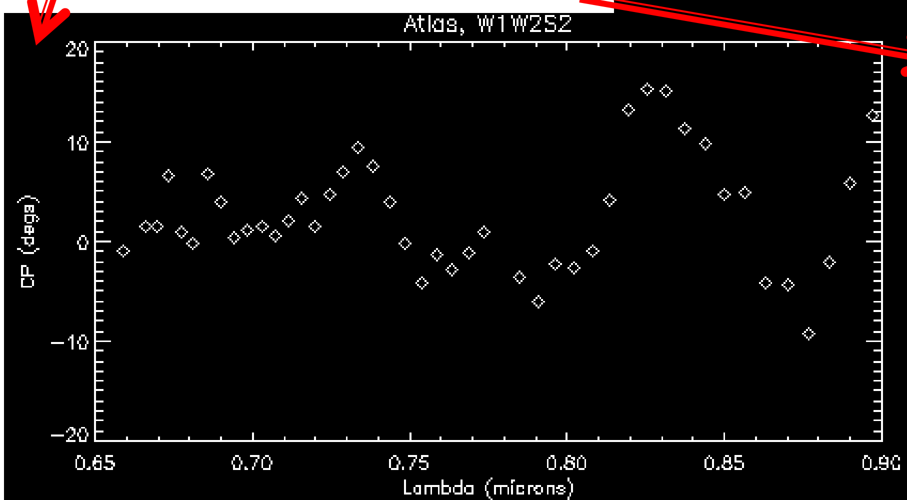
Preliminary Closure-Phases…

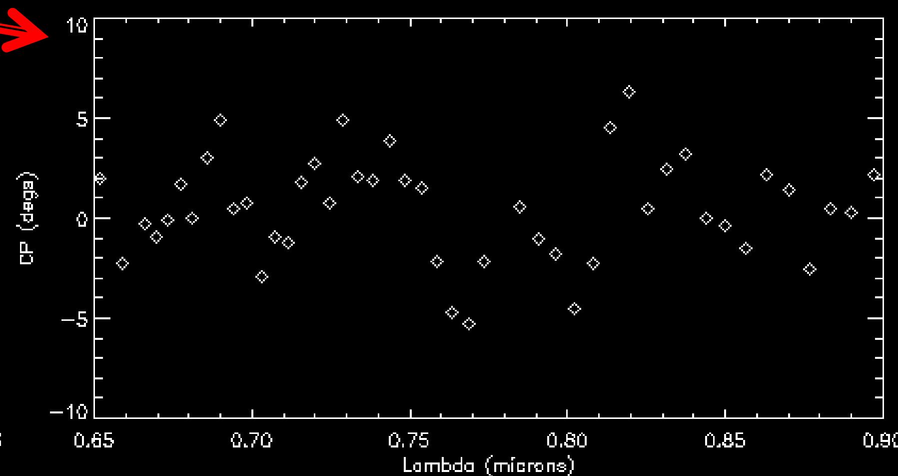
Atlas (SB2 in Pleiades) + 2 Cals: obviously huge Closure-phase signal



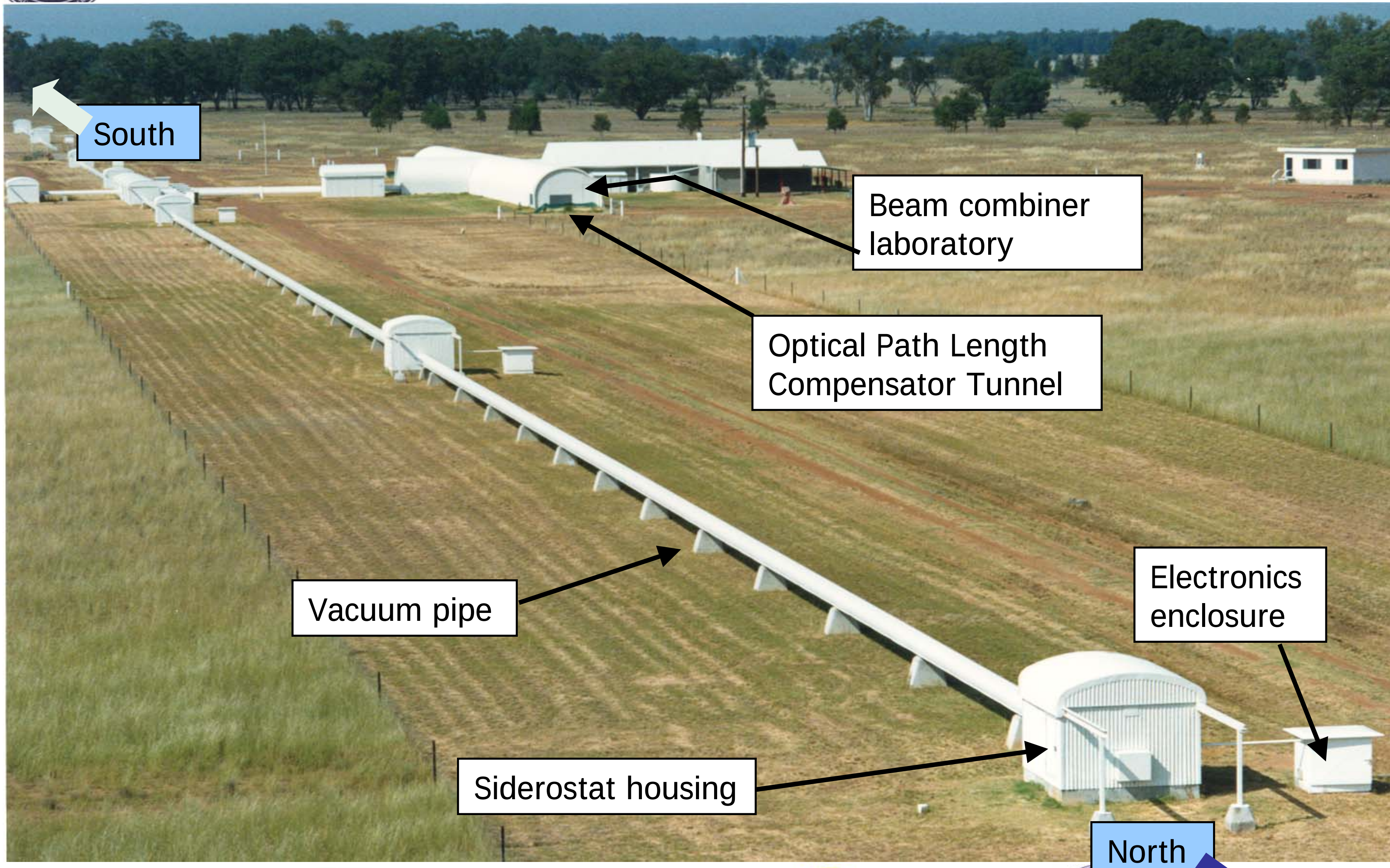
Electra, Cal 1 (binary?)

Cal 2, R=5.5





SUSI – overall view



SUSI – main specifications

Latitude: –30° 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

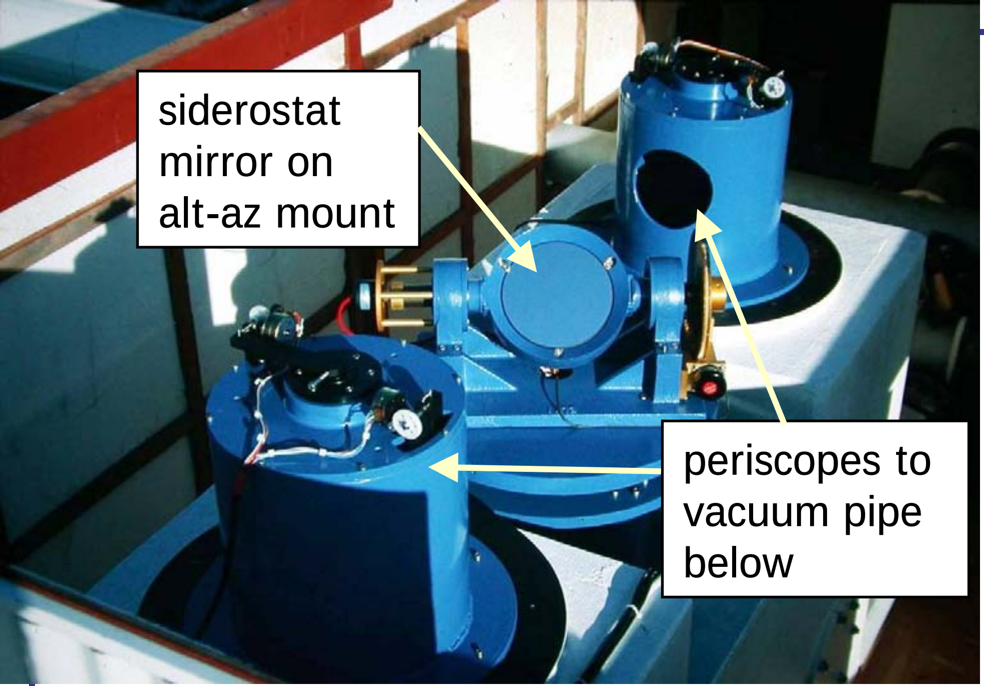
Piezo-actuated tip-tilt mirrors

Optical Path Length Compensator

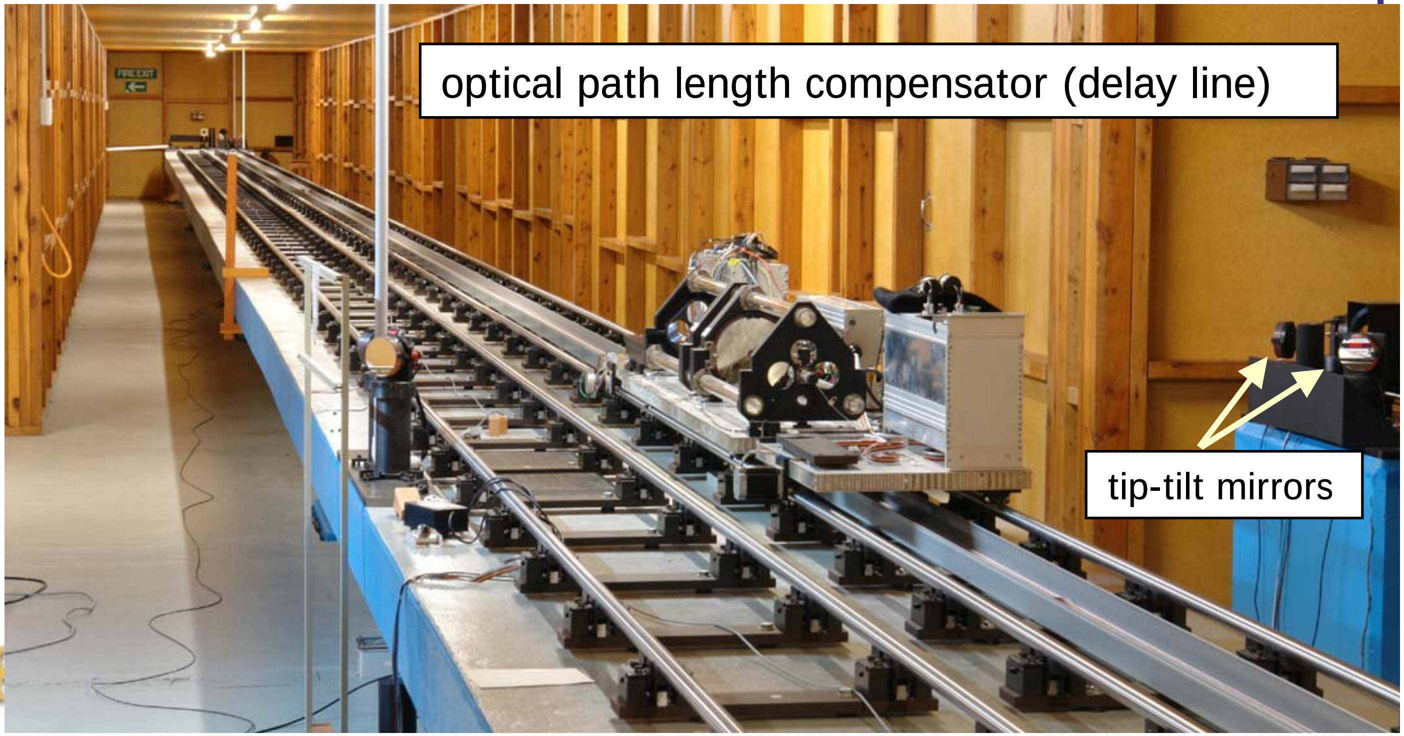
Longitudinal Dispersion Corrector

Beam combiners:

- Blue Table (to 2006)
- Red Table (to 2009)
- PAVO (from 2009)



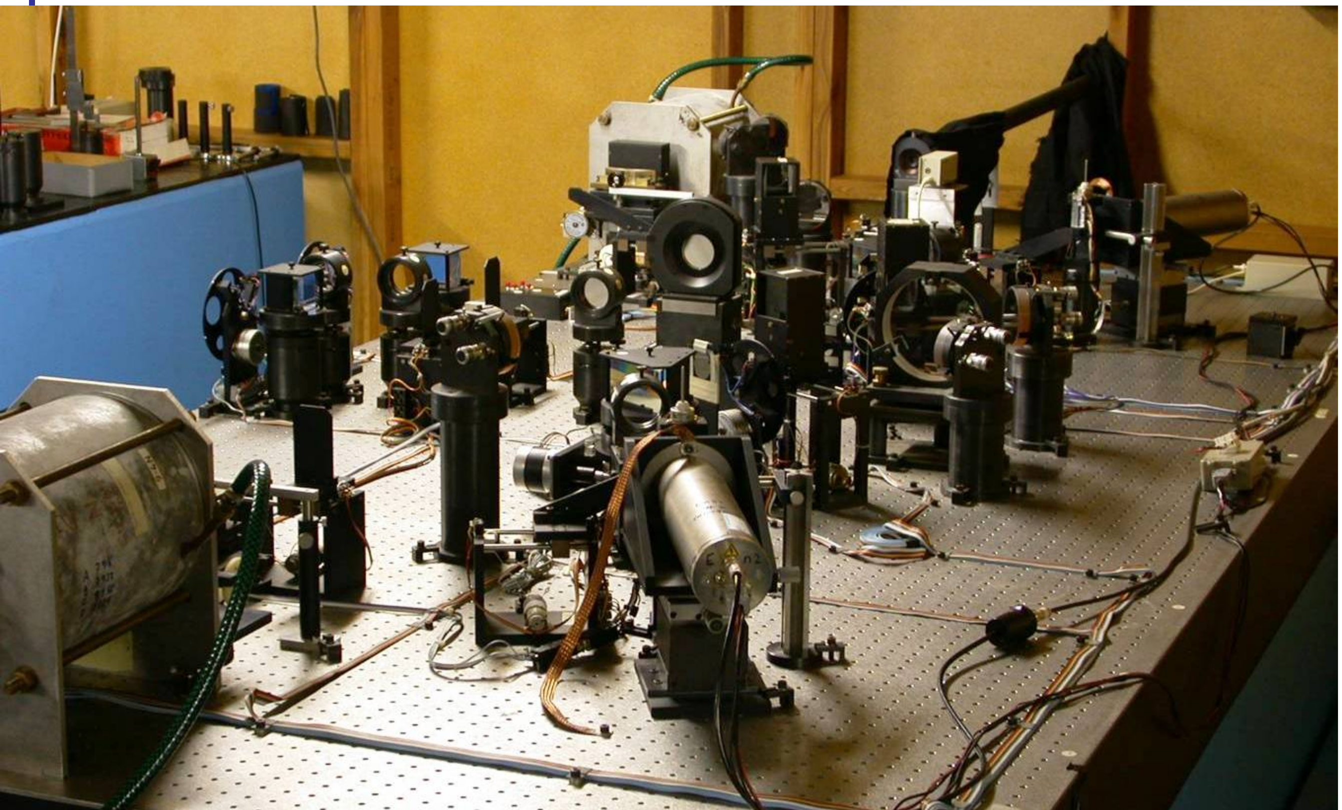
SUSI optical train



Georgia State University

NSF

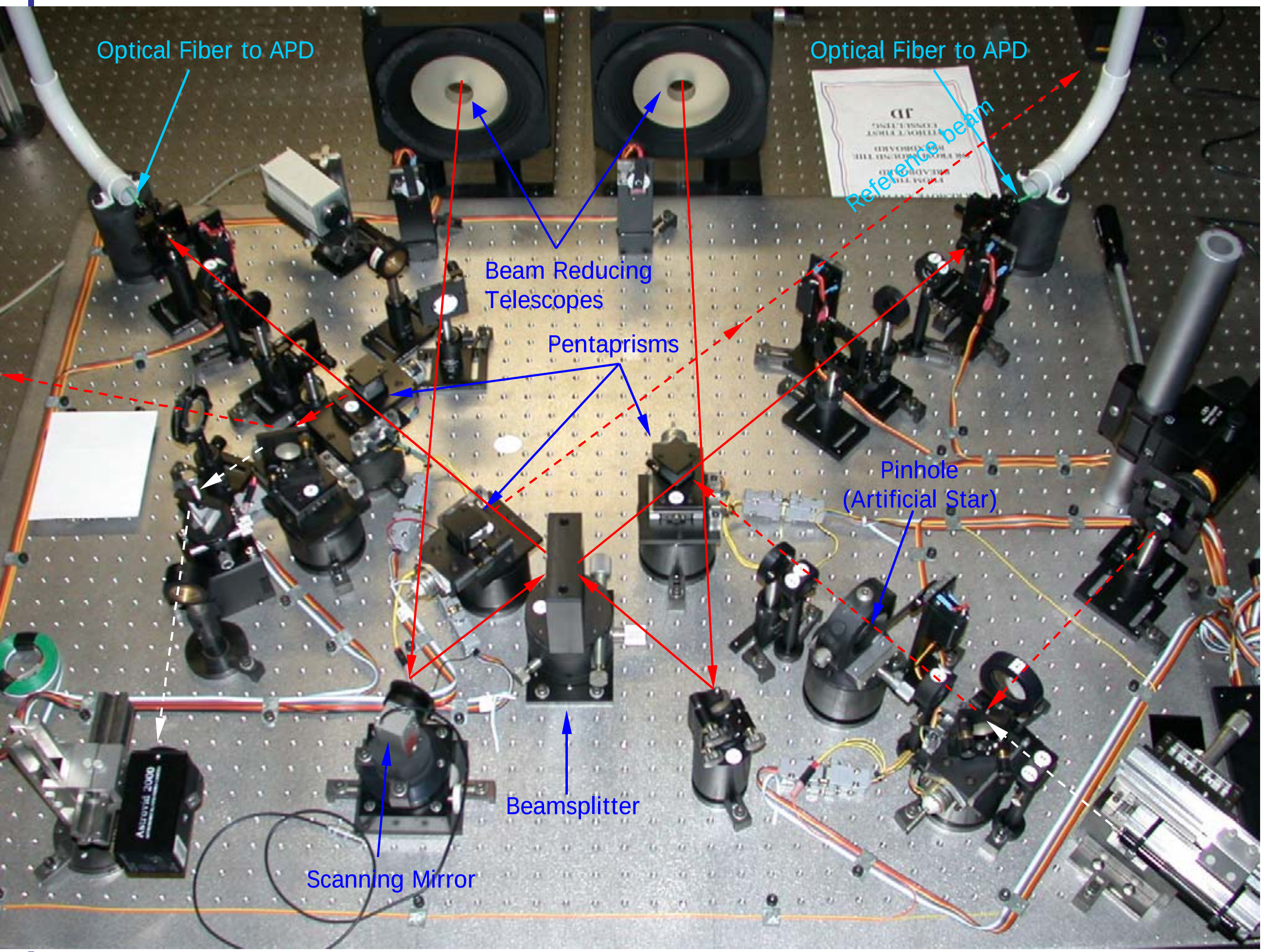
Blue table beam combiner



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

<u>Programs</u>
Early-type stars
Emission lines
Early-type binaries

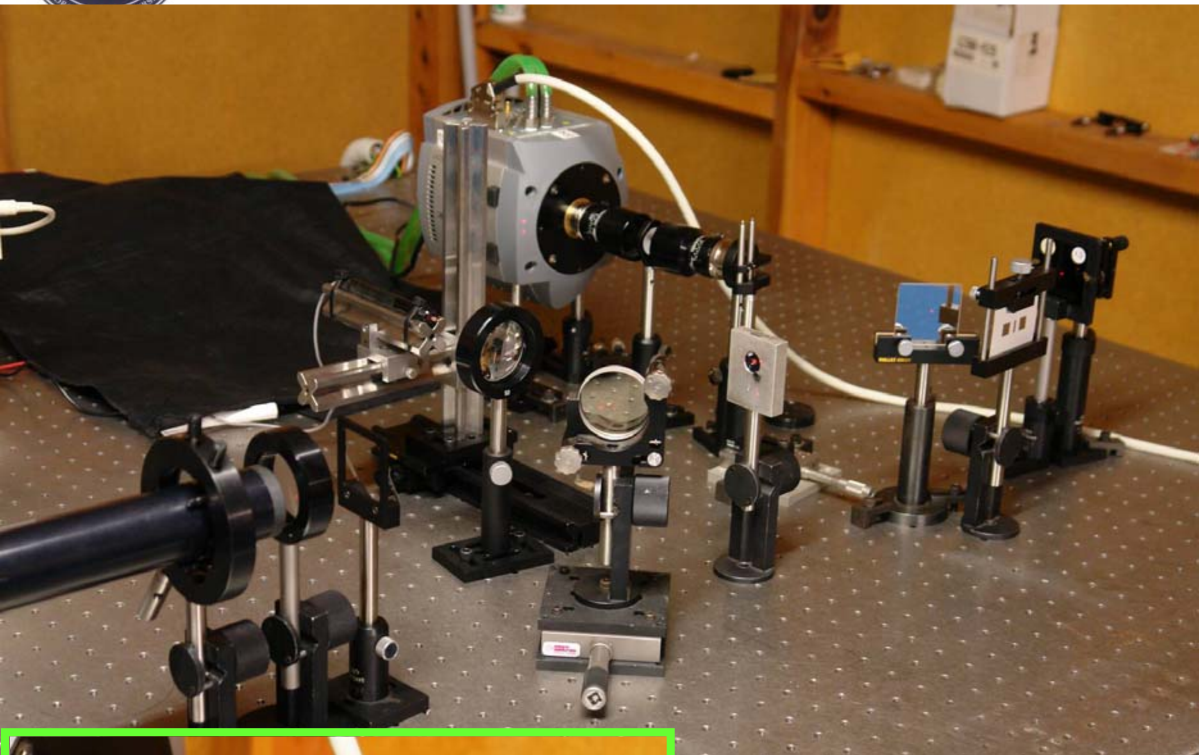
Red table beam combiner



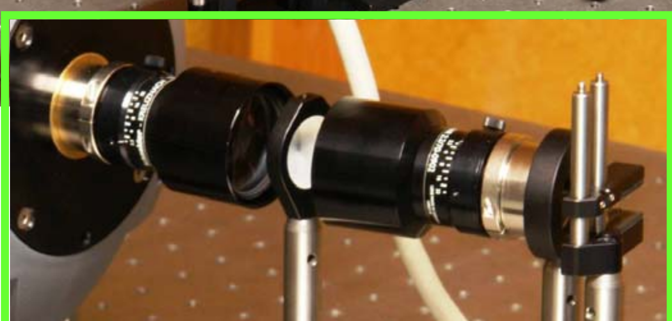
- 2004 to 2008
- piezo-scanning system
- APD detectors
- tip-tilt on CCD
- λ 500 – 950 nm
- $\Delta\lambda$ 5% - 20% e.g. 80 nm at 700 nm
- R_{limit} ~ 5.0

<u>Programs</u>
Late-type stars
Binaries
Cepheids

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 λ < 520 nm, to *same CCD*
- limit R ~ 6.5
- 800-950nm for astrometry



Programs

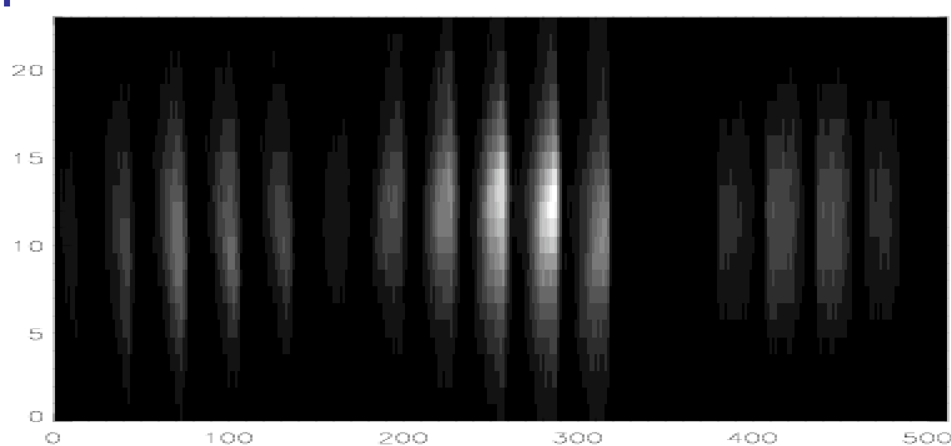
Binaries; low mass ratio

diverse stellar types

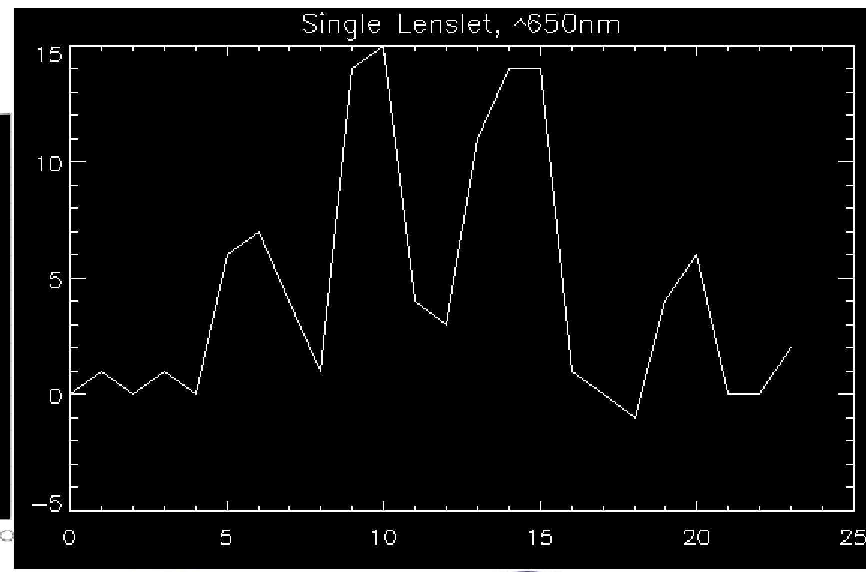
Progress…

- 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.

South North Fringes



Cut through fringes



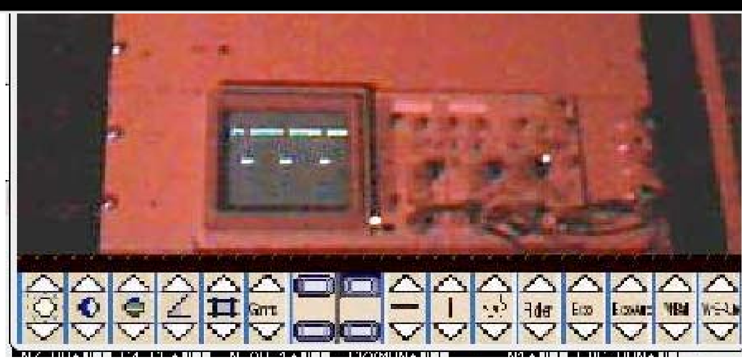
Remote Observing…

- 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.

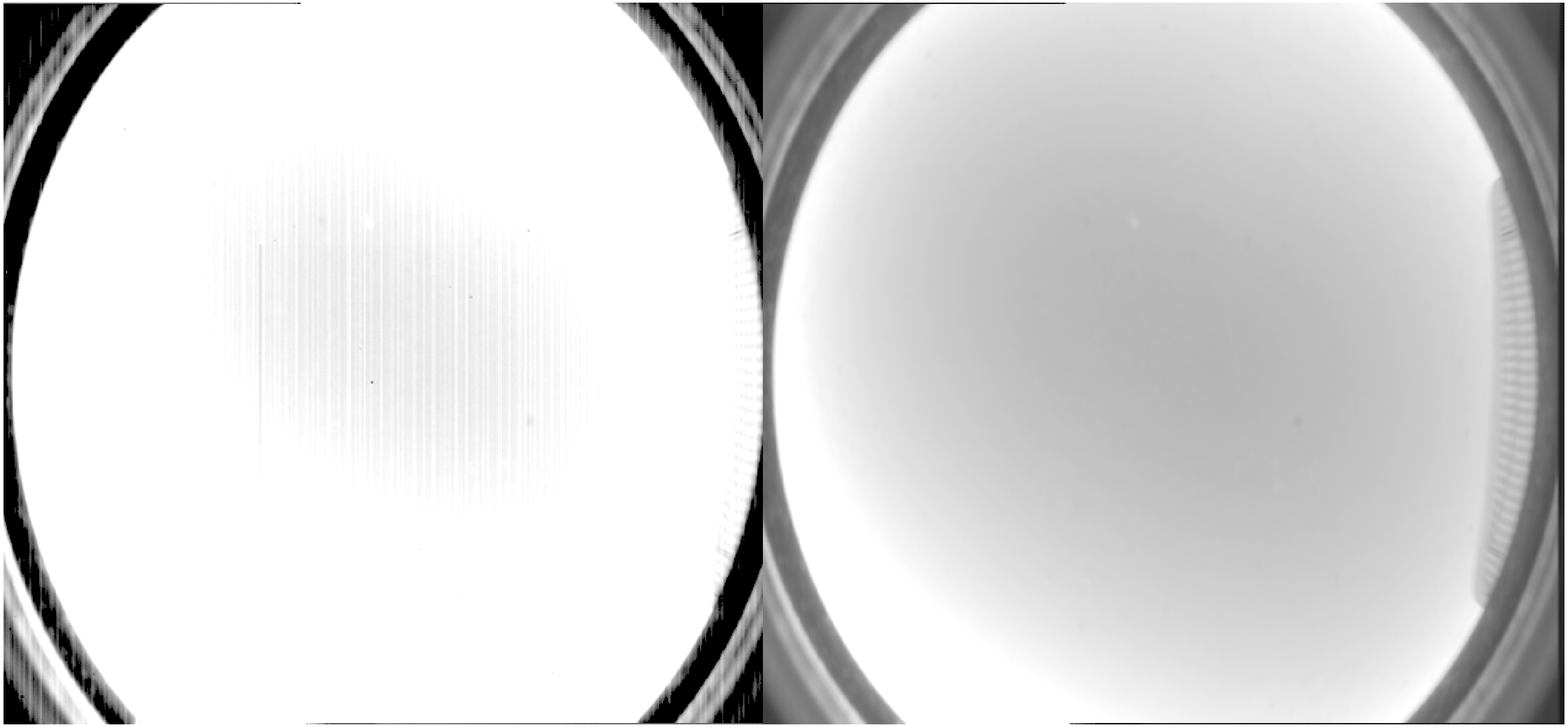
Remote Observing…

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

Security Cameras/Webcams

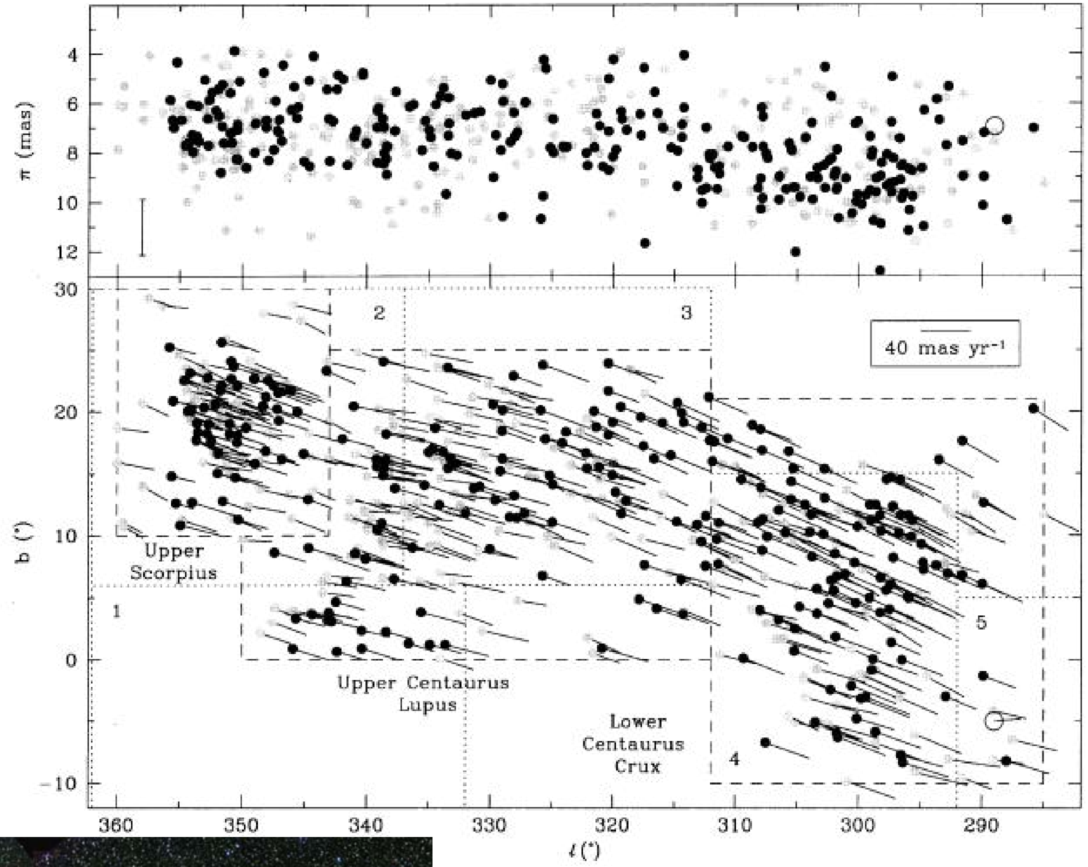


Sky Monitoring

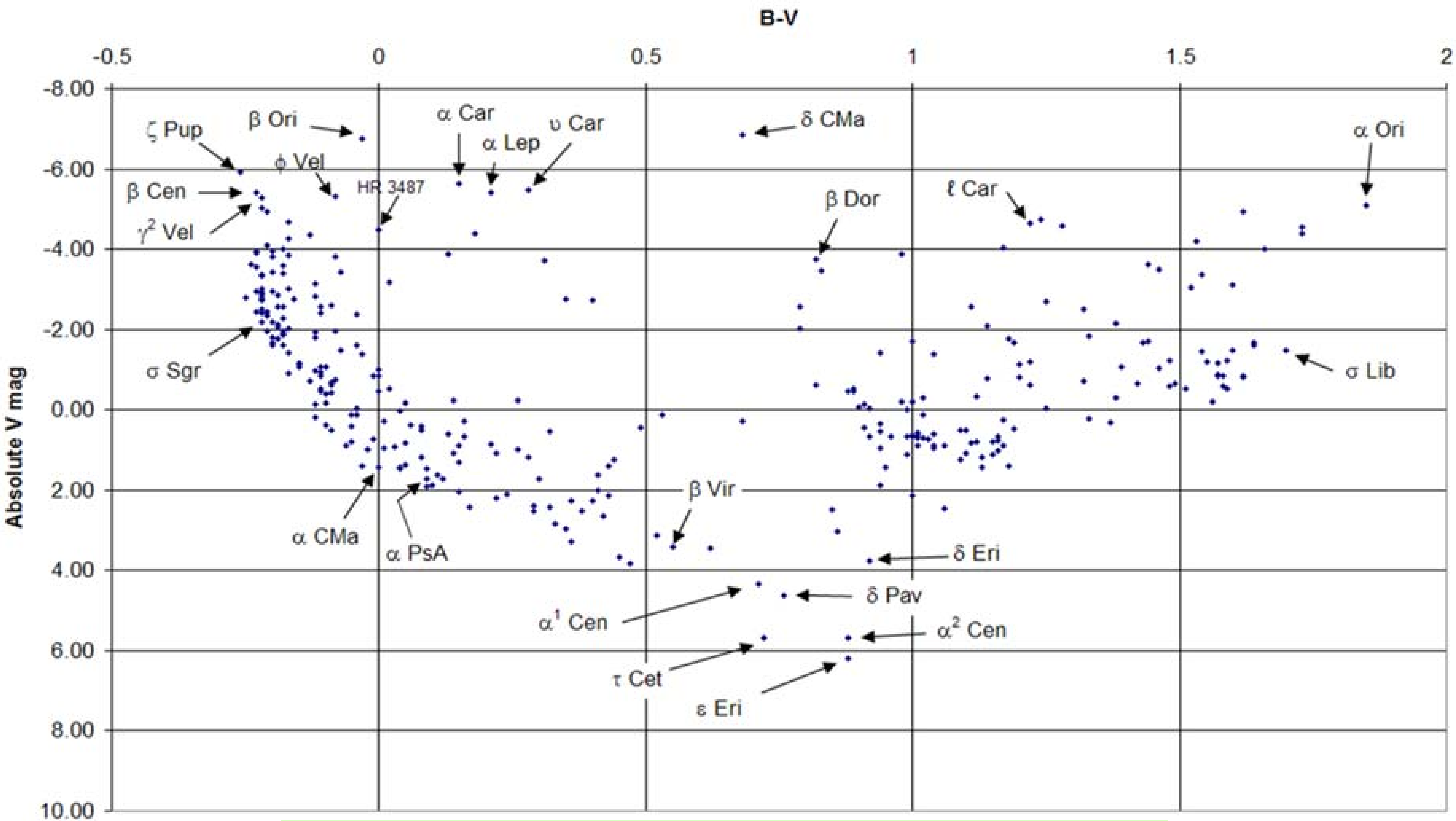


Science - Sco-Cen

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%

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…