Astro 500

Techniques of Modern
Observational Astrophysics

Matthew Bershady
University of Wisconsin

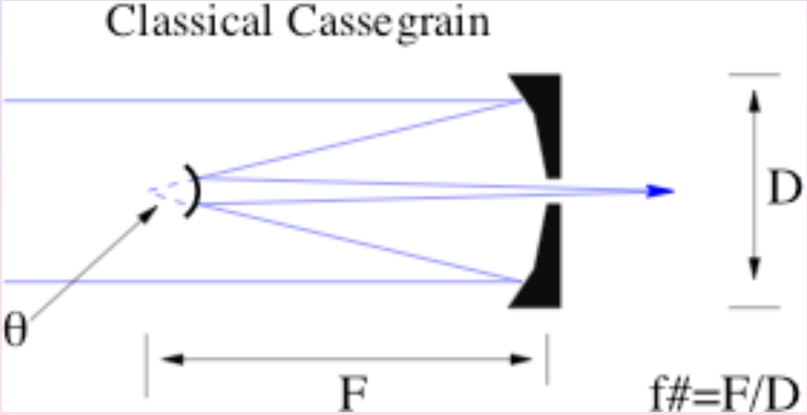
Lecture Outline

- Direct Imaging
  - A little review: optics, filters
  - Imaging Cameras: design considerations
  - Unusual modes (beyond the glazed stare)
  - Examples
    - o SALT: SALTICAM & RSS
    - o WIYN: ODI
  - Photometry
    - o Point sources
      - Aperture
      - PSF fitting
    - o Extended sources (surface photometry)
    - o Star-galaxy separation

deferred (Photometry)

Imaging Cameras

- Imagers can be put at almost any focus, but most commonly they are put at prime focus or at cassegrain.



…..or in the case of WIYN: Nasmyth

Focal Plane Scale (rev)

- Remember: the scale of a focus is given by

$$S=206265/(D \times f\#) \quad \text{(arcsec/mm)}$$

Examples:

1. 3m @f/5 (prime) 13.8 arcsec/mm (0.33"/24μpixel)
2. 1m @f/3 (prime) 68.7 arcsec/mm (1.56"/24μpixel)
3. 1m @f/17 (cass) 12.1 arcsec/mm (0.29"/24μpixel)
4. 10m @f/1.5 (prime) 11.5 arcsec/mm (0.27"/24μpixel)
5. 10m @f/15 (cass) 1.15 arcsec/mm (0.03"/24μpixel)

Abberations (rev)

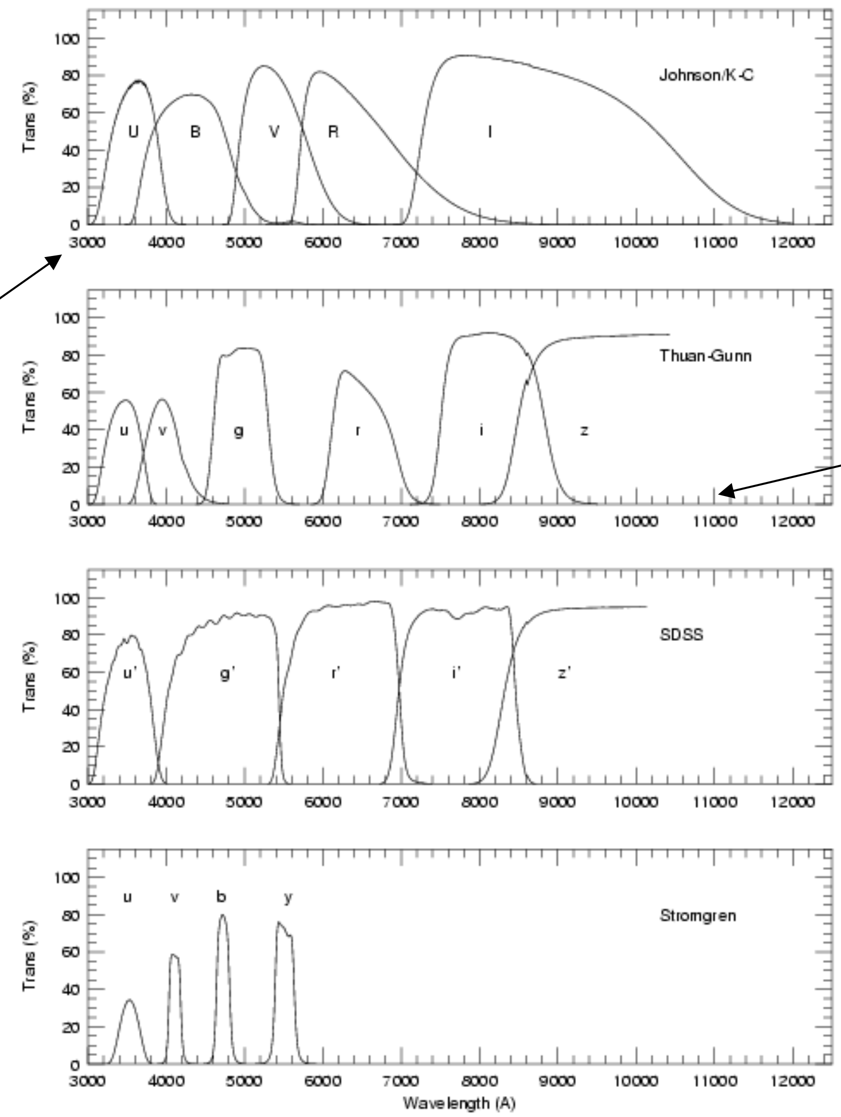
- Classical cassegrain (parabolic primary + convex hyperbolic in front of prime focus) has significant coma.

$$\beta_{\mathrm{coma}} = \frac{3\theta}{16(f/D)^2}$$

  - For Lick 3m (Shane), 1” blur at 2’.2 armin field-angle
- For a classical cassegrain focus or prime focus with a parabolic primary you need a corrector.
- The Richey-Chretien design has a hyperbolic primary and secondary designed to balance out coma and astigmatism in the focal plane, but for very wide field (>10-15 arcmin) you still need a corrector (e.g., ODI).

Filter Systems

- There are a bunch of filter systems
  - Broad-band (~1000Å wide)
  - Narrow-band (~10Å wide)
  - Some were developed to address particular astrophysical problems, some are less sensible.



3100Å is the UV atmospheric cutoff

1.1μ silicon bandgap

Filter Choice: Example

- Suppose you want to measure the effective temperature of the main-sequence turnoff in a globular cluster.

color	relative time to reach δT_{eff}=100
B-V	4.2
V-R	11.5
B-I	1.0
B-R	1.7

***Obvious*?**

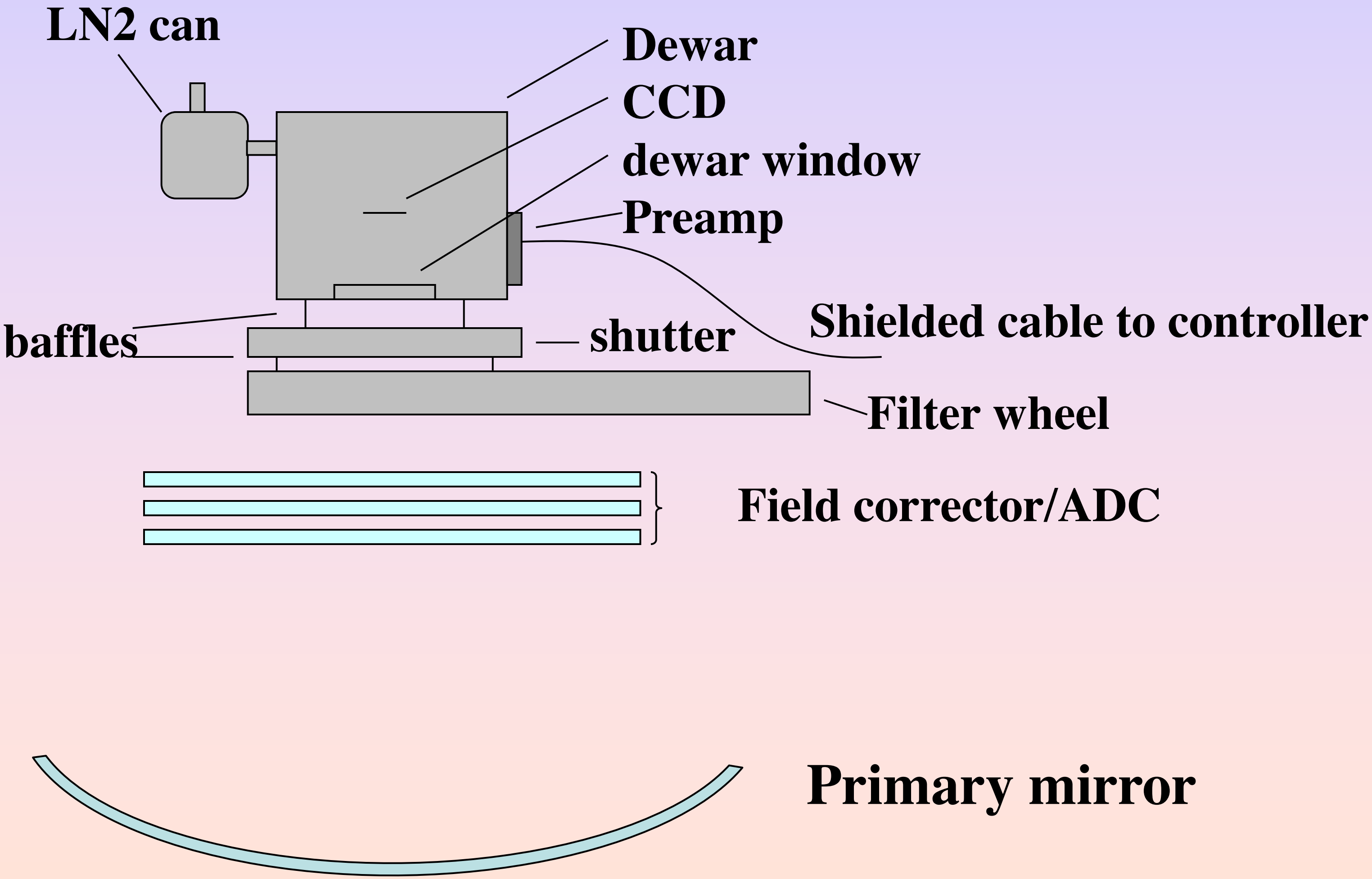
Narrow-band Filters

- Almost always interference filter bandpass is affected by temperature and beam speed:

$$\Delta CWL = 1\text{Å} / 5^{\circ}C$$

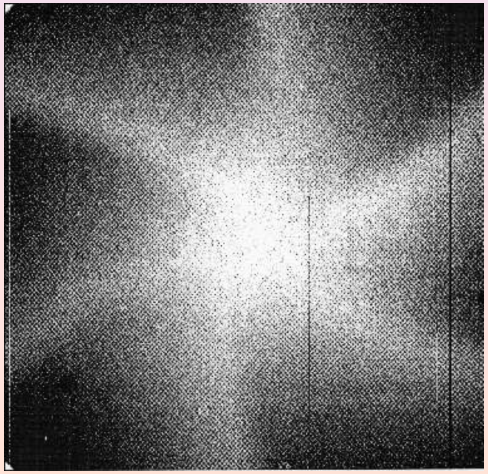
$$\Delta CWL = 17\text{Å} \text{ for } f/13 \rightarrow f/2.8$$

Design Considerations



Shutters

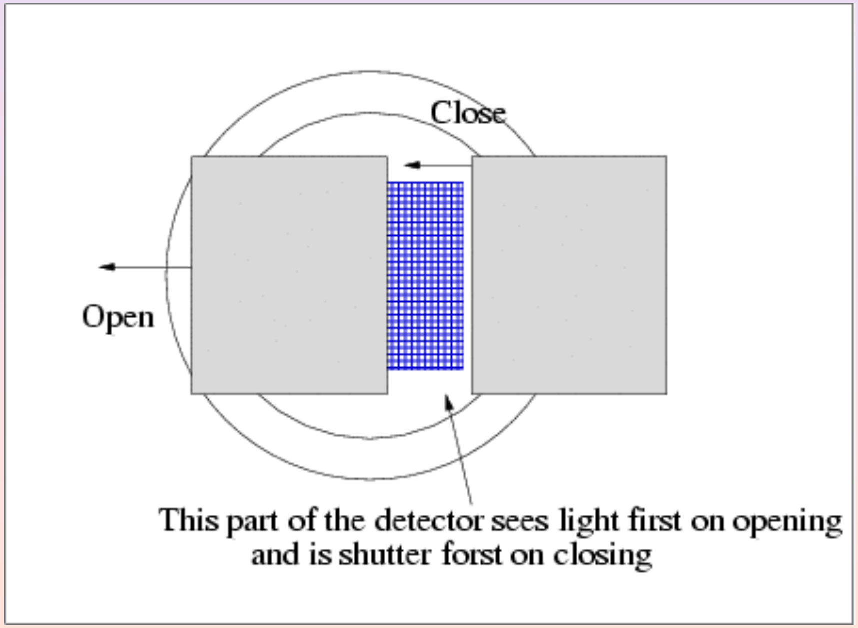
- Historical standard is a **multi-leaf iris shutter**.
- As detectors got bigger, finite opening time and non-uniform illumination pattern started to cause problems.
  - o 2k x 2k 24μ CCD is 2.8 inches along a diagonal.
  - o Typical iris shutter - 50 milliseconds to open. Center of a 1s exposure is exposed 10% longer than the corners.



Shutter vignetting pattern produced by dividing a 1 second exposure by a 30 second exposure.

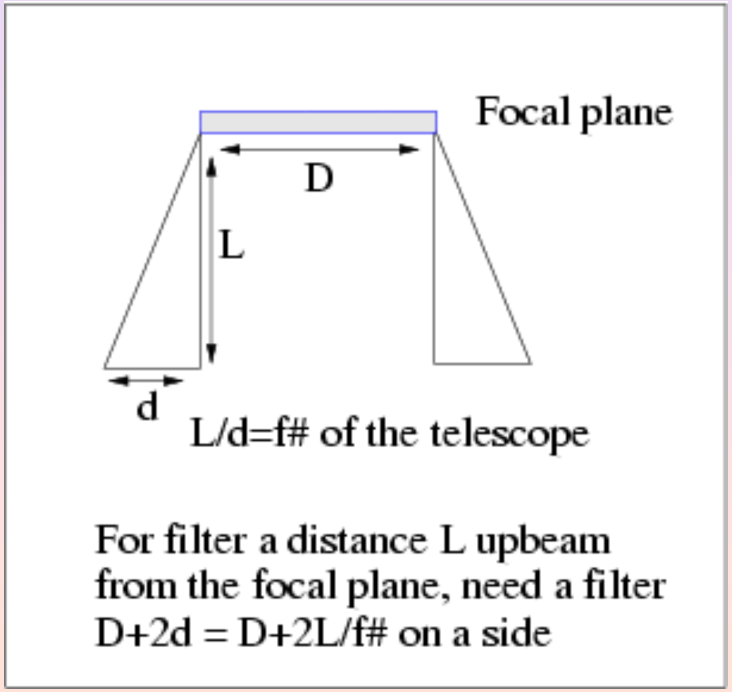
Double-slide system

- The solution for mosaic imagers and large-format CCD has been to go to a 35mm camera style double-slide system.



Filter Wheel

- Where do you put the filter? There is a trade off between filter size and how well focused dust and filter imperfections are.



Other issues:

- **Dewar hold time:** Good fill-tube geometry required to not spill LN2 at certain HA. Good dewar design (thermal loading, large size) required for long hold time.
- **RF pickup:** Electronics must be well shielded and grounded.
- **Reflections, glints and ghosts:** Good baffles, masking of edges, excellent coatings are essential.

Other modes

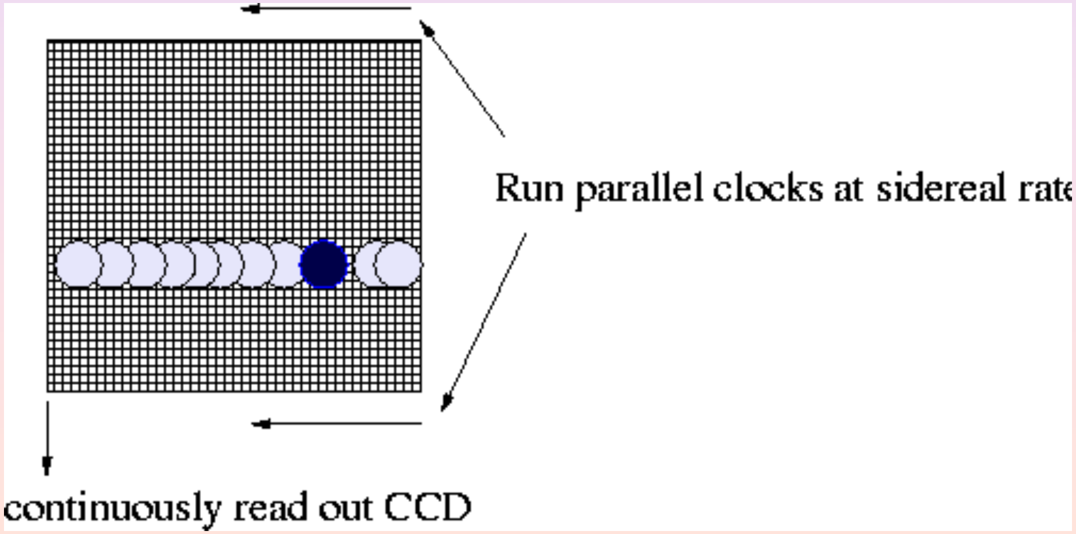
- ✓ On-chip binning
- Drift-scanning
- Frame-transfer / slot-mode: high-speed photometry
- Orthoganal transfer (OTA): tip-tilt image correction

SALTICAM
RSS (Drift-scanning; Frame-transfer / slot-mode)

ODI (Orthoganal transfer)

Drift Scanning

- An interesting option for imaging is to park the telescope (or drive it at a non-sidereal rate) and let the sky drift by.
- Clock out the CCD at the rate the sky goes by and the accumulating charge ``follows'' the star image along the CCD.



Drift Scanning

- End up with a long strip image of the sky with a \`height' = the CCD width and a length set by how long you let the drift run (or by how big your disk storage is).
  - The sky goes by at 15 arcseconds/second at the celestial equator and slower than this by a factor of $1/\cos(\delta)$ as you move to the poles.
  - At the equator a CCD camera with 2048 x 0.3" pixels yields an integration time per object of about 40 seconds.

Drift Scanning

- What is the point?
  - Superb flat-fielding (measure objects on many pixels and average out QE variations)
  - Very efficient (don't have CCD readout, telescope setting)
- Problem:
  - Only at the equator do objects move in straight lines, as you move toward the poles, the motion of stars is in an arc centered on the poles.
- Sloan digital survey is a good example
- Zaritsky Great Circle Camera is another

Frame-transfer/slot-mode

- A method for high-speed photometry:
  - A portion of the CCD is masked and used as a storage area.
  - The detector is used without a shutter
  - After each of regular number of short durations, a portion of the unmasked (active) region of the detector containing the source(s) of interest is “frame-transfered” to the storage region.
  - The storage region is filled in, and then read out.

SALTICAM
SALT prime-focus imaging camera

PI: Darragh O'Donoghue (SAAO)

- Efficient imager over entire science FoV (8') and down to 320 nm.
- Broad to narrow-band imaging.
- High time-resolution photometry.
- Drift-scanning (not yet implemented)

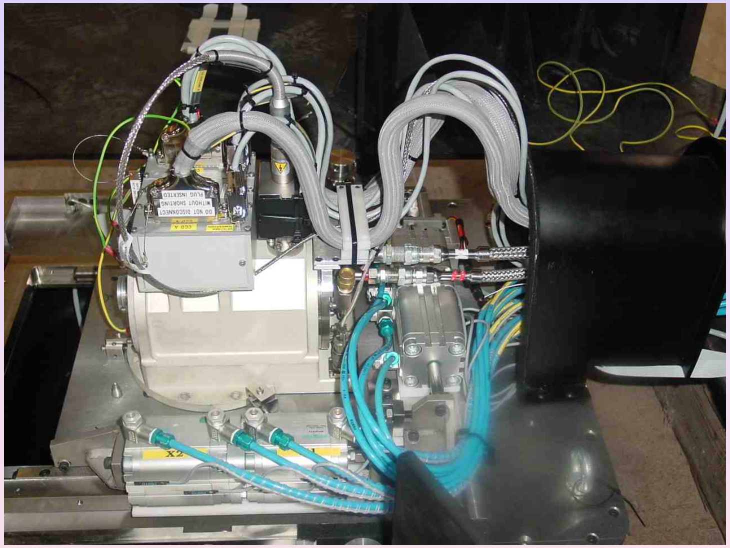
Two incarnations/roles:
(1) commissioning/verification instrument (VI)
(2) Acquisition camera and science imager (ACSI) and commissioning

How you use it

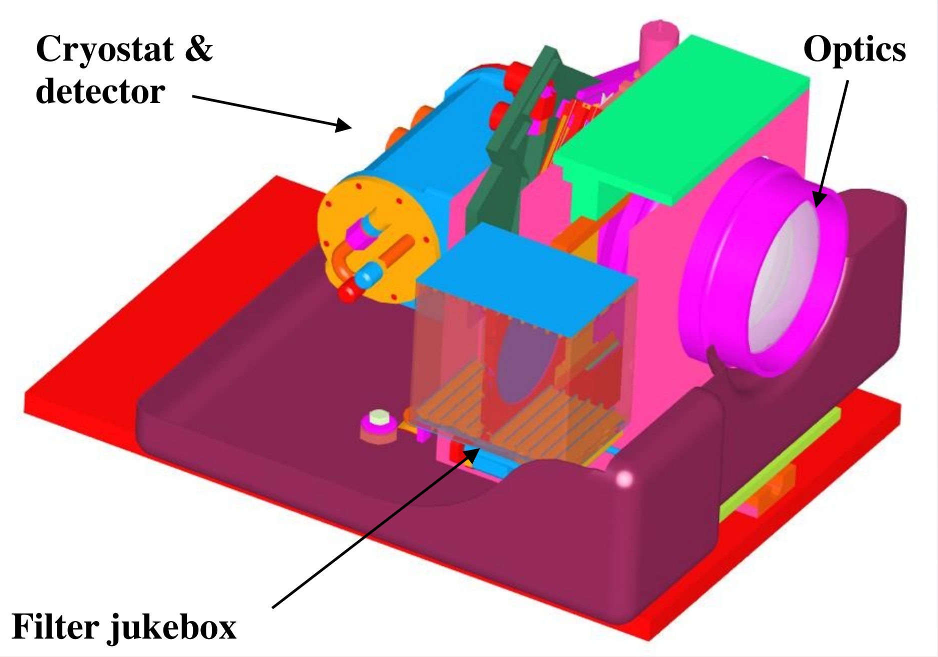
SALTICAM enables unique science, particularly:

- *UV and fast photometry (~70-50 ms)*
- *Deep, narrow-band drift-scanning (not implemented)*
- *Parallel deep UV-imaging (not implemented)*

SALTICAM



SALTICAM VI



SALTICAM ACSI

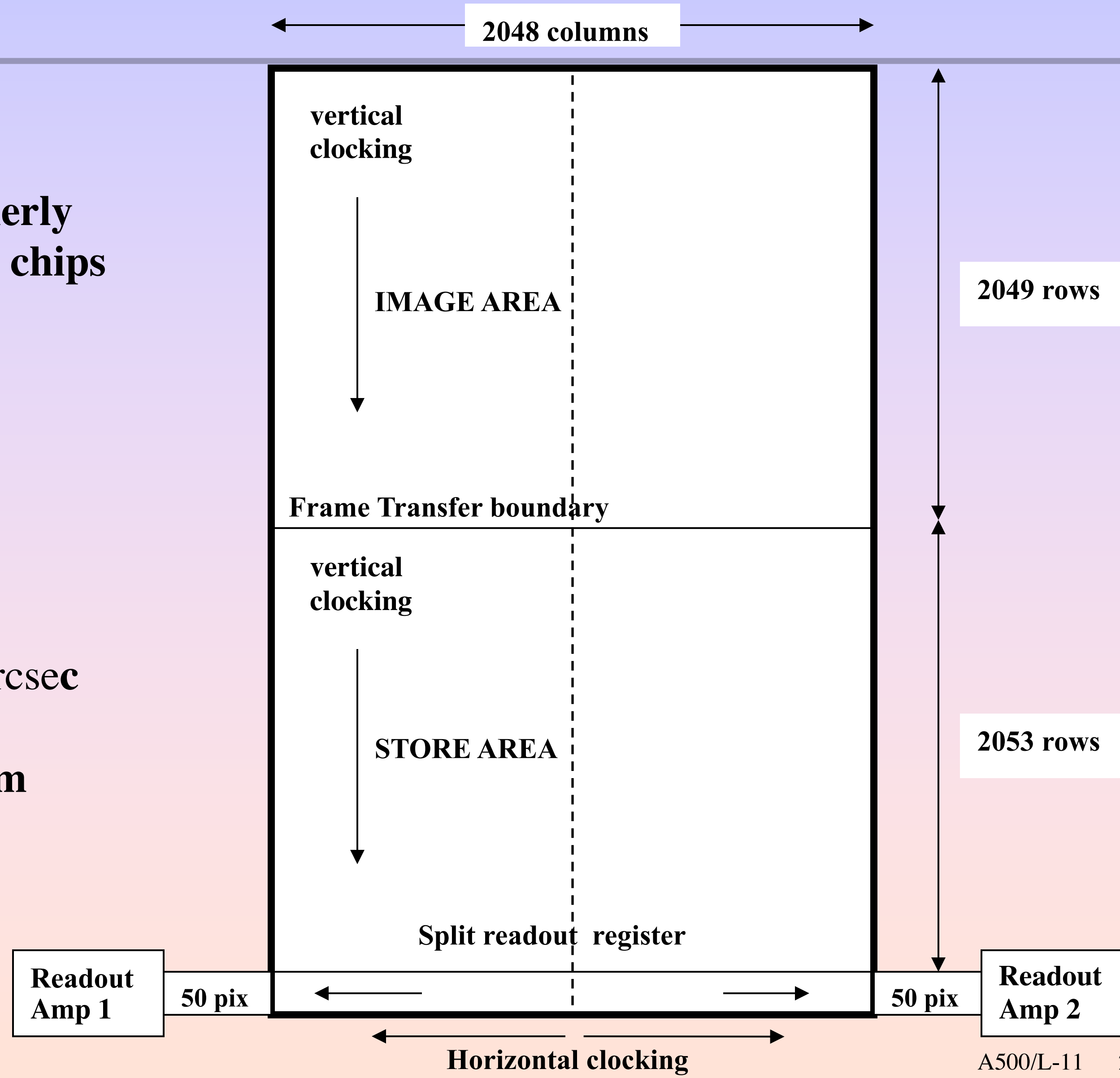
SALTICAM CCD detectors

Frame transfer E2V (formerly Marconi, EEV) CCD44-82 chips

- back illuminated
- thinned
- frame transfer
- deep depletion
- "Astro-BB" coating
- 2048 x 4096 x 15 microns
- 1 unbinned pixel = 0.14 arcsec

Two chips mosaiced to form 4k x 4k area.

Same chips used in RSS.



RSS: Robert Stobie Spectrograph

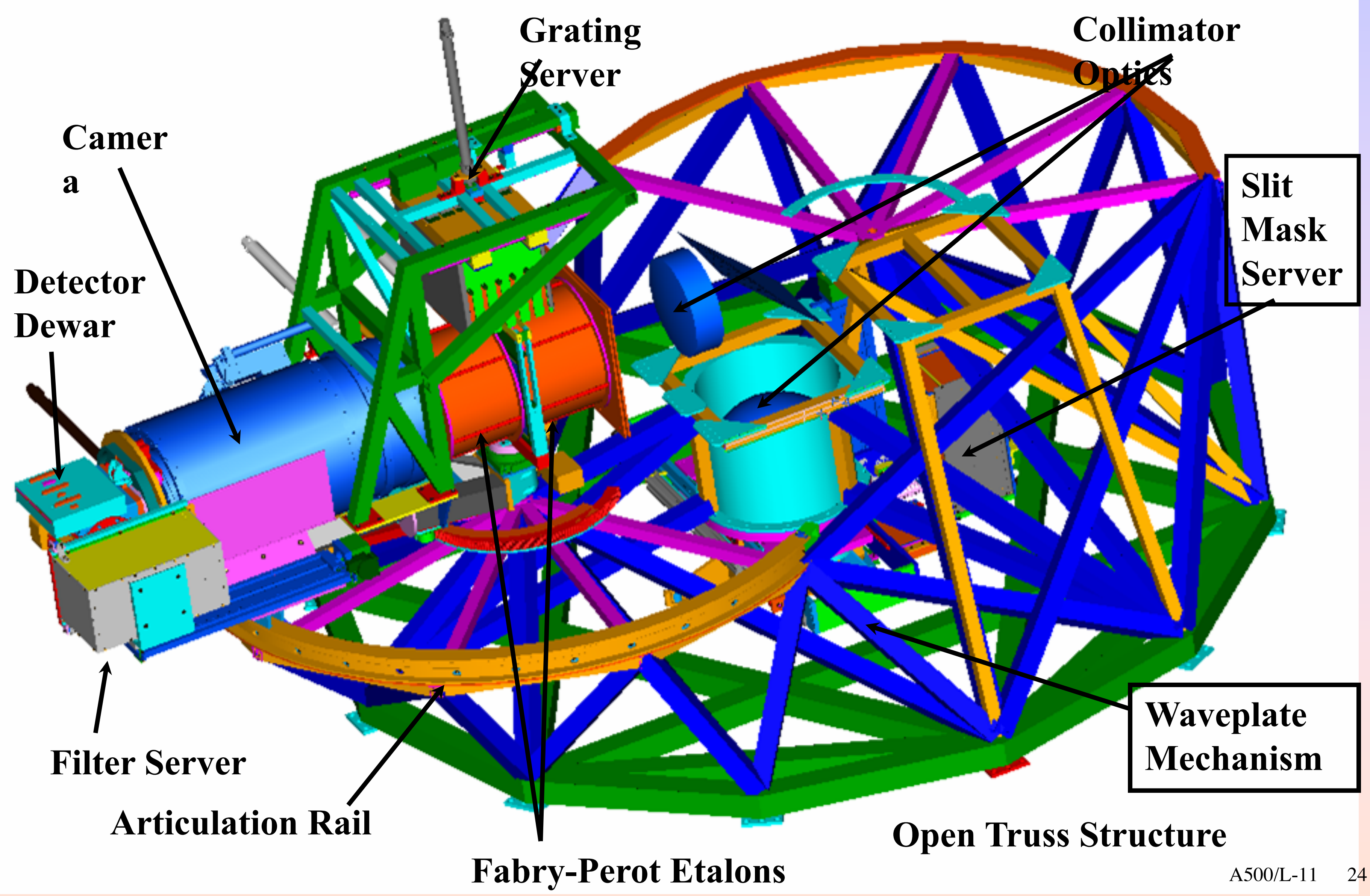
PI (visible beam): Ken Nordsieck, University of Wisconsin-Madison

- High-throughput medium resolution (*R* < 8,000 @ 1 arcsec) spectroscopy:
  - 8’ FoV, 320-950 nm range
- Multi-object spectroscopy: >100 slitlets
- Fabry-Perot imaging: R = 500 to 12,500 beween 450-900 nm
- Imaging polarimetric and spectropolarimetric modes into the UV (320 nm).
- Fast spectrophotometric modes: 100 ms (no dead-time)

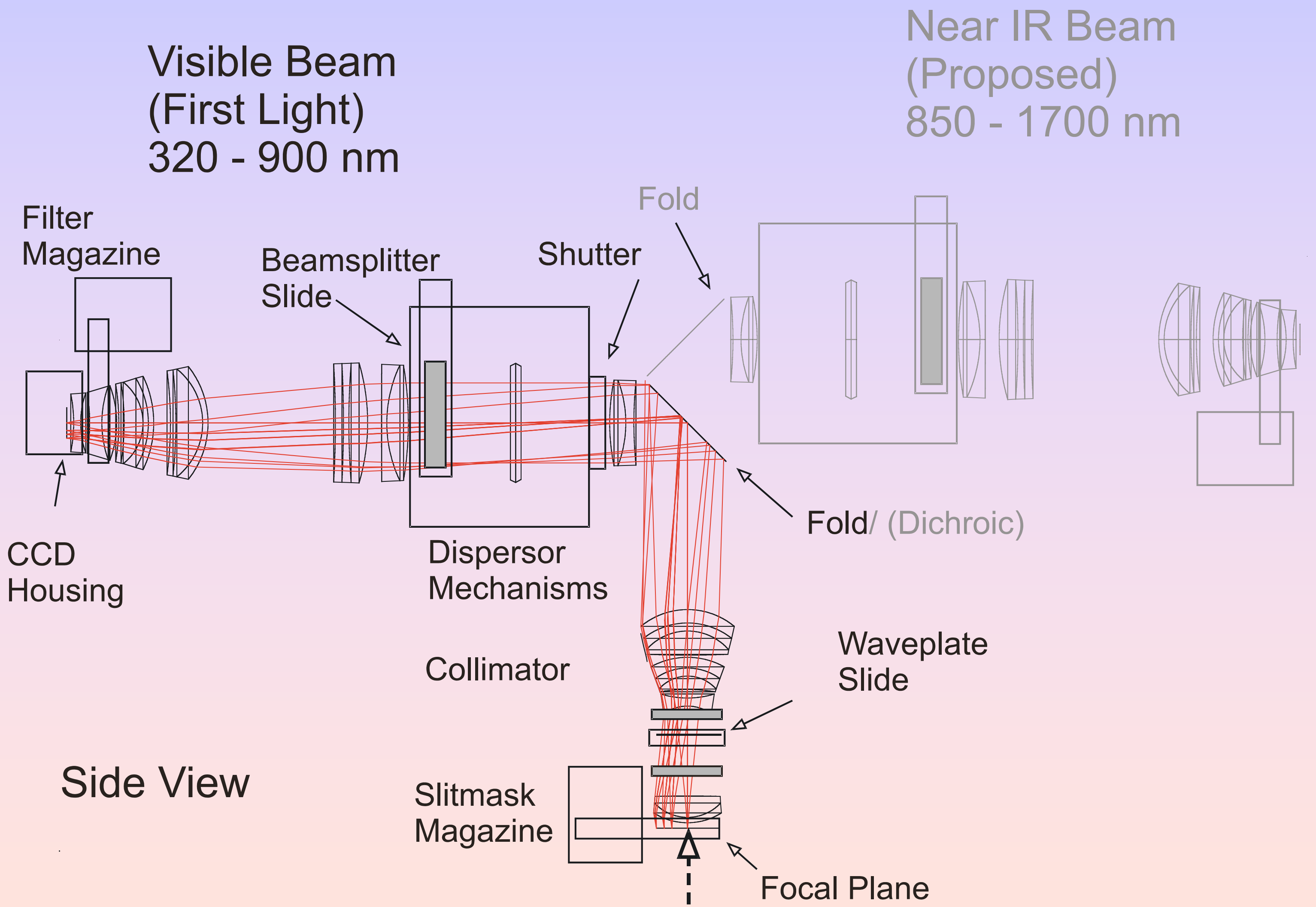
The major science ‘niches’ for RSS are:

- **UV to NIR spectroscopy**
- **High time-resolution astrophysics**
  - » **Rare on large telescopes**
  - » **Dark sky; Good use of natural seeing large telescope**
  - » **Exploit SALT UV sensitivity and access to prime focus**

RSS: Schematic (vis only)



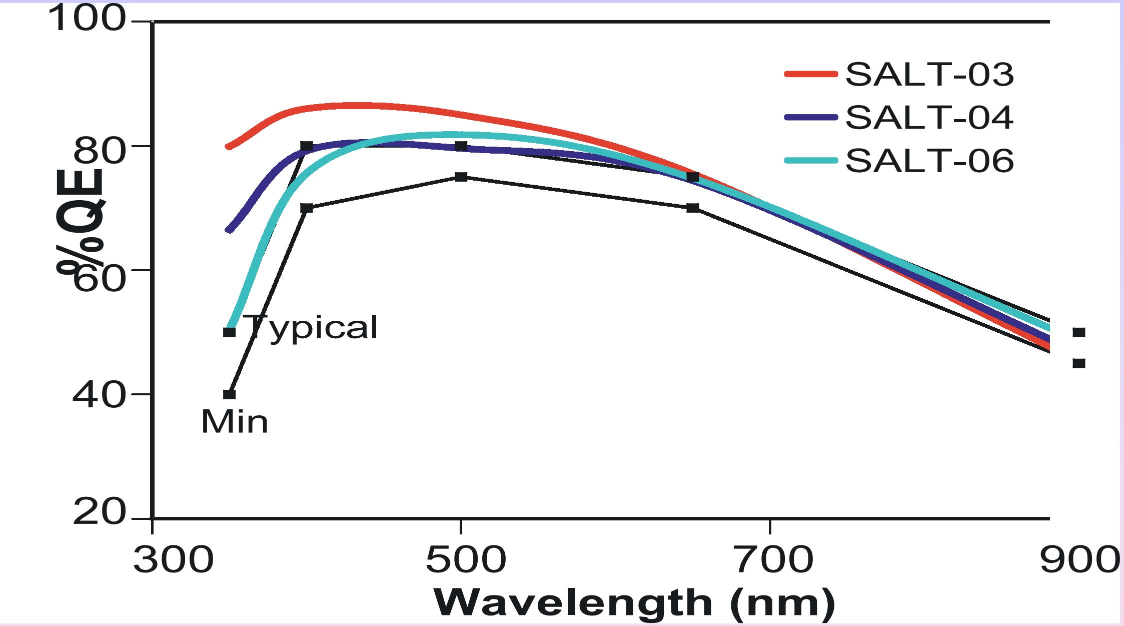
RSS Layout:


Visible Beam
(First Light)
320 - 900 nm
Near IR Beam
(Proposed)
850 - 1700 nm
Filter
Magazine
Beamsplitter
Slide
Shutter
Fold
CCD
Housing
Dispersor
Mechanisms
Fold/ (Dichroic)
Collimator
Waveplate
Slide
Side View
Slitmask
Magazine
Focal Plane

RSS CCDs

SALT CCDs for SALTICAM and RSS delivered Feb 2003.

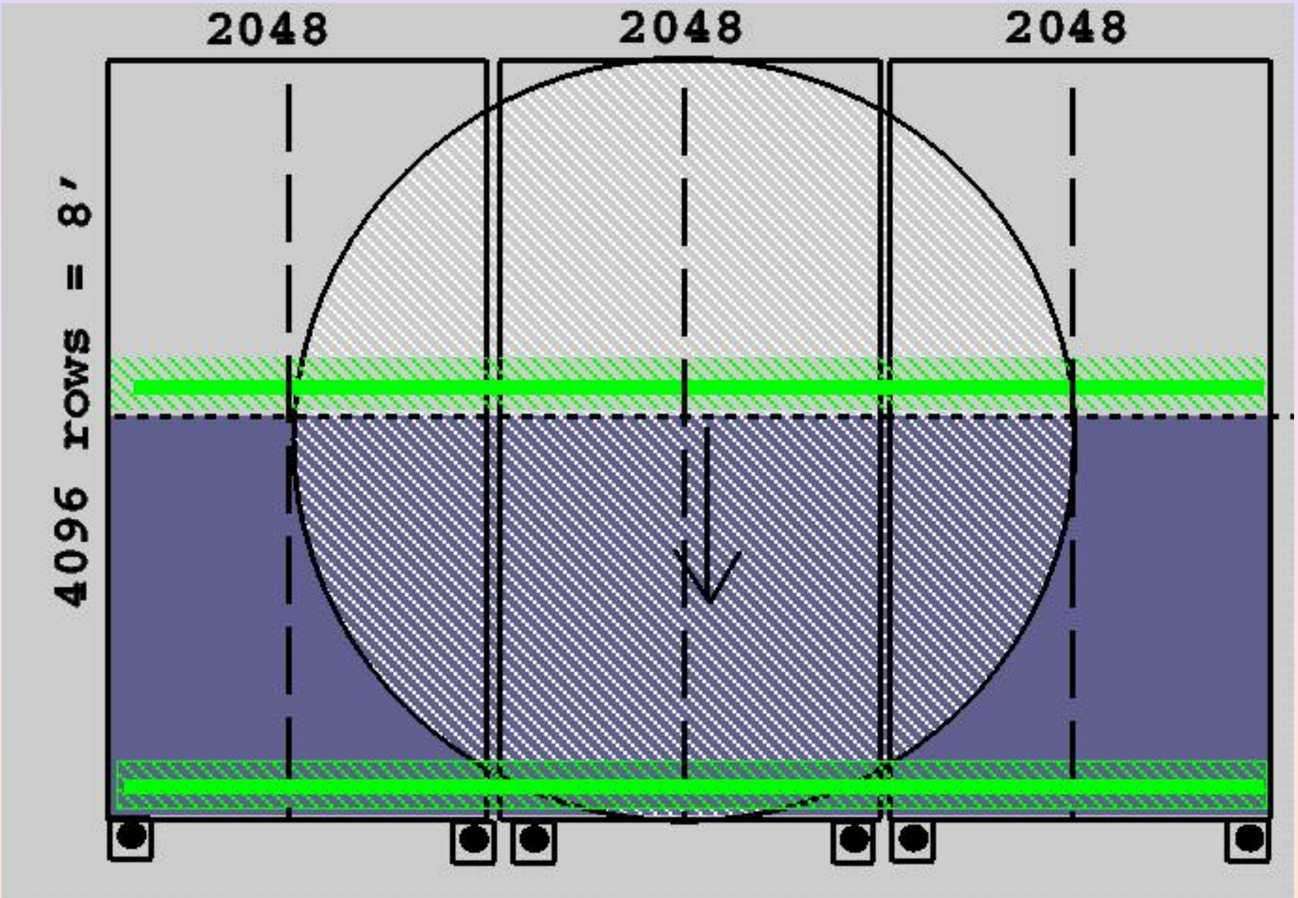
- E2V 2k x 4k deep depletion Grade 0 devices
- custom frame-transfer chips
- thinned & astro-bb coating (good in blue)
- readout noise < 2.4e-



λ (nm)	Min QE (%)	Typical QE (%)	01 SALTICAM (%)	02 SALTICAM (%)	03 RSS (%)	04 RSS (%)	05 spare (%)	06 RSS (%)
350	>40	50	40.5	48.8	79.9	66.5	50.6	50.4
400	>70	80	79.6	71.2	86.0	79.2	71.7	75.6
500	>75	80	81.4	75.5	85.0	79.6	77.7	81.8
650	>70	75	78.0	72.7	75.5	74.4	70.1	74.8
900	>45	50	47.6	45.3	45.4	46.8	45.1	48.7
1000	No spec	No spec	11.2	10.7	10.8	10.7	10.0	10.6

CCD subsystem readout modes

High time resolution with frame-transfer in operation; max 4' spatial field with lower half masked, and possibility for upper portions masked as well (slot mode).



Bin	RN	Read
1x2	3e-	11.0 s
2x2	3e-	5.5 s
1x2	5e-	3.2 s
2x2	5e-	1.6 s

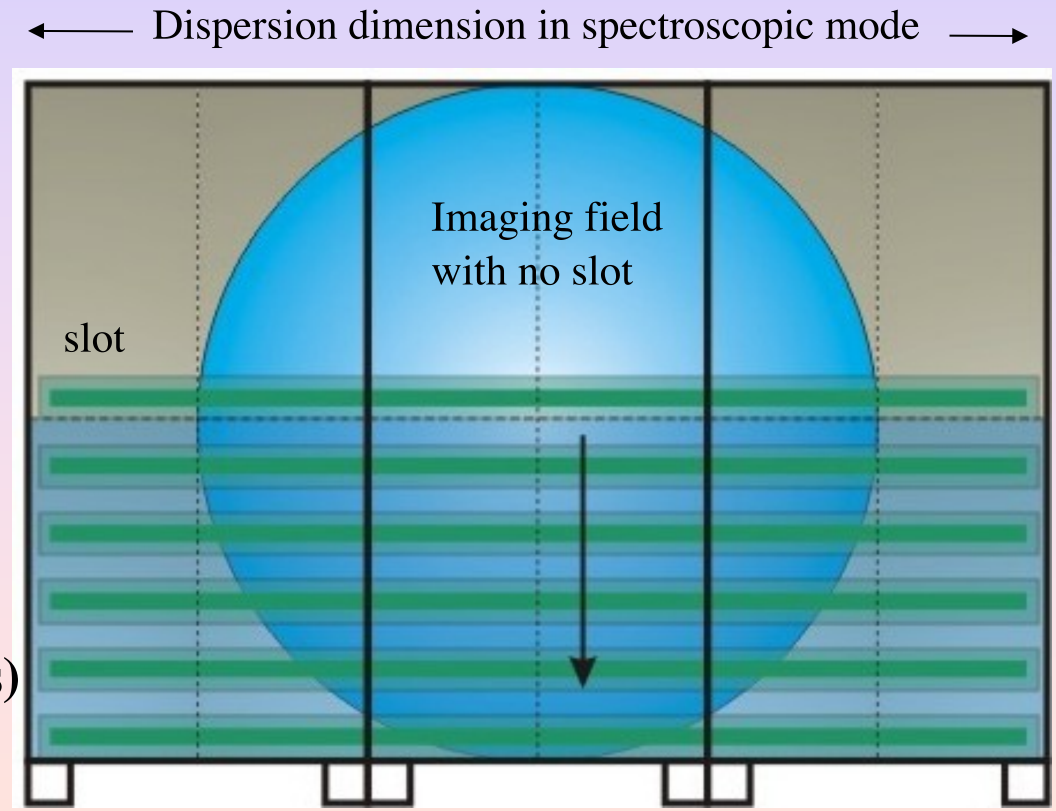
RSS: fast imaging or spectroscopy
‘Slot’ mode

Slot in telescope focal plane placed just above frame transfer boundary

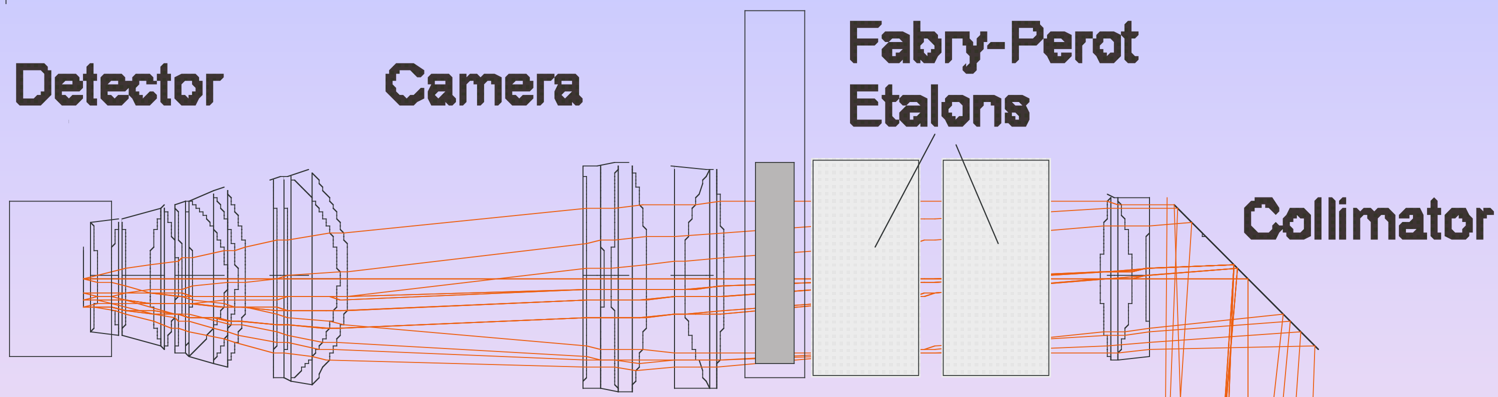
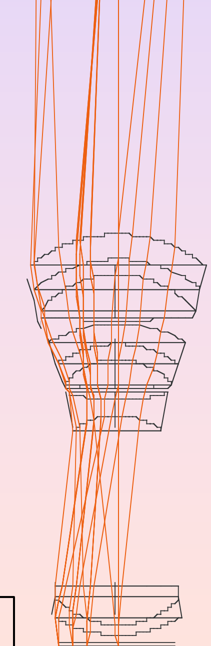
Do 2 x slot width row transfers (discard smeared rows)

This example has 204 pix slot (~27 arcsec), each shifted 408 rows at a time.

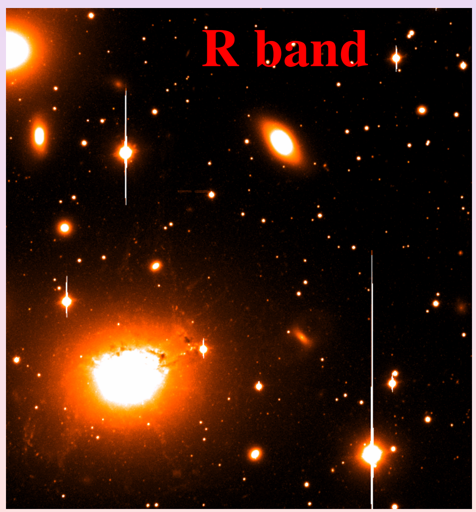
Expect to run at
- **>76 msec integrations**
- **~6 msec deadtime (row transfers)**
  - **fast spectroscopy**
  - **fast spectropolarimetry**

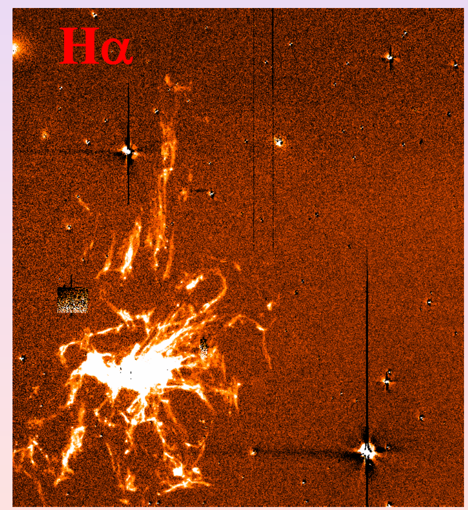


RSS Fabry-Perot Imaging Mode

Perseus cluster





Fabry-Perot: interferometer acting like a tunable, narrow-band filter, with a field-dependent band-pass

Single or dual etalons: ***R*** **= λ/dλ = 500, 1250, 8000**
+ order-block filters covering 450-900nm at *R* = 50

ODI: WIYN's One Degree Imager

Slides (circa 2009) courtesy Daniel Harbeck, *ODI Project Scientist*

ODI: One Degree Imager

- Use WIYN's 1º field of view.
- Utilize the excellent seeing of site & telescope.

- Further enhance image quality by active tip/tilt guiding
  - 20 Hz guide loop speed required, 50Hz goal.
  - Shown to improve median seeing in R by 0.15".

- Sample the focal plane with 0.11" pixels -> 1GPixel camera.

- High observing efficiency, automated cadences:
  - shutter close to open <20 sec in snapshot mode

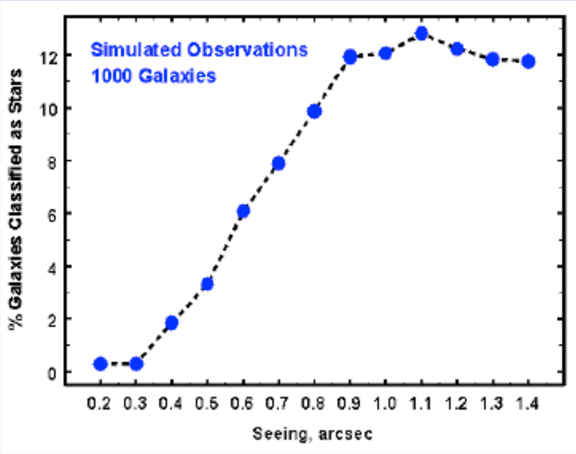
- Provide on-site basic data reduction
  - Instrumental detrending, meta data, WCS...

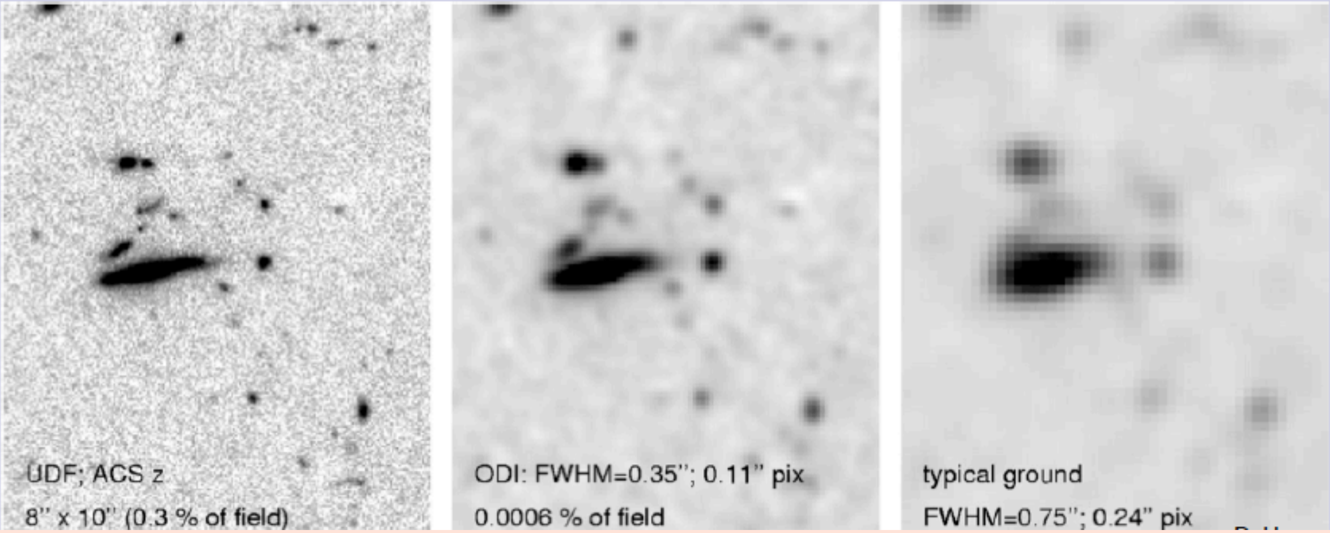
- **Deliver a modern, competitive imager to position WIYN at the forefront of science.**
  - **Enable new science through high-resolution, wide field imaging.**
  - **At 0.4" seeing, a 4m-class telescope can compete with 8m class facilities.**

Science Motivation

- Good seeing allows to resolve galaxies.
  - Star/galaxy separation: at 0.35” everything is resolved!
  - Weak/strong lensing
  - Galaxy evolution
  - Stellar populations in the Local Universe

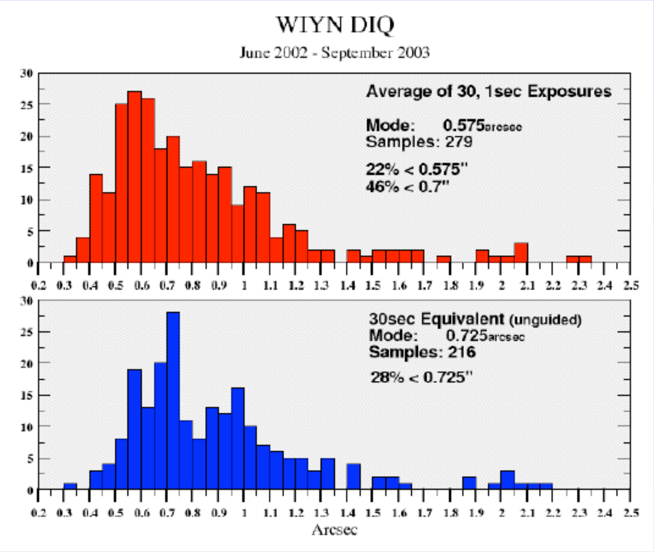
- Narrow band filters enabled by slow f-ration of telescope.
- ODI is always mounted: Access the time domain.
- Good seeing allows detection of faint, distant sources.
- Fast-Cadence photometry.

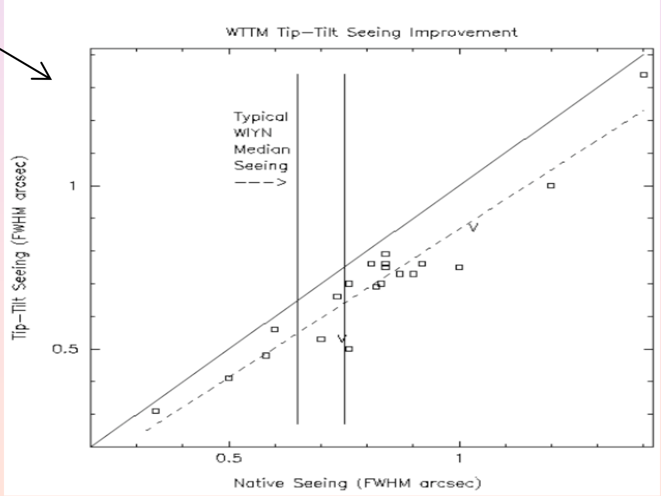


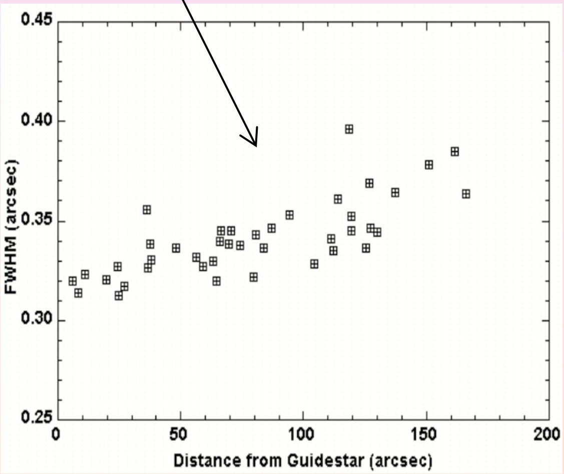


Technical Motivation

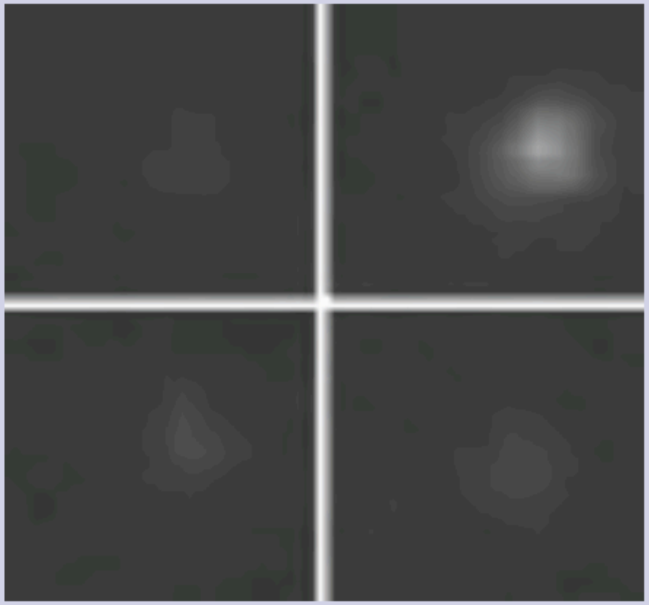
- WIYN has excellent native seeing (median ~0.7” in R)
- WIYN has a 1° field of view
- Tip/Tilt performance at WIYN
  - Improves seeing by ~0.14” in FWHM (typical in R)
  - r’, i’, z’ medians become ~0.54”, 0.43”, 0.35”
  - *But*, at 2 arcmin radius, atmosphere decorrelates: degrades 0.32” images by 10%







Tip/Tilt correction



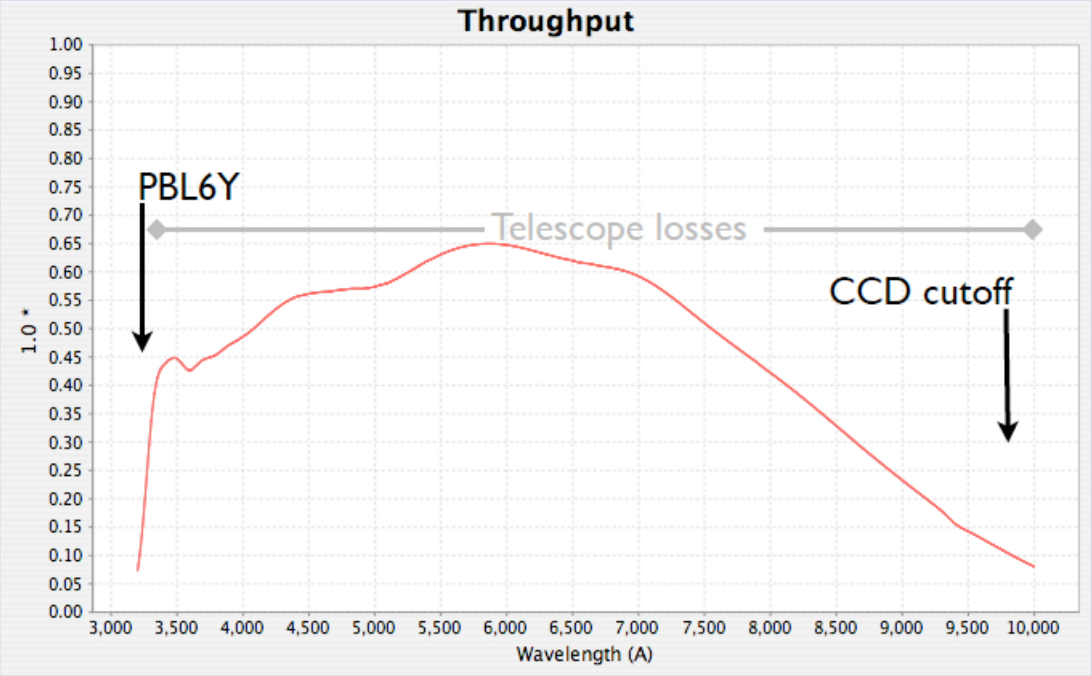
- Atmospheric turbulence, wind-shake cause image motion
- Some image motion is correlated, e.g., due to telescope shake
- Uncorrelated image motion due to atmospheric turbulence
- (Not too new) Idea: sense motion from a bright guide star and compensate for it
  - Active secondary mirror (common in AO systems)
  - Move detector (consumer digital cameras)
  - Move electrons in detector (Orthogonal Transfer CCD)
- **New Idea: do it over 1° FoV**

…and do it efficiently

System Efficiency

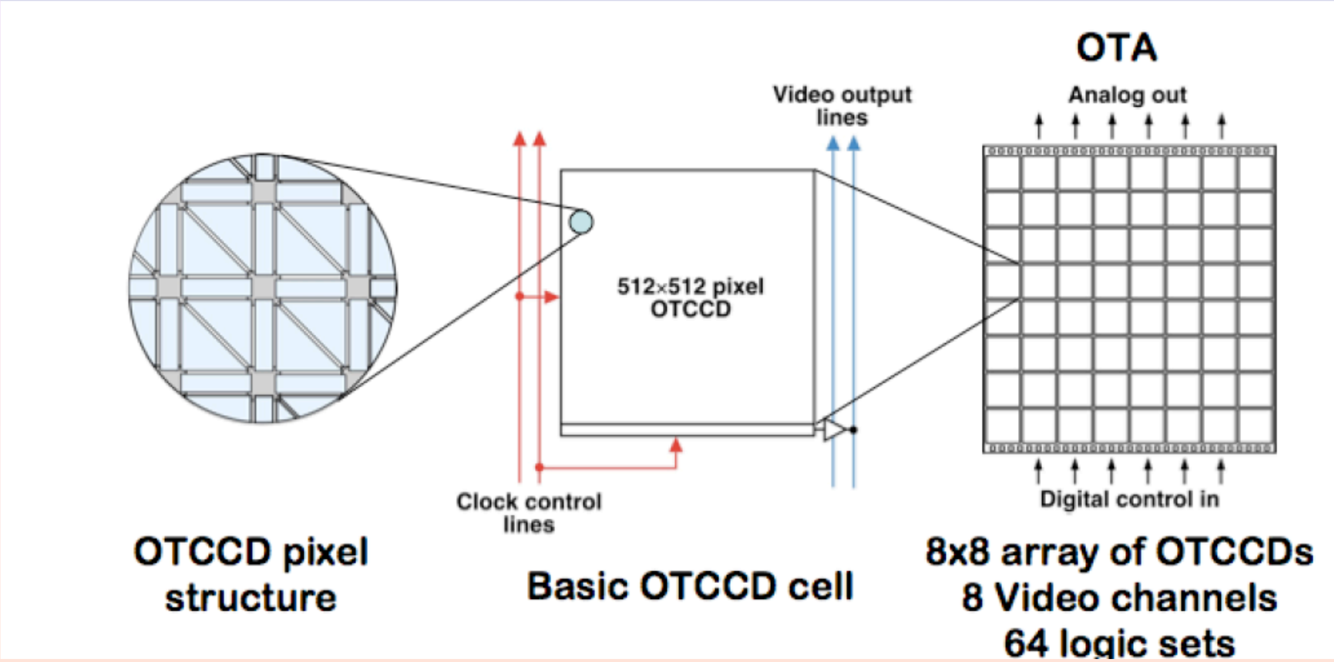
- 3x mirror reflections (Al coating)
- 8x reflection losses at optical surfaces (coatings)
- PBL6Y, Fuse Silica
- CCD sensitivity

- ODI has a good sensitivity in the blue part of the optical spectrum
- Red end expected to perform 25% better than shown.



How you do it:
Orthogonal Transfer Array (OTA) CCD

- Each CCD chip is divided into 8x8 independent CCD cells (1’x1’ per cell)
- Charge can be moved up/down AND left/right
- Assign cells containing bright stars for guide stars probing
  - image acquisition in fast video mode.
  - also allows for high-speed photometry.
- Assign other cells for science integration, charge follows image



each cell is an independent CCD ~1’ on sky

each cell can be read out in video mode

each cell is either imaging or obtaining guiding information at up to 30Hz

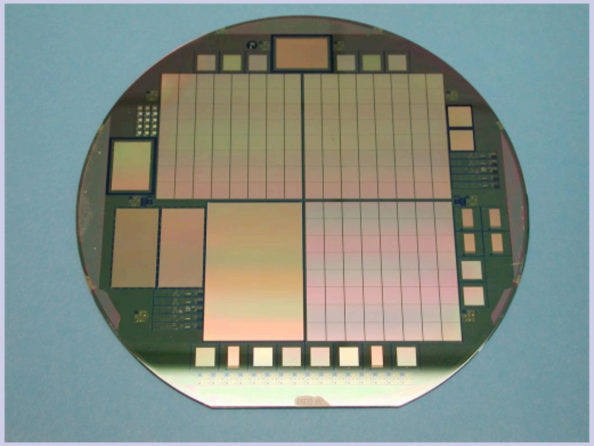
tip/tilt correction can be applied to each individual cell

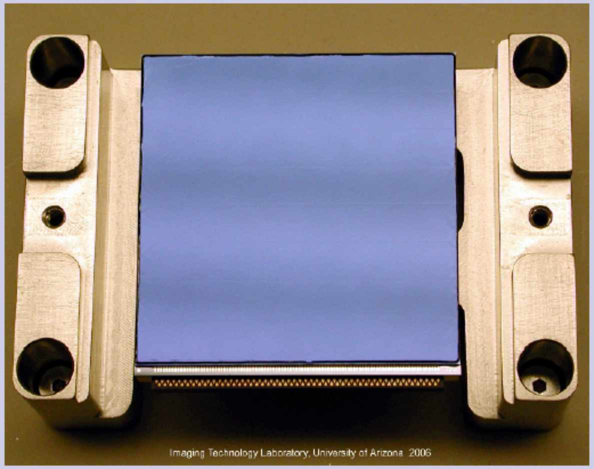
OTA Detector Development

- OT(A) concept invented by John Tonry (IfA)
- Collaborative development of OTAs w/ PanSTARRS project

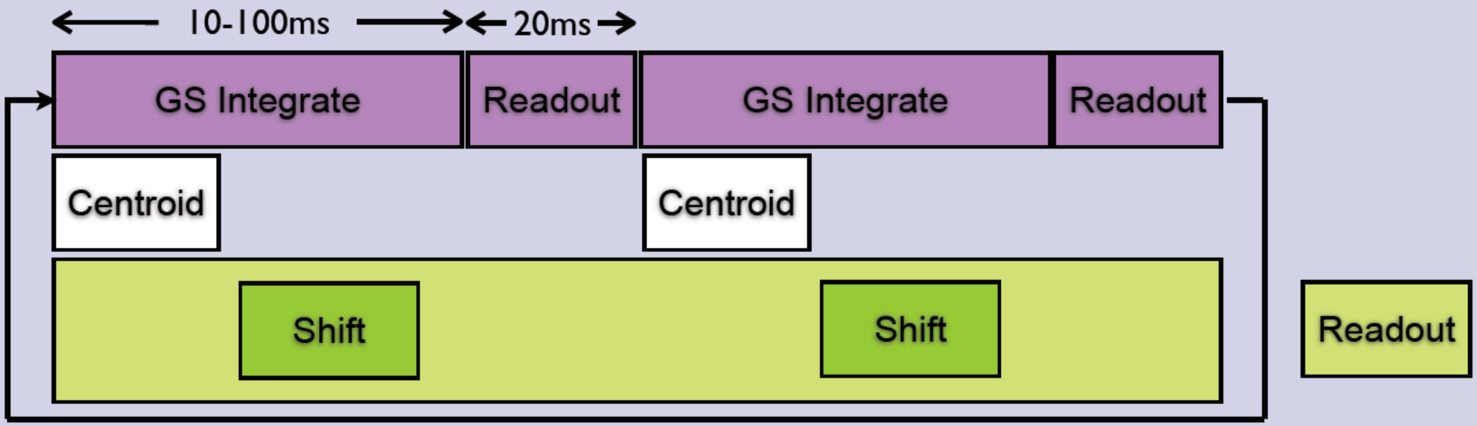
- ODI works with STA/DALSA
- First batch of final production run delivered

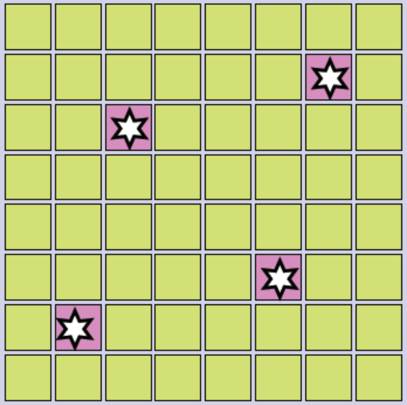
- Processing of wafers done by ITL (University of Arizona)
  - Thinning, packaging, and testing
  - Mounting detectors on SiC focal plane





OTA fast tip/tilt guiding





Weight of guide star *i* on cell *j*:

$$\delta\vec{x}_j = \frac{\sum r_{ij}{}^{-n} \cdot \delta\vec{x}_i}{\sum r_{ij}{}^{-n}}$$

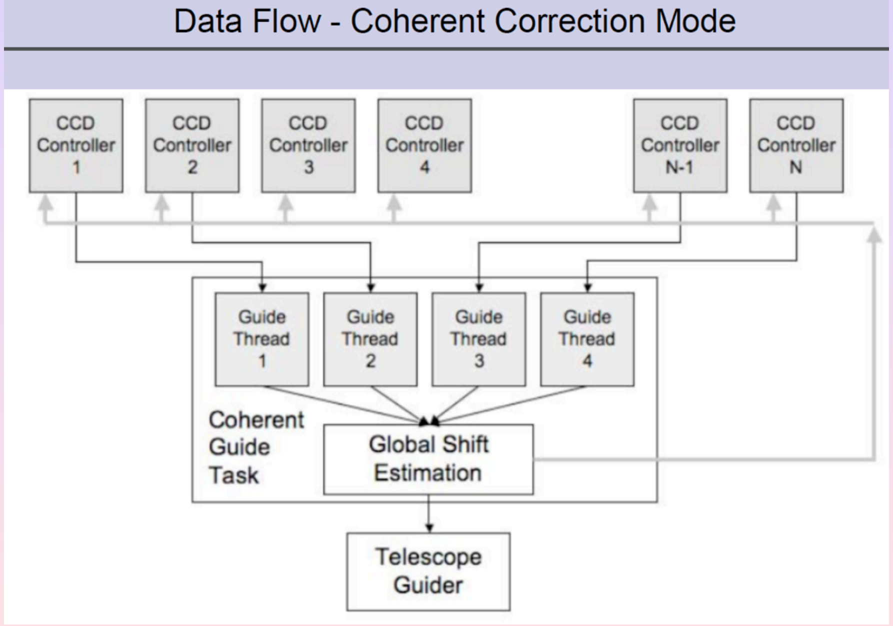
n=0 equal weight, common mode only
n=1..2 distance weighted
n=large nearest neighbour

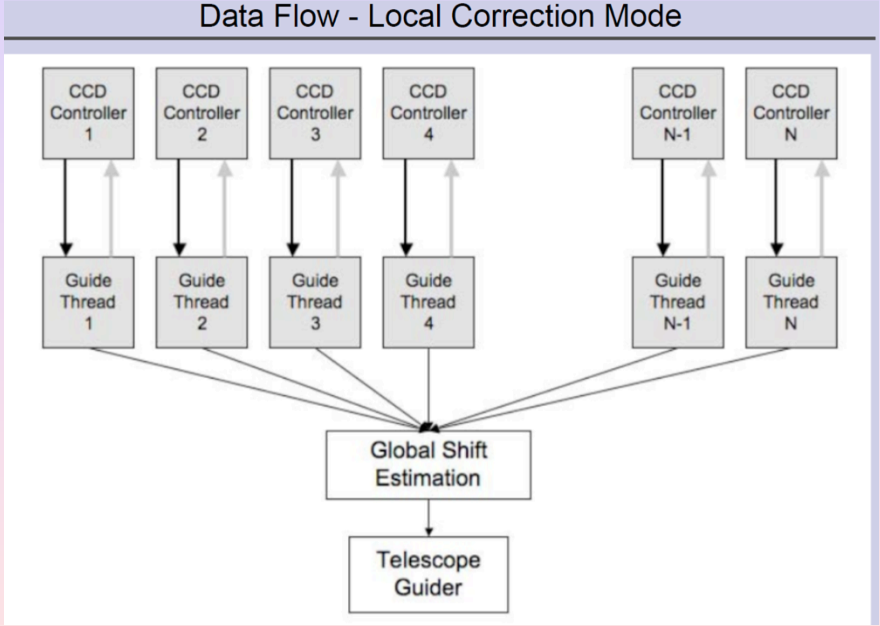
… on a 1 deg FoV

Operational Modes

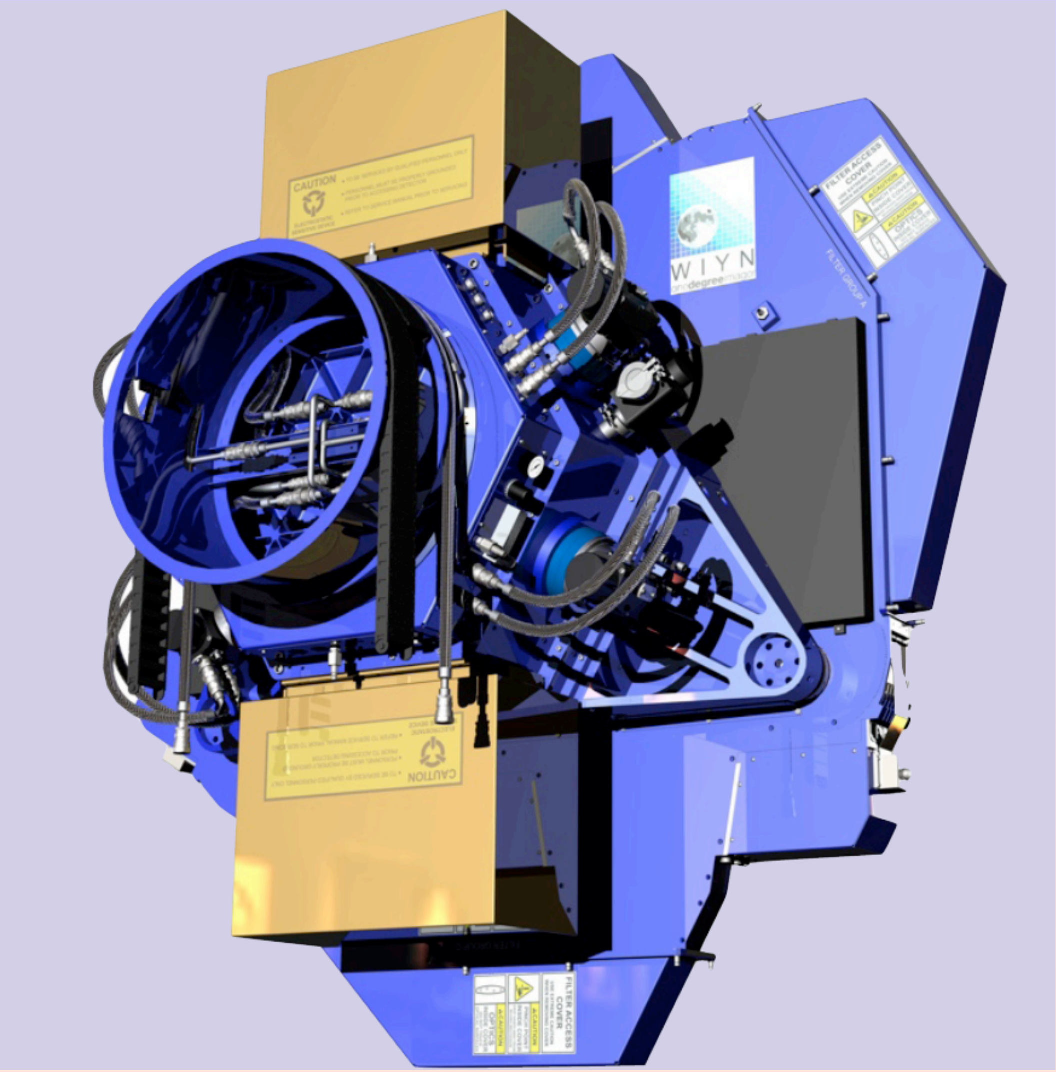
- Static Imaging
  - Use focal plane as conventional imager.
- Coherent Correction
  - Sample only a few guide stars (e.g., one in each corner).
  - Correct 1º field for common-mode image motion.
  - Removes guide error, wind shake.
- Local Correction
  - One guide star every 4 arcminutes; ~200 over 1º!!
  - Correct for atmospheric turbulence (tip/tilt only).
  - Correct in ~4'x4' cells only.
  - Not possible everywhere on sky.
- Targeted Photometry
  - Use guide star for shutterless photometry.
  - Select guide star for science goals (vs. to optimize guiding).
  - up to 512 guide stars.

Operational Modes



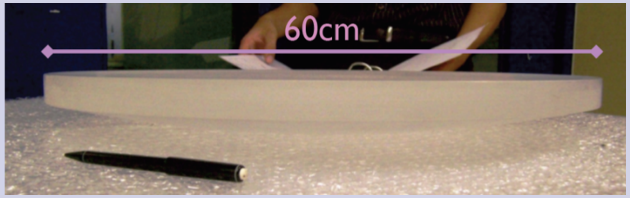


Instrument Components

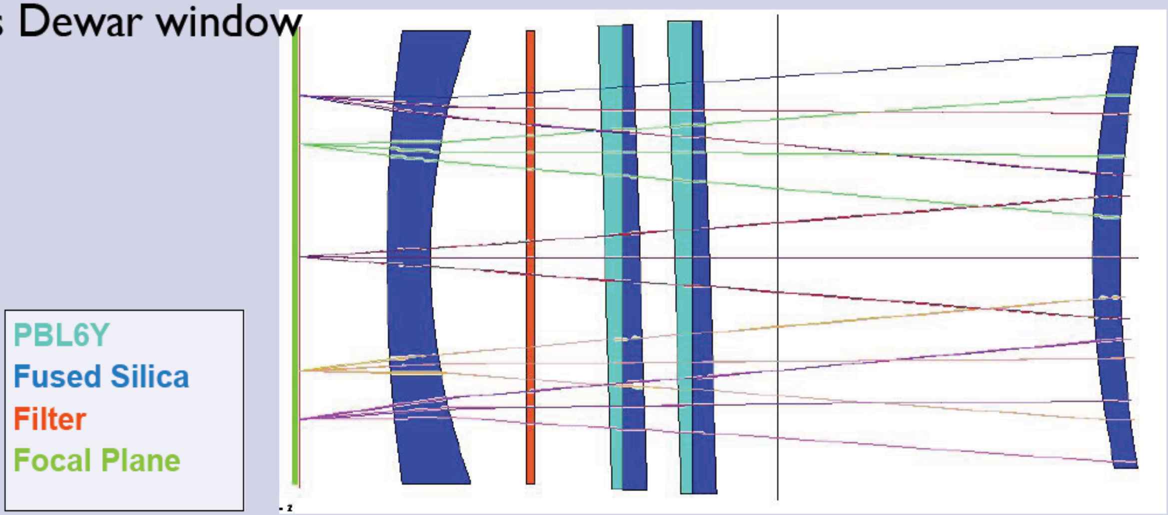


Field Corrector & ADC

- Atmospheric Dispersion Compensator (ADC)
- Telecentricity at filter location (better than 2°)
- No more than 10% image degradation at seeing of 0.25".
- less than 2% distortion over 1° FoV

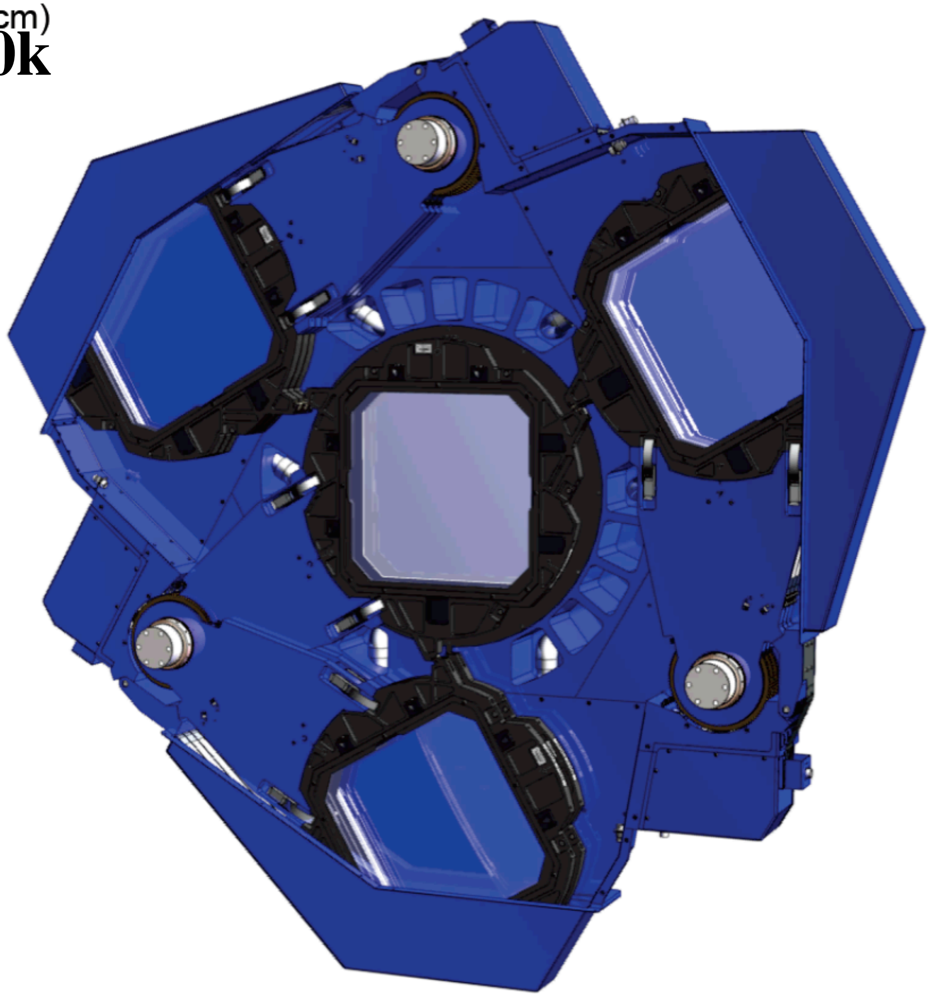


- 2-element Design
- one aspheric surface
- Lens 2 serves as Dewar window



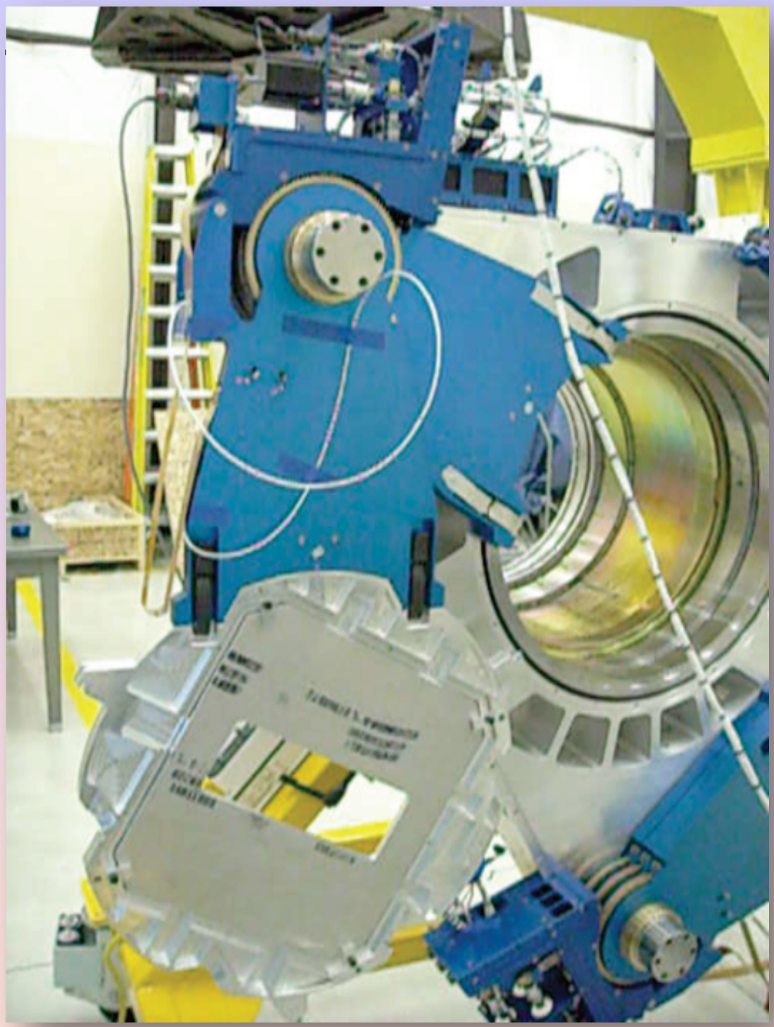
Filter mechanism

- Design challenge: filter size (42cm)
- Filter cost ($60.000 each) **$60k**
- Filter weight
- Safe handling
- Minimum of 8 live filters as requirements



NB filters are ~ $120k
ka-ching!

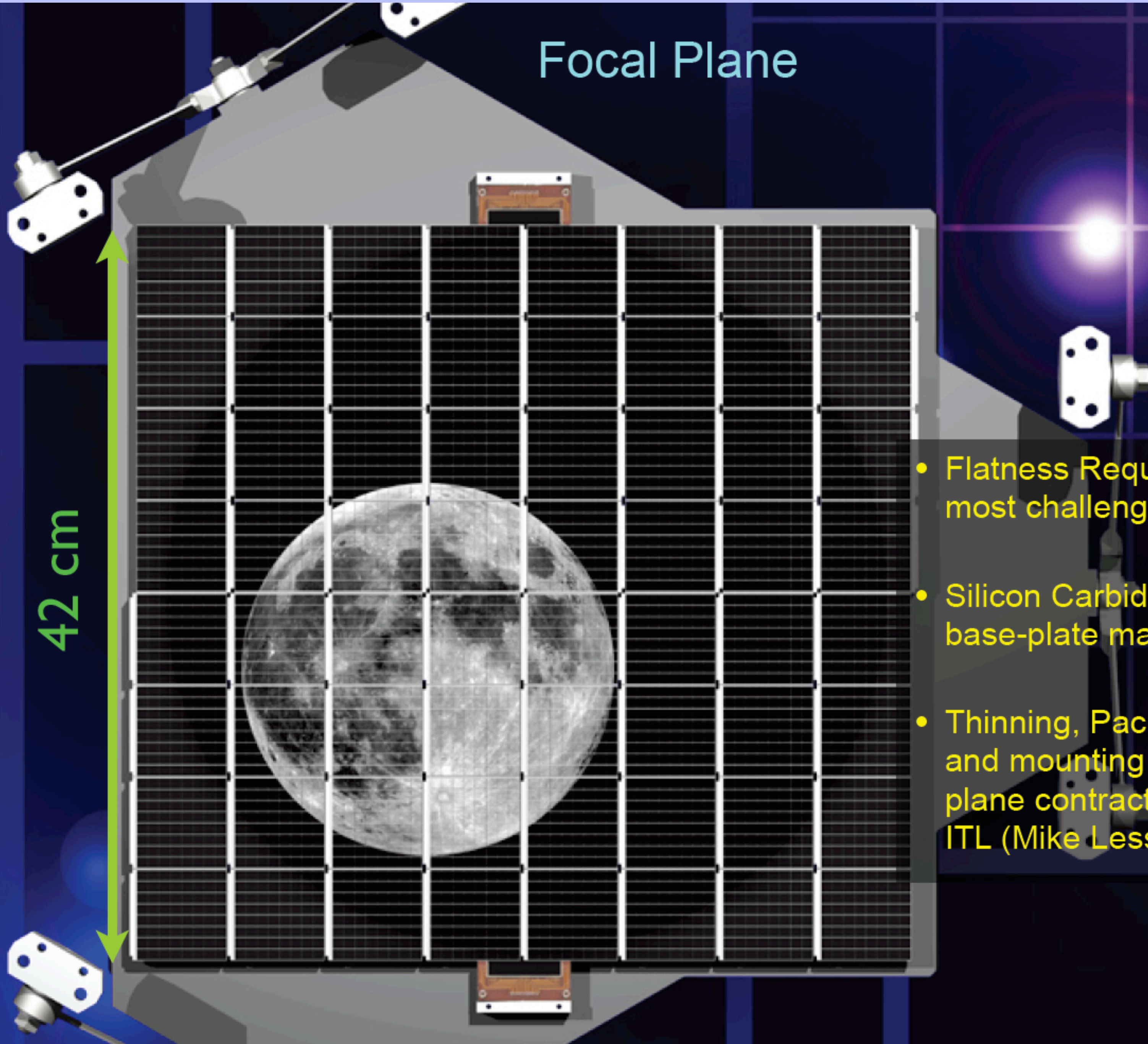
Filter mechanism



Shutter

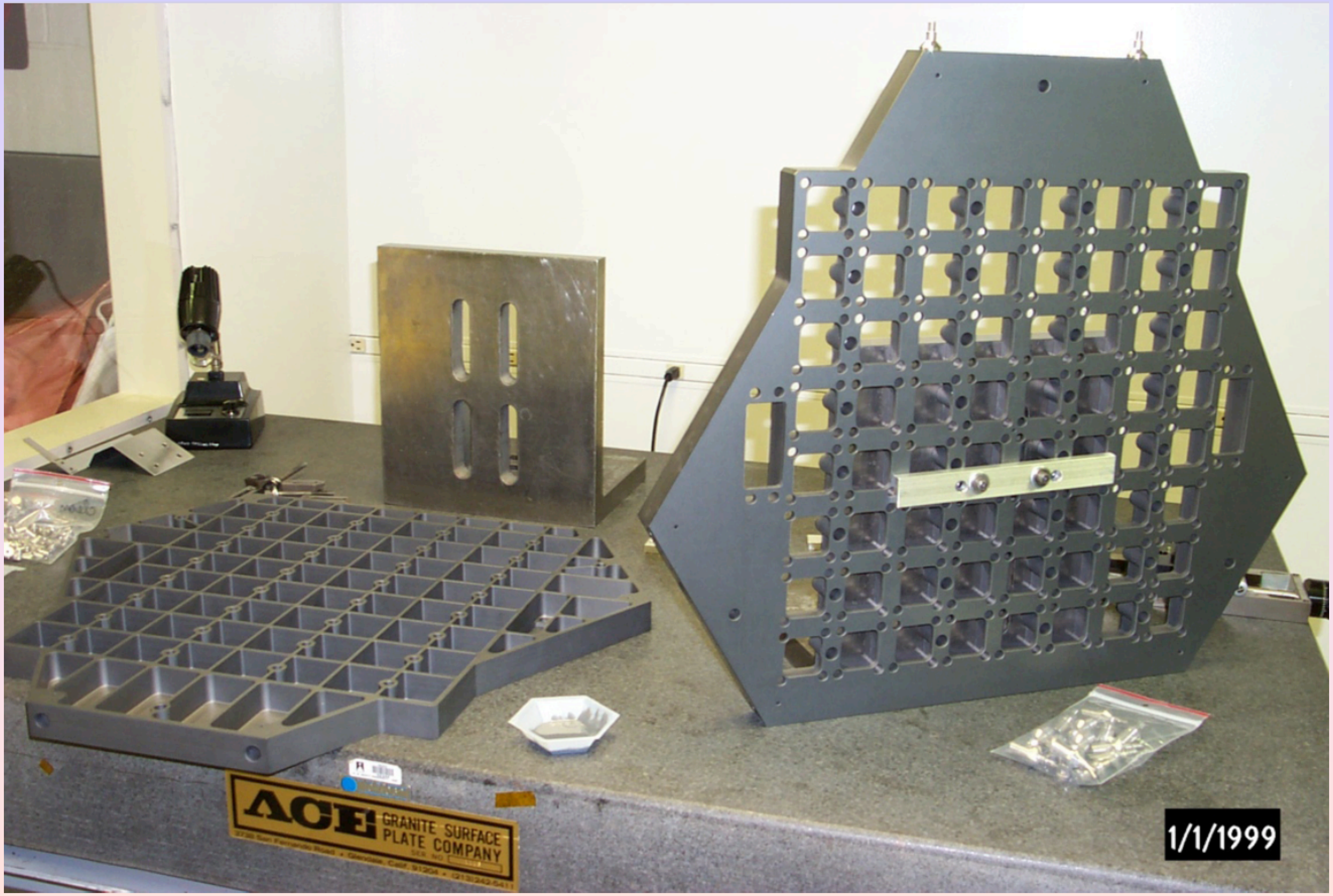
- 2-blade design for accurate timing & short exposure times
- Designed and fabricated by the University of Bonn (Germany)

Focal Plane



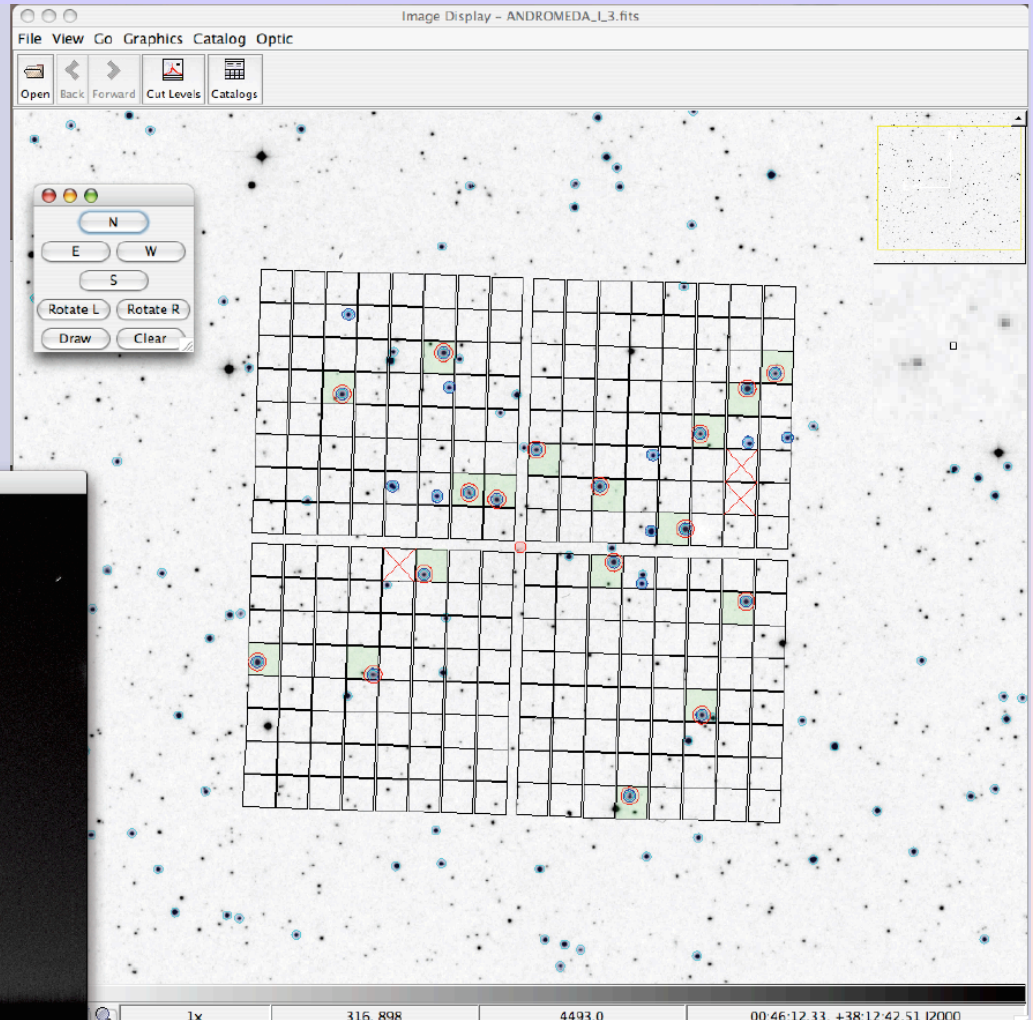
- Flatness Requirement most challenging
- Silicon Carbide as base-plate material
- Thinning, Packaging and mounting of focal plane contracted with ITL (Mike Lesser)

Detector array base plate



Support software

- Need to configure up to 250 guide stars.
- Similar to multi-object spectroscopy setup.
- Tedious task if done manually.
- Software support critical for efficient telescope use.



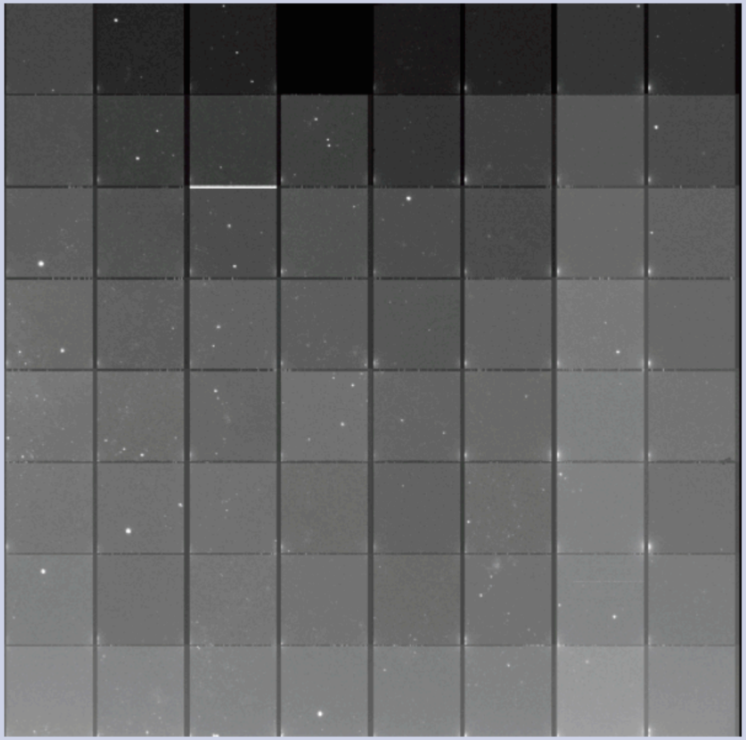
Operations concepts

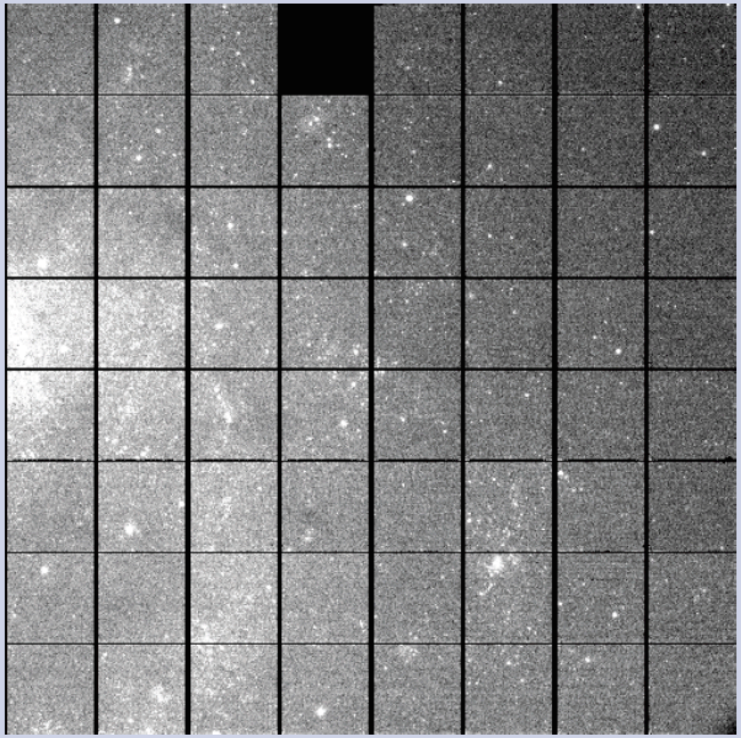
- Complex OTA modes require preparation of observations.
- ODI might be best operated in service or queue mode.
- Phase II tools should greatly help in this process.
  - Setting up guide star configurations
  - Predicting guide star flux and possible guide modes
  - Exposure time calculators, etc....
- Expect ODI to operate in Queue Mode
  - Prepare observation run at home.
  - Depending on operational model:
    - receive data from WIYN once it is observed.
    - travel to WIYN and execute your own queue.
    - ad-hoc observations possible.
  - Largely automated operations envisioned.

Not implemented
Why not?

Data processing requirements

- Raw image show strong instrument signature
  - 64 different bias levels per detector (64 detectors in ODI)
  - Enable quick look and quality assessment





QUOTA: prototype

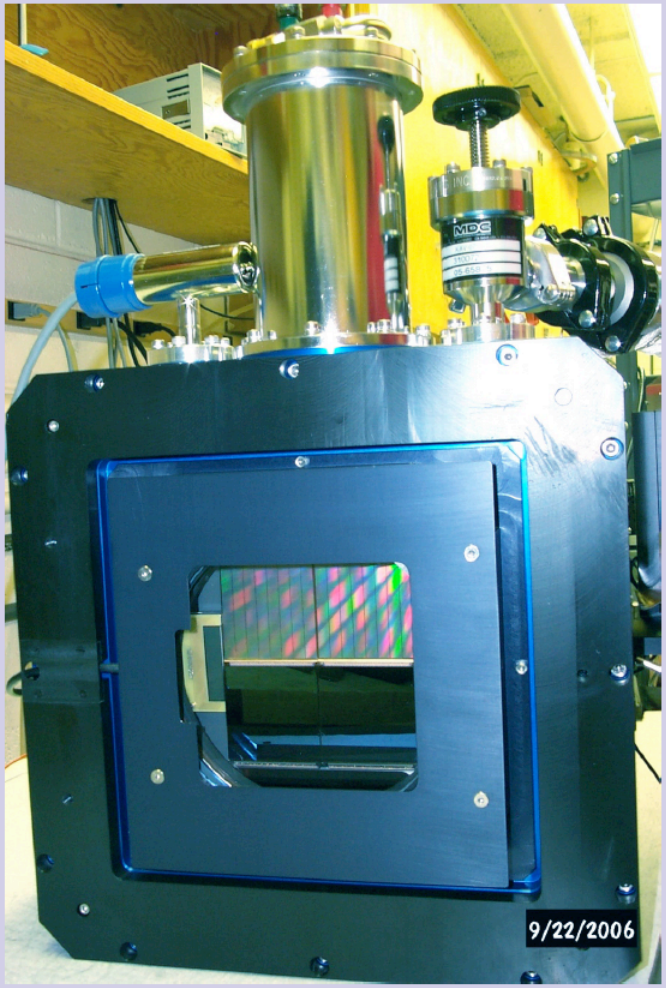
- Prototype camera to test OTA detectors
- Potentially for prototype science

- Several on-sky campaigns on sky
  - latest two weeks ago

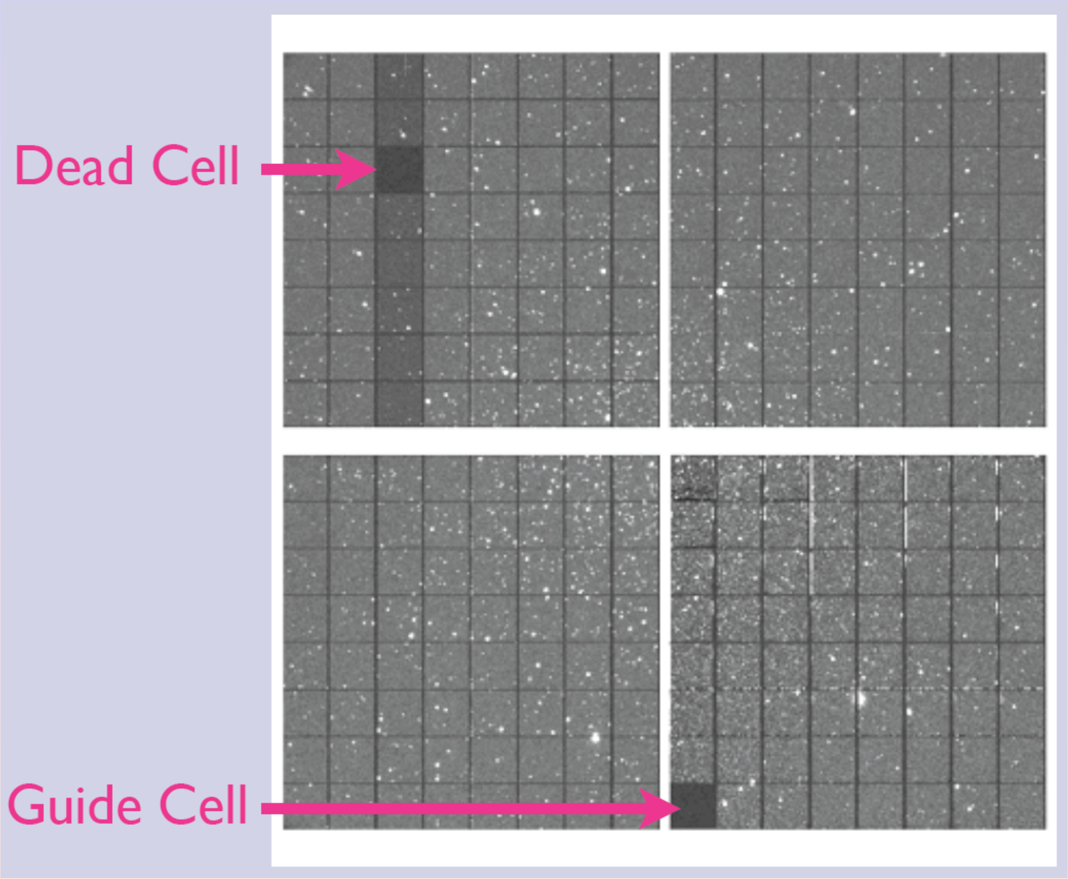
- Demonstrated so far:
  - Detector operations
  - WIYN's image quality
  - On-chip guiding

- Shown in 2006 configuration:
  - two thick, two thinned Lot 2 devices

- Current configuration:
  - four thick Lot 3 devices
  - one coated with Lumigen for blue response.



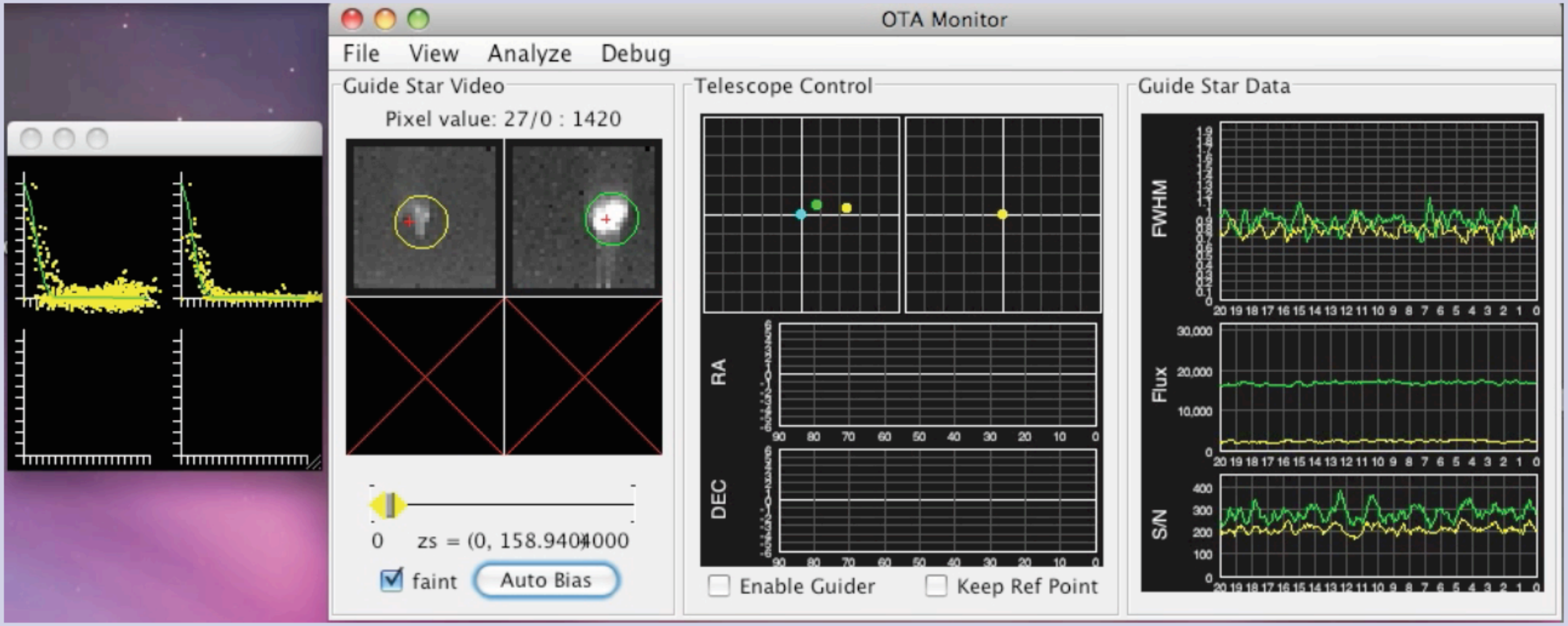
Guide Star Readout



NGC 6791
Open cluster

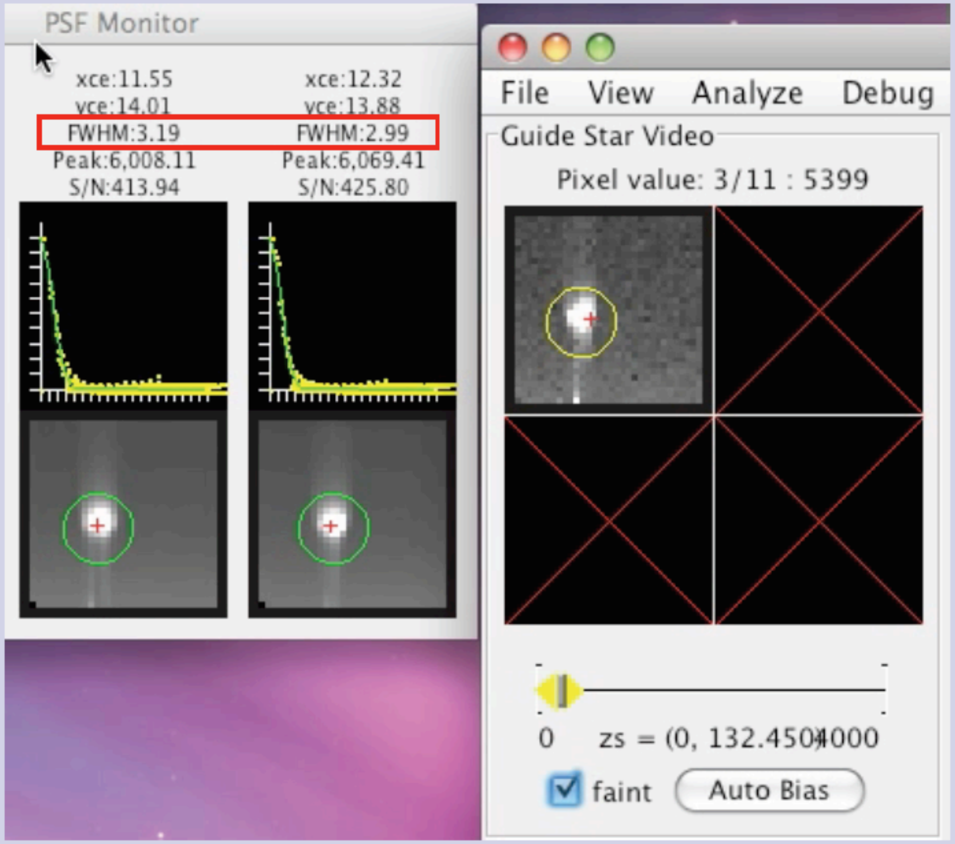
Guide Star Readout

- Aug 2008 QUOTA on-sky campaign.
- First time to operate QUOTA in full orthogonal transfer array mode.

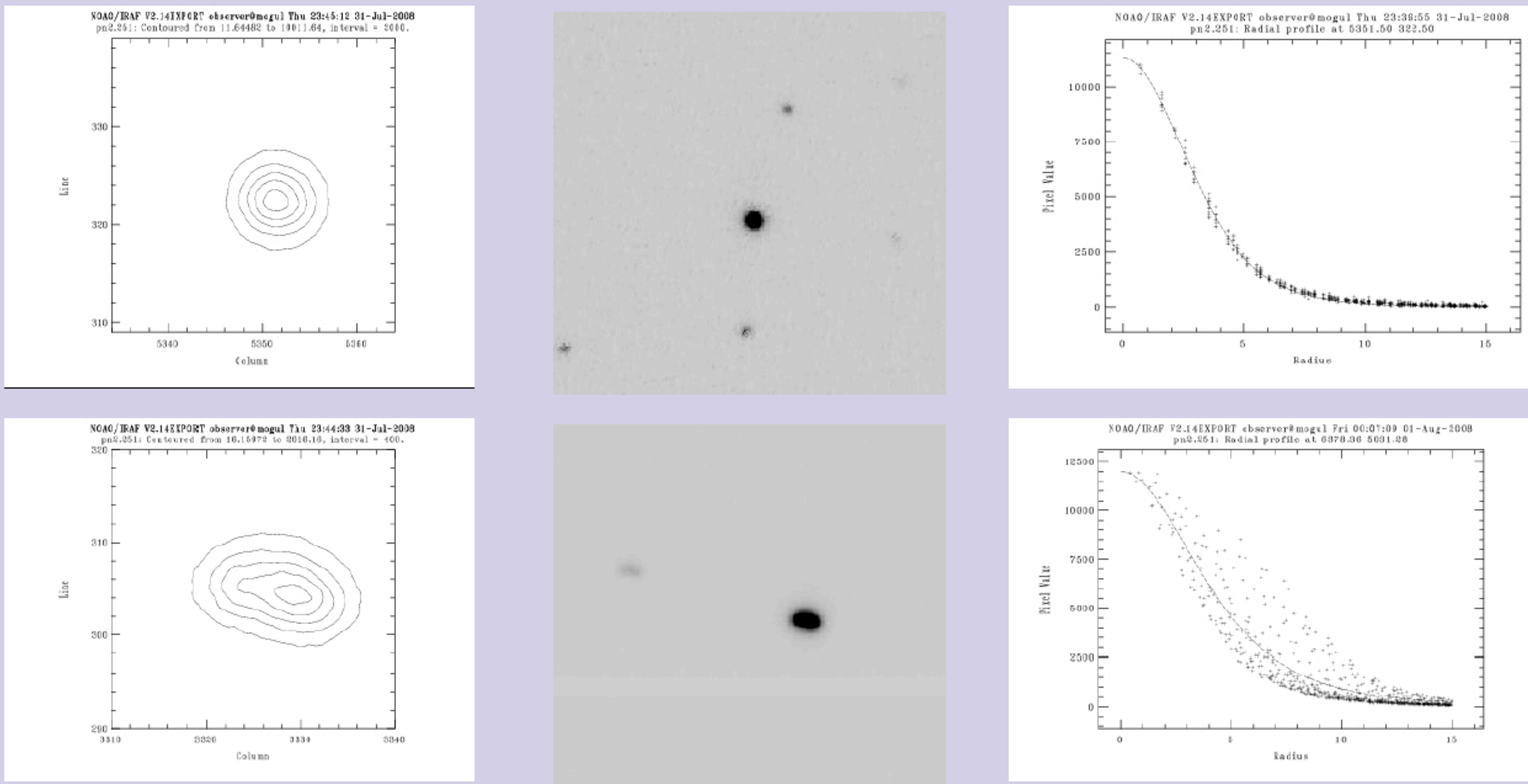


On-chip Guiding

- one guide star on one device
- telescope was not well-guided, drifting...

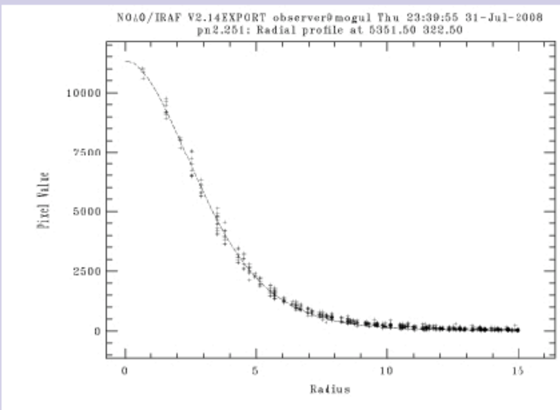


OT Image Improvement

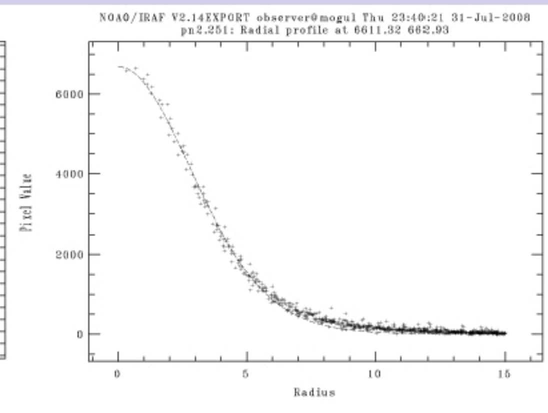


Guided Region - Top
Unguided Region - Bottom

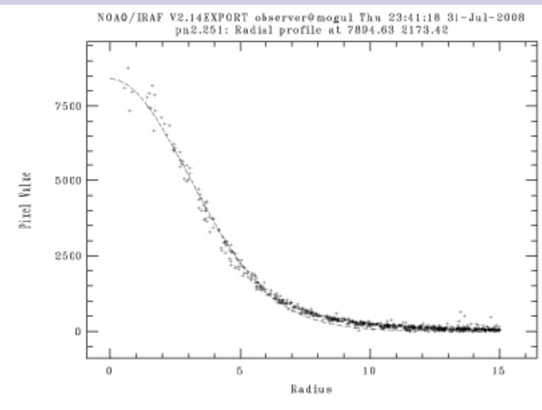
FWHM vs field distance



Distance: 2’
FWHM: 0.66”



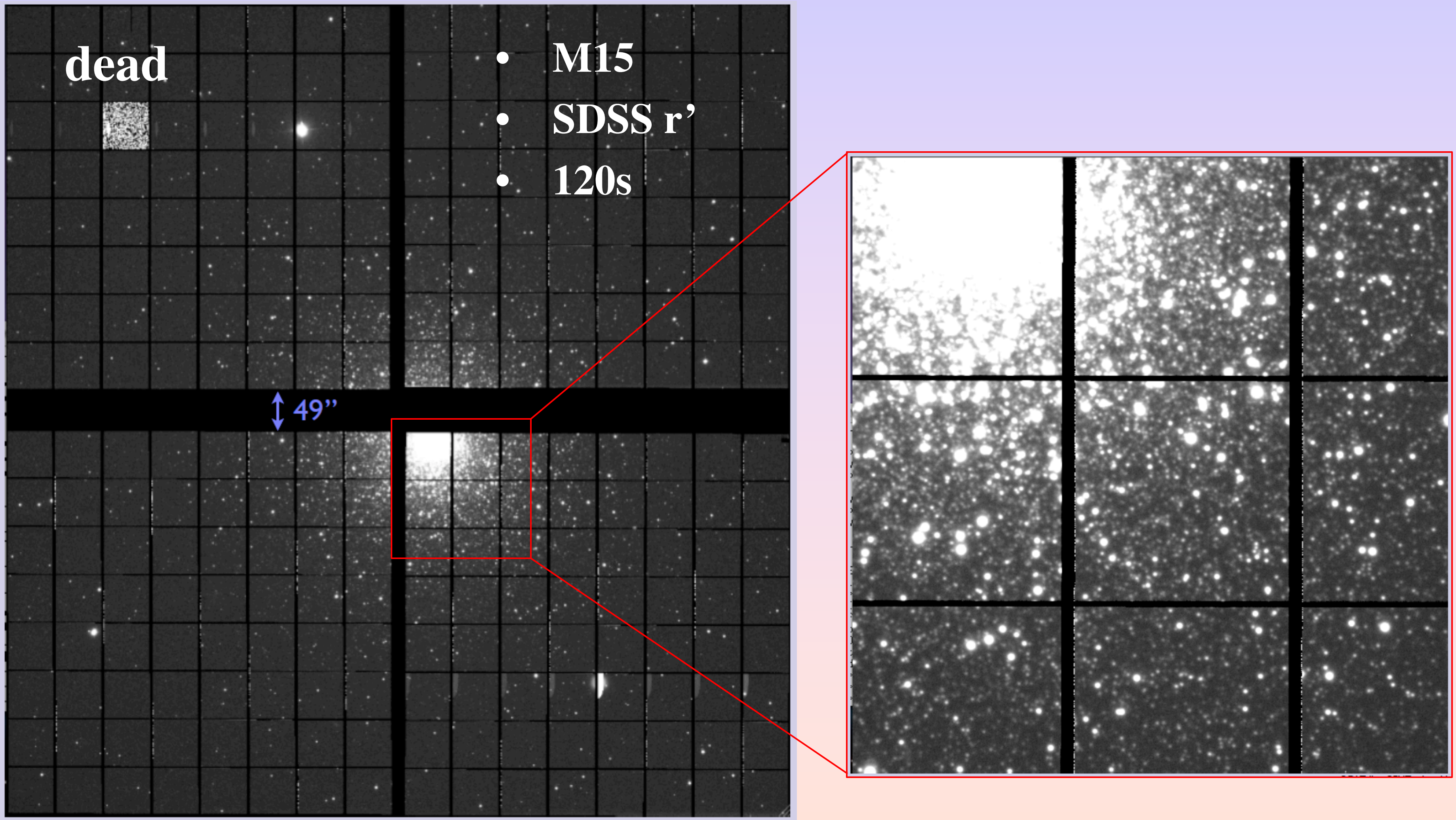
Distance: 4’
FWHM: 0.72”



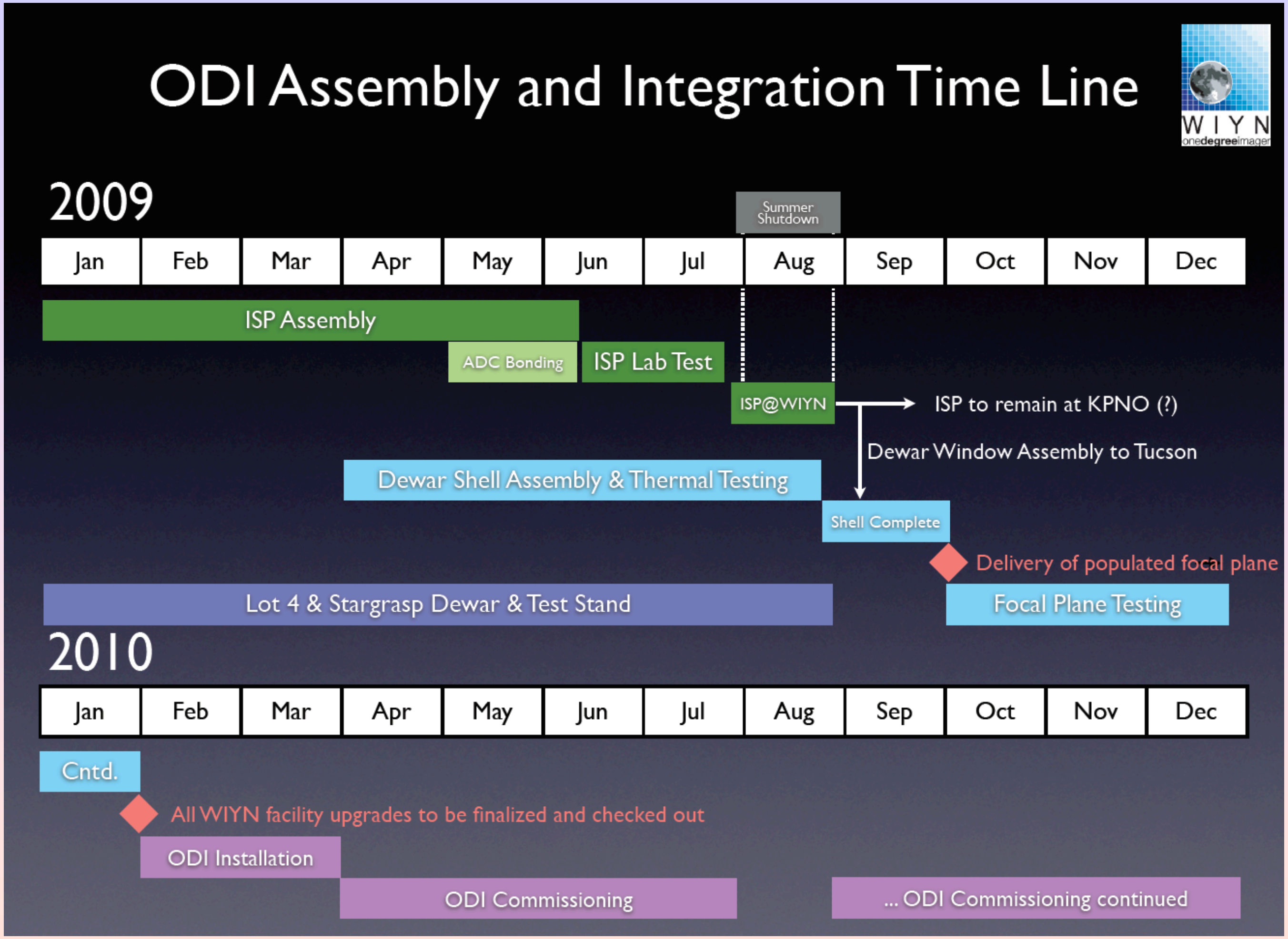
Distance: 8’
FWHM: 0.78”

Distance from guide-star

QUOTA OTA Imaging



The promise


ODI Assembly and Integration Time Line
WIYN
onedegreeimager
2009
Summer Shutdown
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
ISP Assembly
ADC Bonding
ISP Lab Test
ISP@WIYN
ISP to remain at KPNO (?)
Dewar Window Assembly to Tucson
Dewar Shell Assembly & Thermal Testing
Shell Complete
Delivery of populated focal plane
Lot 4 & Stargrasp Dewar & Test Stand
Focal Plane Testing
2010
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Cntd.
All WIYN facility upgrades to be finalized and checked out
ODI Installation
ODI Commissioning
... ODI Commissioning continued

The promise

ODI's place in the Astronomical Landscape

- ODI will be the best wide-field imager in these areas:

- Best images – median seeing ~0.54", corrected R-band
  - best sampling – 0.11"/pixel
  - OT correction (atmospheric tip/tilt, shake, guide errors)

- Time resolution
  - Fast readout of entire array (<10sec)
  - Very fast readout of regions of interest (20-50 Hz)
  - always mounted at the telescope

- Excellent blue response - unique feature

- Narrow-band filters – slowest f/ratio

- Access – no other wide-field imager is generally available to the US community.
  - Complementary to Dark Energy Survey Camera in the South

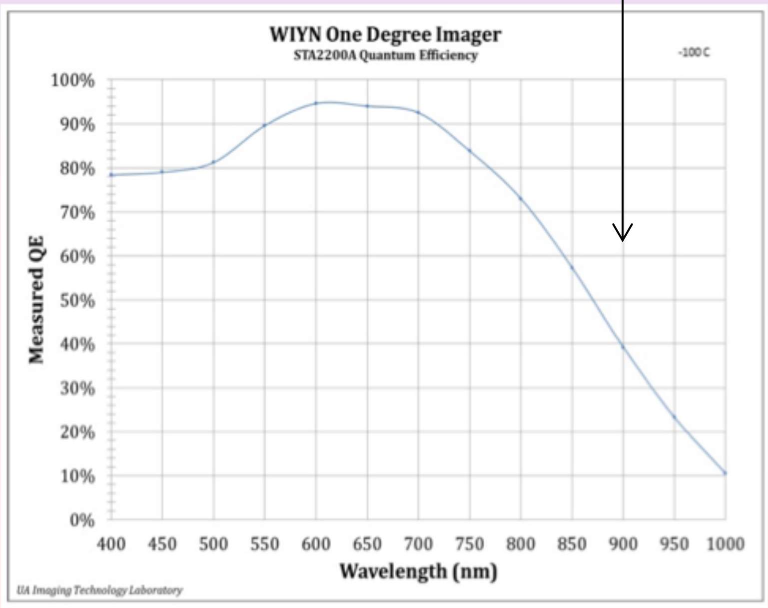
- Twice the information rate of any other *current* imager
  - but will be dwarfed by LSST, Subaru's Hyper-SuprimeCam

The reality

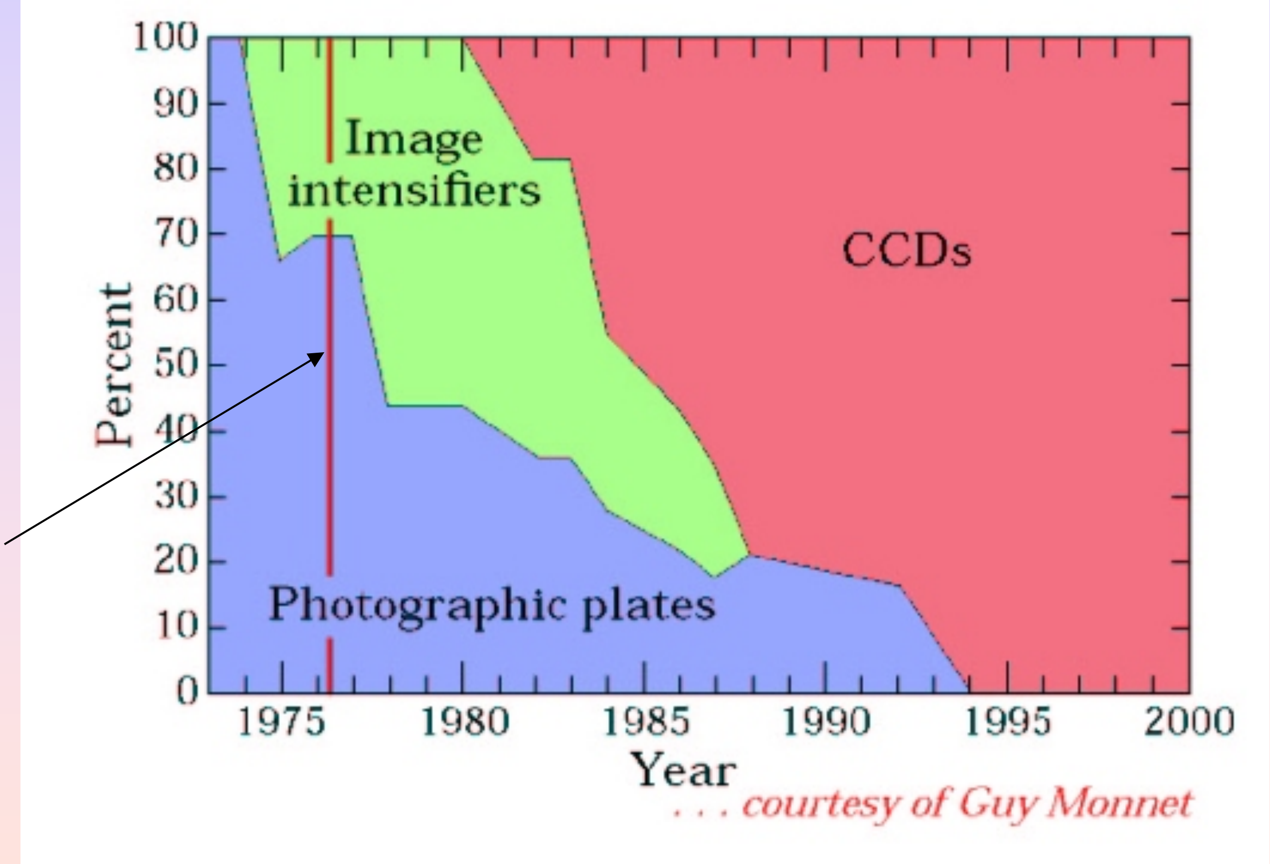
http://www.wiyn.org/ODI/index.html

- 40x48 arcmin (0.53 deg^2) - **hODI**
- 30 OTA, each with 64 x 480x496 pix
- 7-11 e- rms read-noise
- u'g'r'I'z' and NB695 filters
- **Static Imaging - no OT shifting; detectors are operated like CCDs because of amplifier glow**

Where
TT is best
oops

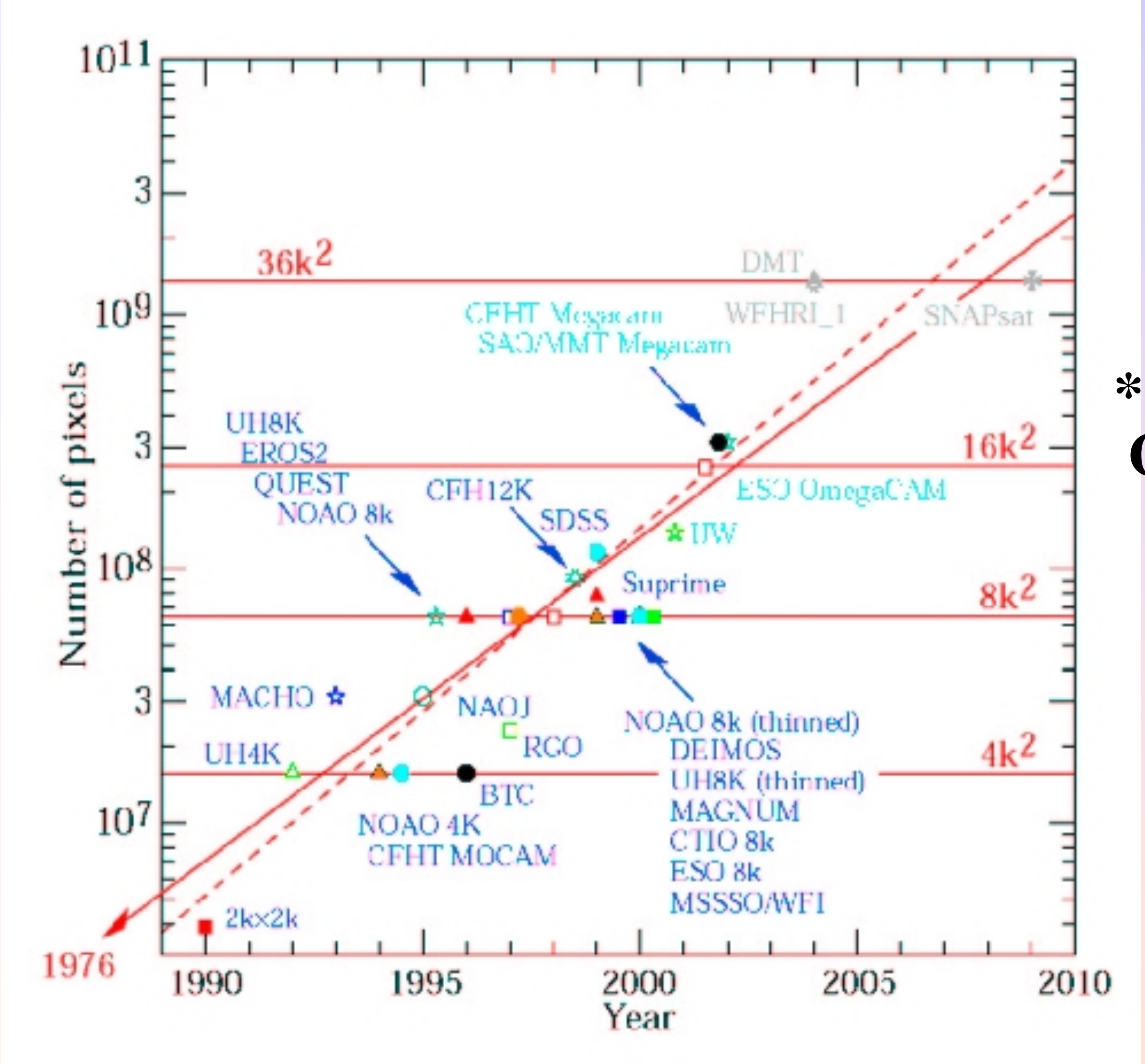


Detectors (ESO transition to CCDs)



First astronomical CCD, JPL 400x400

Pixels/Camera



*
ODI