From the Heart of
Red Sox Nation

And the University
Overlooking
Fenway Park…

Mimir *– The Facility-Class Near-Infrared Imager, Spectrometer, and Polarimeter for the Perkins Telescope*

Dan Clemens

Institute for Astrophysical Research

Boston University

Outline

- **Mimir**
  - –What it is (“NIR Swiss Army Knife”)
  - –Design and fabrication of Mimir
    - BU + Lowell Observatory joint development
  - –Lots ‘o pics
  - –Completion this past summer
  - –August saw delivery to 1.8m Perkins Telescope, outside Flagstaff, AZ
    - BU is 50:50 partner with Lowell Observatory in use of Perkins
  - –First light and second light images, capabilities

Readers Digest Version of Mimir Part of Talk

We took Mimir to the Perkins telescope outside Flagstaff, AZ

We tested Mimir in our BU Lab

We put Mimir on the telescope

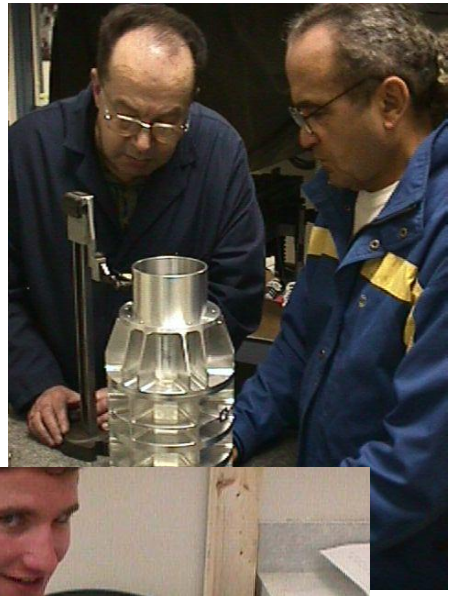
We took images, spectra, and polarimetry with Mimir and the Perkins Telescope this August

We designed & built Mimir parts at BU

We put the parts together to form Mimir

Mimir Team Members

- Boston University (Cryostat, Optics, Mechanisms, Electronics)
  - –Dan Clemens (NSF, Keck PI)
  - –Eric Tollestrup (Project Scientist), now at IRTF
  - –Domenic Sarcia (Senior Mechanical Engineer)
  - –Alex Grabau (Senior Laboratory Technician)
  - –BU Machine Shop (Bob Fazio, Bob Kingsland, Bob Snee, Heitor Murato, Buddy Boudreau, Sam Ma, Leo Dumais, Mike McKenna)
  - –Amanda Bosh (Operations @ Lowell)
- Lowell Observatory (Detector Operation)
  - –Marc Buie (NASA PI)
  - –Ted Dunham
  - –Brian Taylor
  - –John Spencer



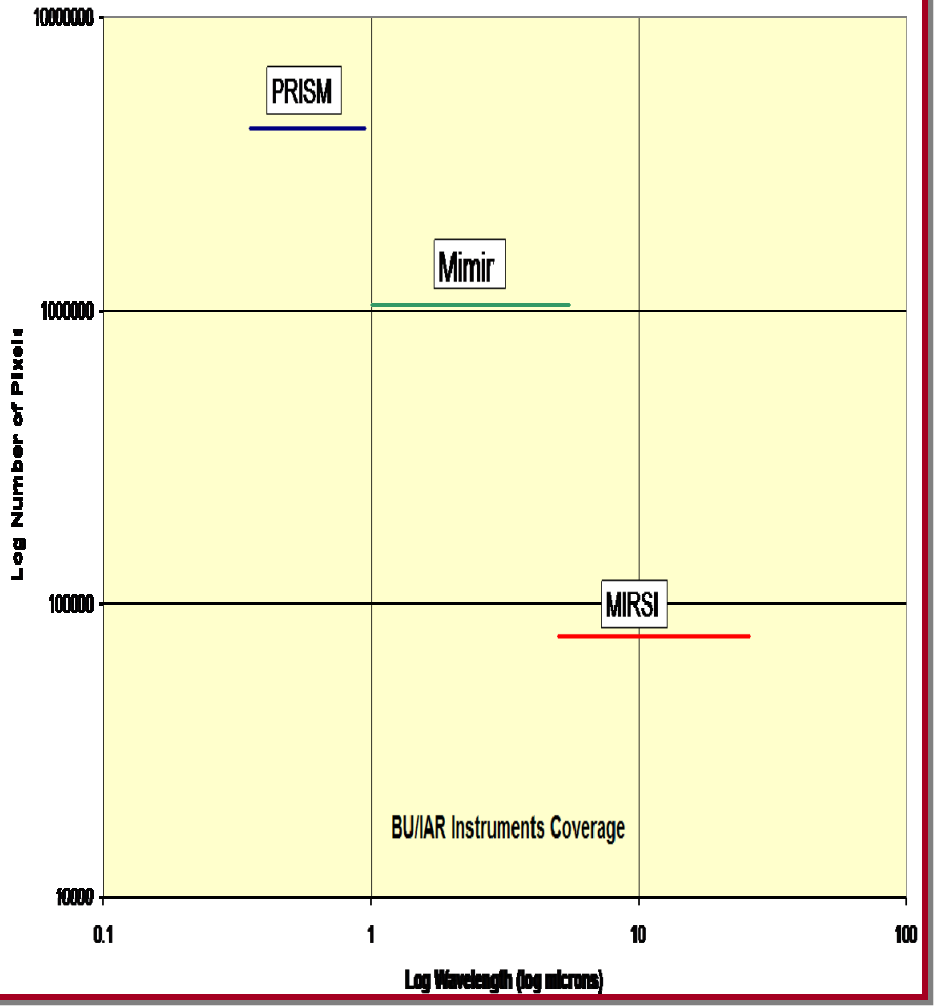
Highly-Leveraged Mimir Funding

- External Support
  - –NASA (to Lowell, subcontract to BU) – Major Planetary Instrumentation Program ($566k)
    - Spectroscopy Mode of Mimir
  - –NSF (to BU) – Advanced Technologies and Instrumentation (ATI) Program ($308k+$30k+$65k+$5k = $408k)
    - Imaging Mode of Mimir
  - –W.M. Keck Foundation (to BU) - $500k
    - Wide Field and Polarimetry Modes of Mimir (including array detector)
- Internal Support
  - –Boston University
    - Sabbatical Support
    - IAR – salary gaps, some small parts, some travel
  - –Lowell Observatory
    - Salary Support
    - Operations Readiness
    - Small parts

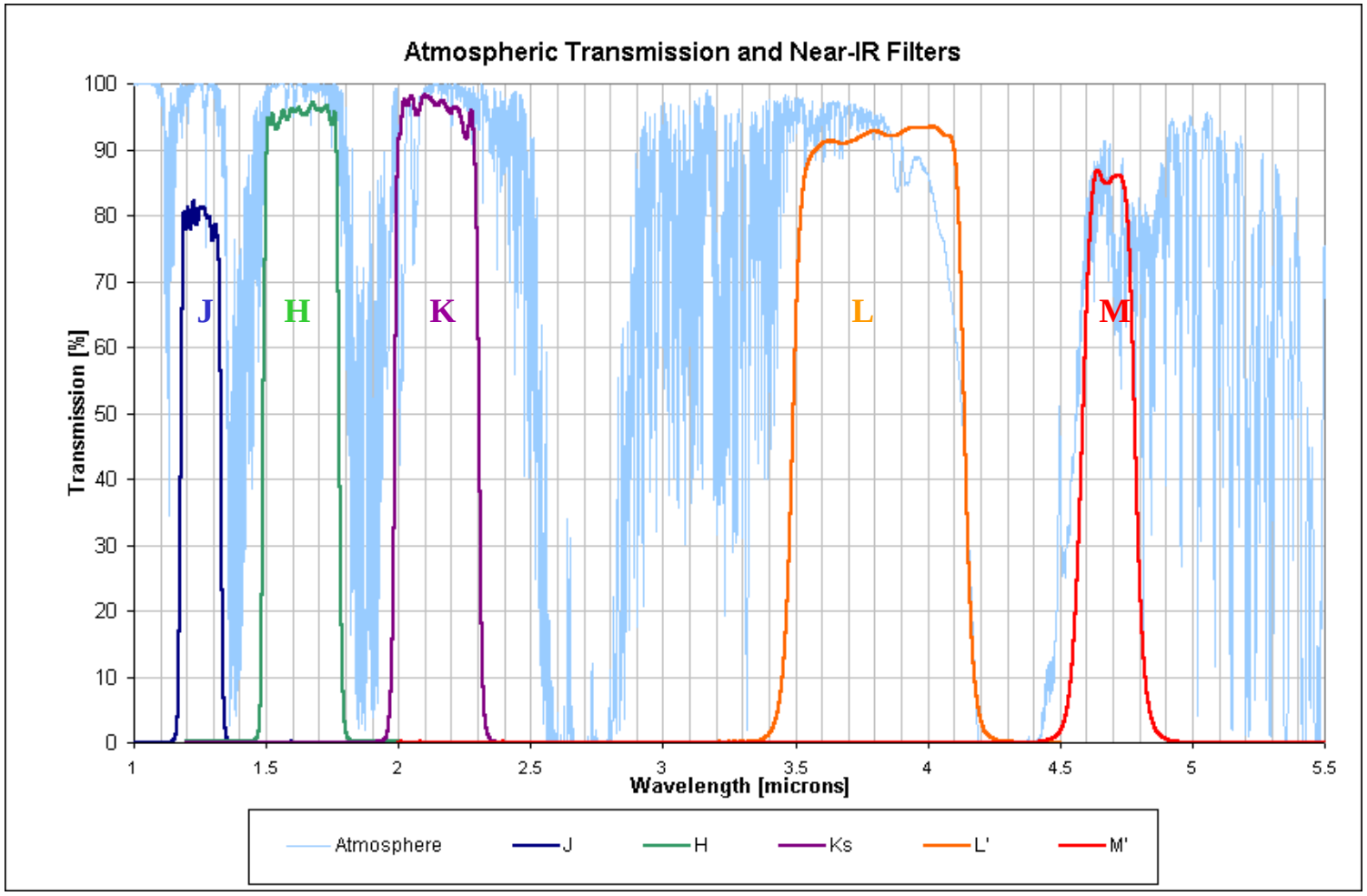
Term Glossary

- **Near-Infrared** – wavelengths of light from the red end of the optical band (about 9000 Angstroms, or 900 nm, or 0.9 microns, or 0.9 μm) extending to the longer wavelengths normally considered "thermal infrared" where terrestrial bodies and the atmosphere glow brightest (roughly 5-30 microns). (aka between PRISM and MIRSI wavelengths)

- **J, H, K, L, M** – "bands" in the near-infrared that more or less match atmospheric transmission wavelength windows.
  - The optical window spans 0.34 – 0.9 microns and is sampled by broad-band filters called U, B, V, R, I.
  - The near-IR bands are similar, but not overlapping.
  - Mean wavelengths are:
    - **J** 1.25 μm, **H** 1.65 μm, **K** 2.1 μm, **L** 3.6 μm, and **M** 4.7μm.
  - Mimir uses multilayer interference filters to define these standard bandpasses, though updated for the Ks (K-short), L', and M' bands which better match the atmospheric windows.



Atmosphere + Near-IR Filters

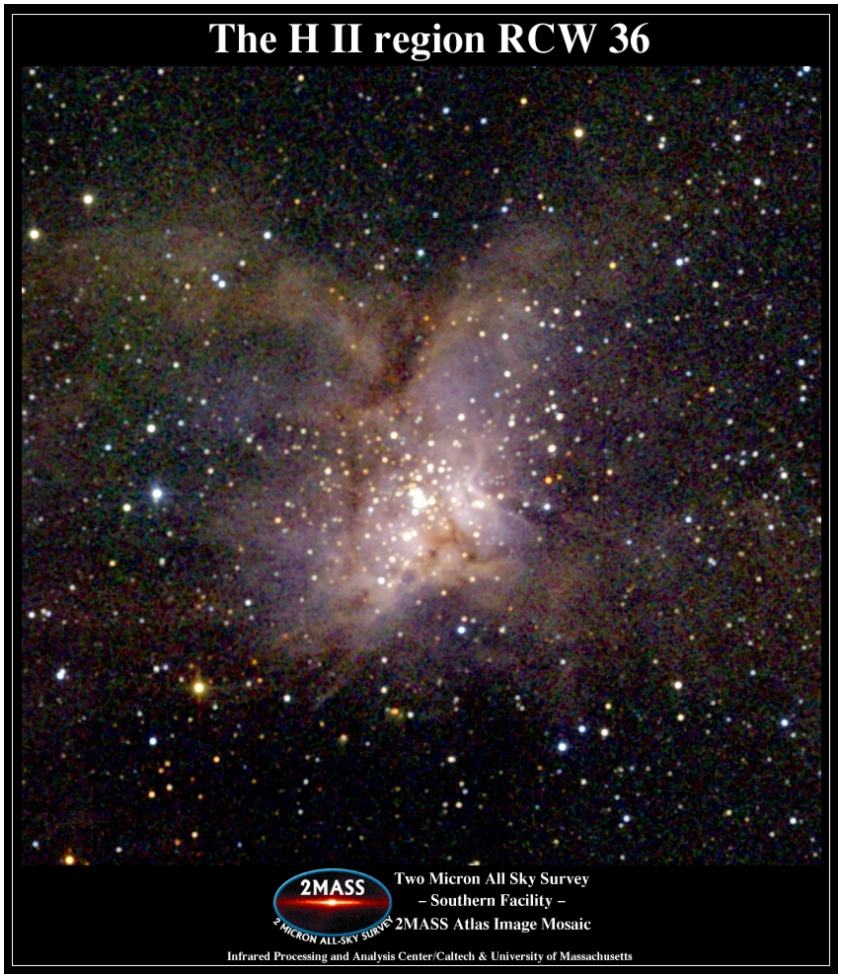


Science Drivers for Mimir: Galactic Science & Star Formation Studies

Galactic Science

- Multiplicity in Star-Forming Regions, Embedded Stellar, and Pre-stellar Clusters
- Luminosity Functions
- Initial Mass Functions
- All Used to Test Models of Star Formation and Galactic Structure

Star Formation Studies (continued)



Drivers for *Mimir*

- *Longer Wavelength (L&M) to penetrate dust better*
  - *–2MASS was J, H, K only*
  - *–More distant sources for Mimir*
  - *–More deeply embedded sources for Mimir*
- *Narrow-band Imaging over Wide Fields (none such for 2MASS)*
  - *–H_2 – traces shocked or fluorescent material*
  - *–PAH – small dust grains trace photodissociation regions*
  - *–Water Ice – composition of dust grains and mantles*

Mimir Science, Con't

- **Spectroscopy**
  - –Probe HII and YSO enviroments
  - –Measure Extinctions
  - –Spectral Typing of Embedded or Extincted Objects
- **Polarization**
  - –Unique probe of magnetic fields and reflection nebulae
- **Planetary Science** – Lowell Observatory
  - –Pluto spectrum – evolution of seasons
  - –Thermal IR fluxes, spectra of NEOs
  - –Io vulcanism
- **X-Gal**
  - –Galaxy Clusters in X-ray and NIR (E. Blanton)
  - –Galaxy Rotation Directions (T. Brainerd)
  - –Blazar polarization monitoring (A. Marscher, S. Jorstad)

Mimir Instrument

- **Optics** – refractive optics design (yes, with LENSES! – 21 of 'em)
  - –Collimator – reimages focal plane to clean, masked, cold pupil
  - –Camera(s) – images pupil onto 1024x1024 InSb infrared array detector
  - –Filters, Grisms, HWPs, Wire Grids, located near pupil (between collimator and camera(s)
- **Mechanics** – support optics, esp when cold
  - –Lenses need to be positioned to about 0.002"
  - –Lenses to operate at 65-70K – will come into alignment only when cold!
  - –Stop stray light and parasitic radiation (enclosed optical train, baffles)
- **Mechanisms** – filter wheels, camera selector, slit system
  - –All moving units driven by stepper motors operating in cold, vacuum
  - –All moving unit positions sensed and reported back to computer
- **Thermal** – Optics to 70K, Detector to 30K
  - –Closed-Cycle Helium Refrigerator with two cold stations (50K, 10K).
  - –Long, stable, robust operation

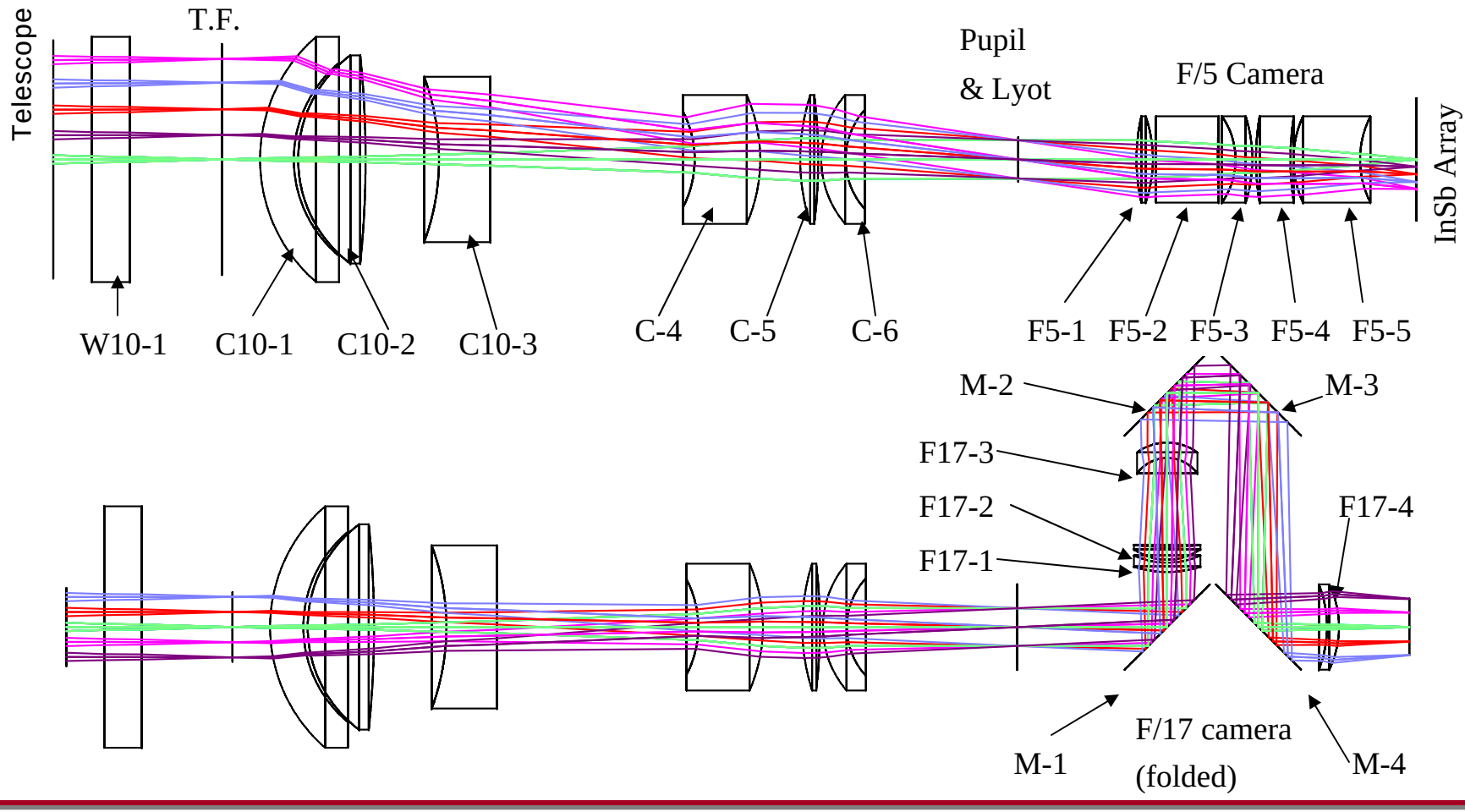
Mimir Operating Modes

- **Wide field Imaging**
  - 10x10 arcmin Field of View at 0.6 arcsec per pixel
  - 1024x1024 InSb ALADDIN III detector array – largest available
  - 0.9 – 5.5um wavelength
    - Using newly optimized J, H, Ks, L', M' filter designs of Tokunaga
    - H2 S(1) on, off and other narrow-band filters (3.4um, etc)
- **Single-Grism Spectroscopy**
  - 1024 pixel detector permits no folding of spectrum and higher throughput
  - Better Signal to Noise vs time than cross-dispersed
  - 3 Grisms: R ($\lambda/\delta\lambda$) = 725 for **JHK**; R = 400 for **LM**; R = 100-200 **SED**
- **Wide field Polarimetry**
  - 10x10 arcmin FOV – ***unique capability***
  - Low instrumental polarization, low background from cold elements
  - H-band initially – room for 5 rotating half-wave plates
- Expandability
  - many unassigned filter, grism, polarization positions in the four wheels (3x10 + 1x6 positions = lots of new combinations!)

Mimir Operating Modes (con't)

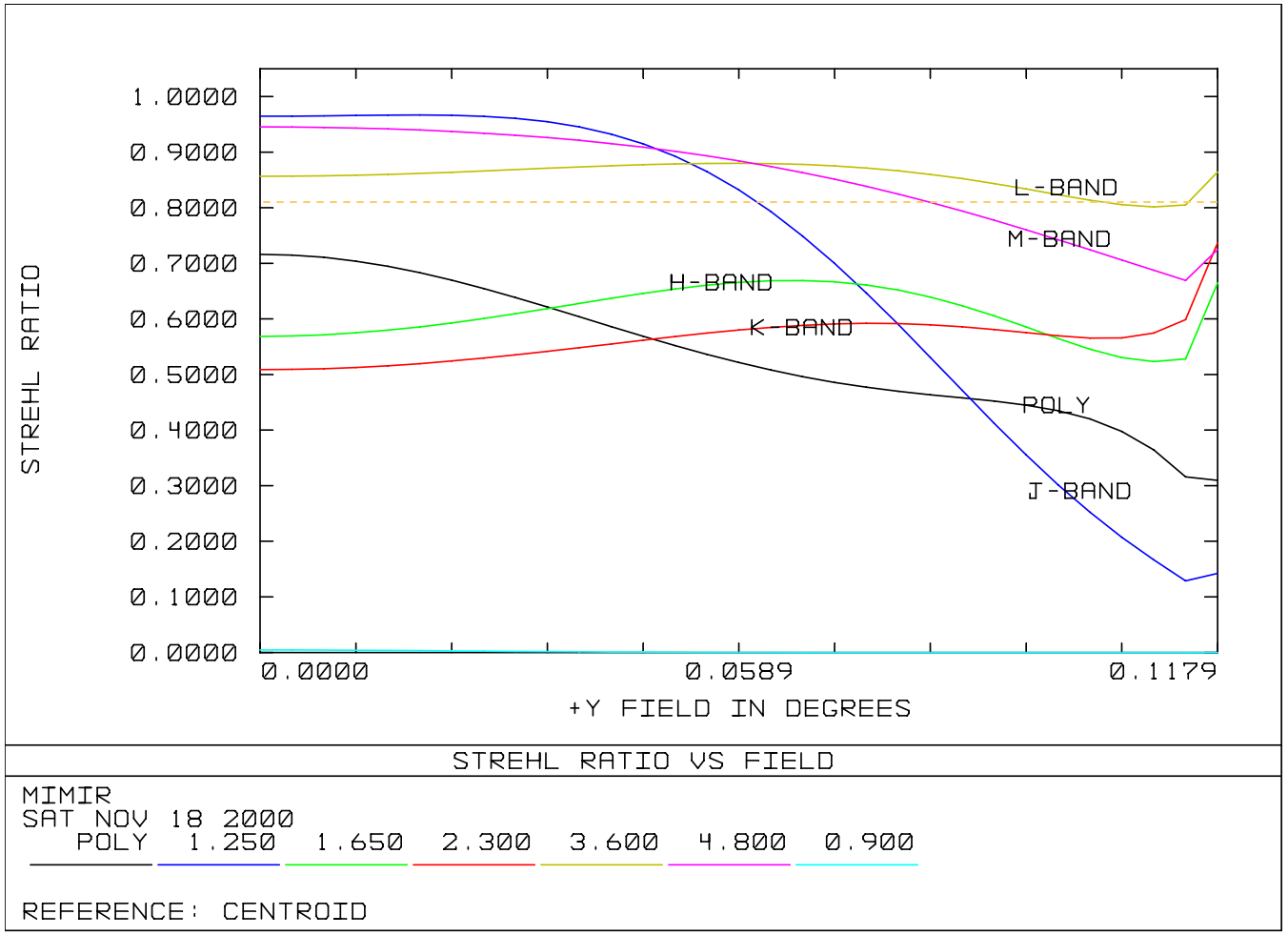
- **High-resolution Imaging**
  - –F/17 camera gives 3x3 arcmin FOV with 0.18 arcsec per pixel
  - –Diffraction-limited performance
    - Occultation work
    - Shift-and-add speckle work
    - Exploit periods of excellent seeing at Perkins telescope
- Rapid Mode Changes
  - –Slit Decker carries 13 different slits/scenes with rapid change
  - –All spectroscopic and polarimetric analysis units are located on conventional filter wheels – rapid changeover (***seconds***)
  - –Imaging to spectroscopy mode change in 2 seconds
  - –Can change from wide-field (f/5 camera) to high-resolution (f/17 camera) in less than a minute
- No spectroscopic tuning required
  - –Fixed-tuned grisms

Imaging – Optical Layout

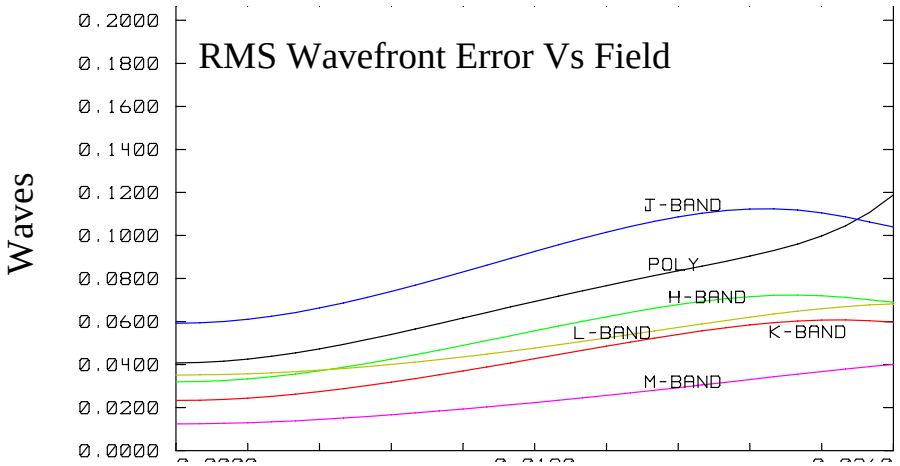


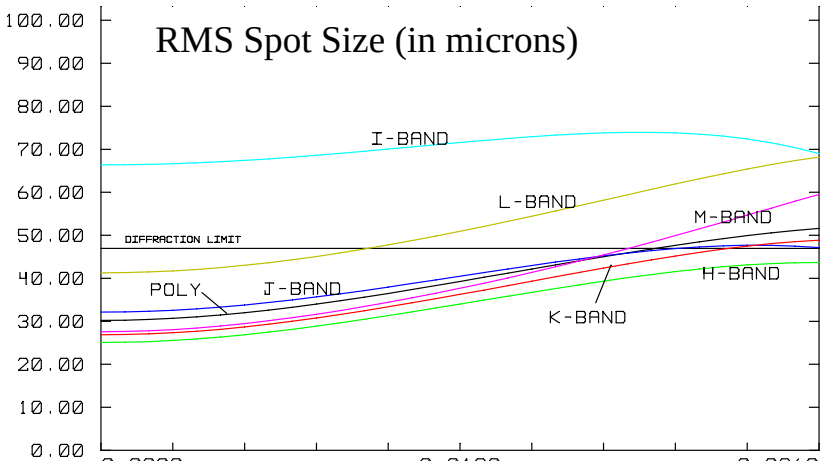
10’ FOV, F/5 Performance (Strehl Ratio)

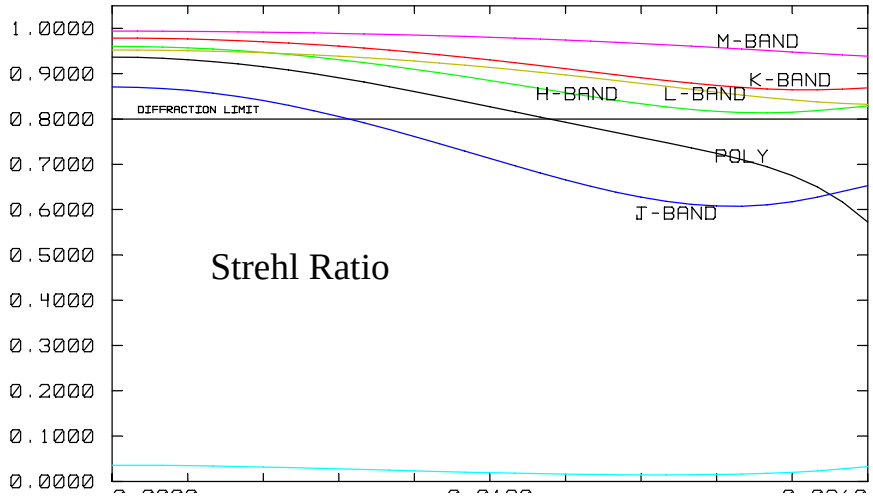
Strehl Ratio = ratio of power in the main lobe of the Airy pattern (PSF = Point Spread Function) to the total power in the pattern (or PSF). The “Diffraction-Limited” condition is reached for a Strehl ratio of 0.8. Here, Mimir is mostly diffraction-limited for L & M bands, nearly so for H and K, but less so for J band outside the central 5x5 armin. To improve J-band a corrector lens is added via a filter wheel location.

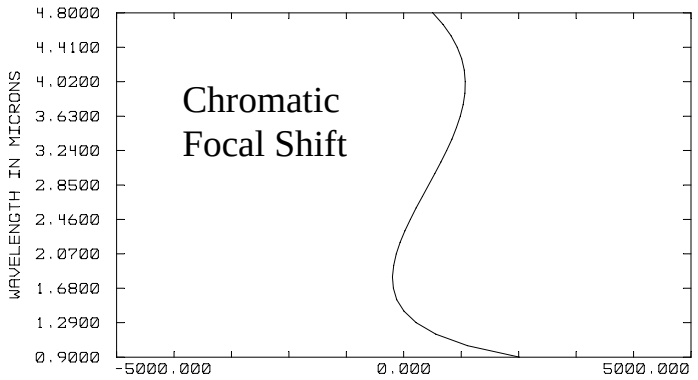


F/17 Performances (3x3' FOV)







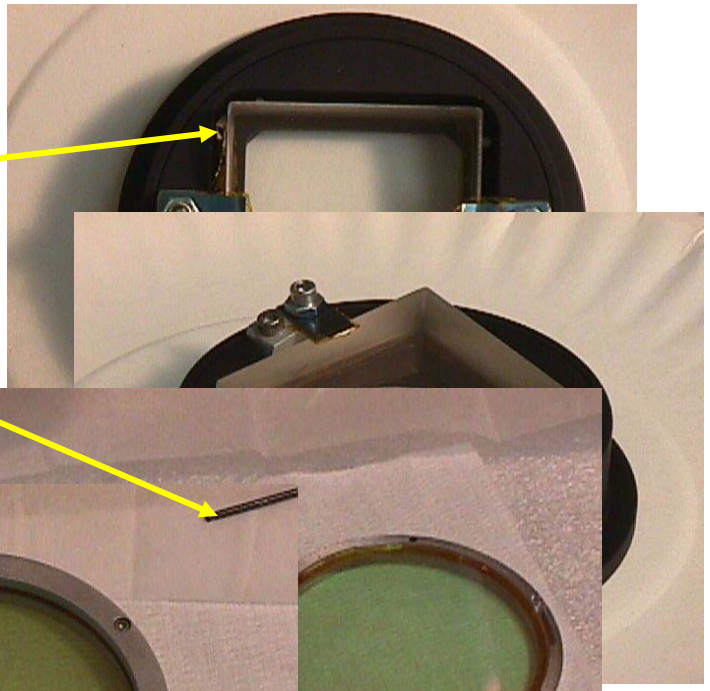


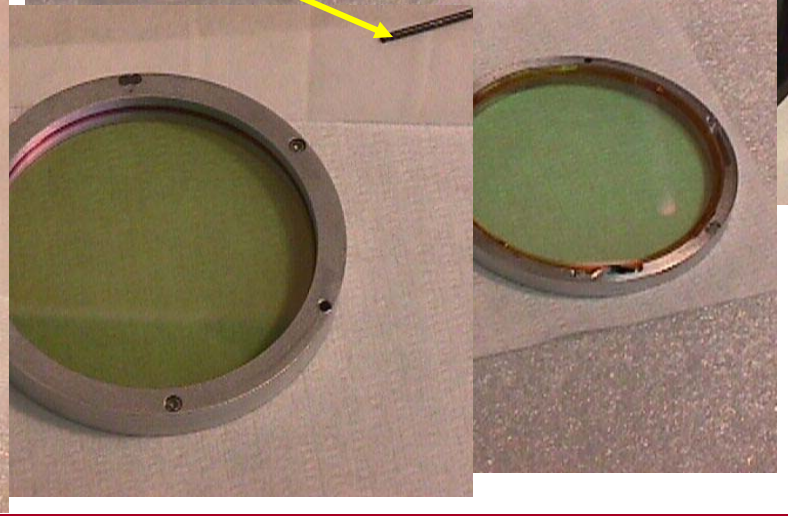
Mounting of Lenses & Filters

- Simple, high precision lens cells
- Capable of holding lenses within 0.0005” of correct locations in the optical path
- Lenses and Lens cells move with respect to each other during cooldown (different Coefficients of Thermal Expansion, or CTE)
- Cells designed so that lenses move into correct positions only when cold

Filters, HWPs, Grisms Similar

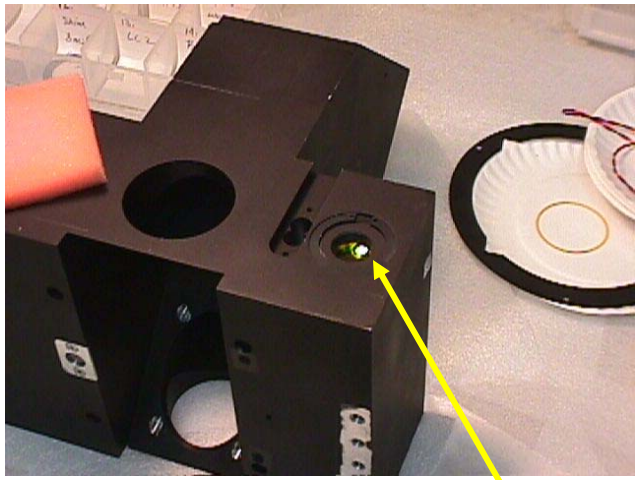
- Filters are tilted 5 deg to reduce "ghost" reflections
- Grisms are mounted against hard pins to provide excellent location knowledge and reference
- Half-wave Plate consists of two 1mm thick MgF2 pieces separated by 0.003" Kapton

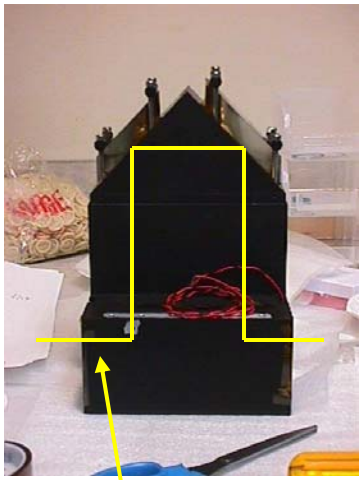


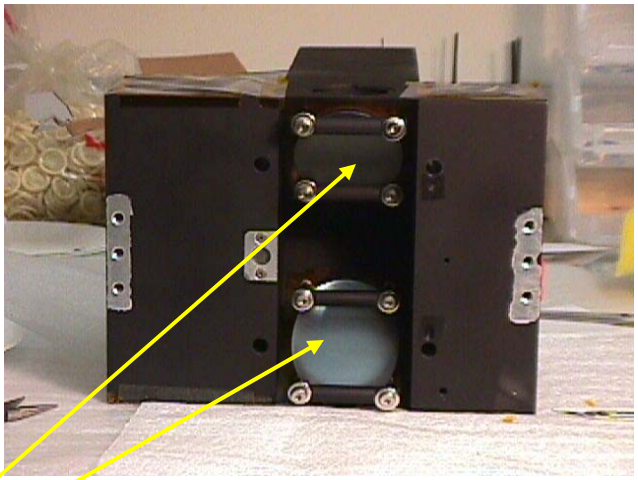


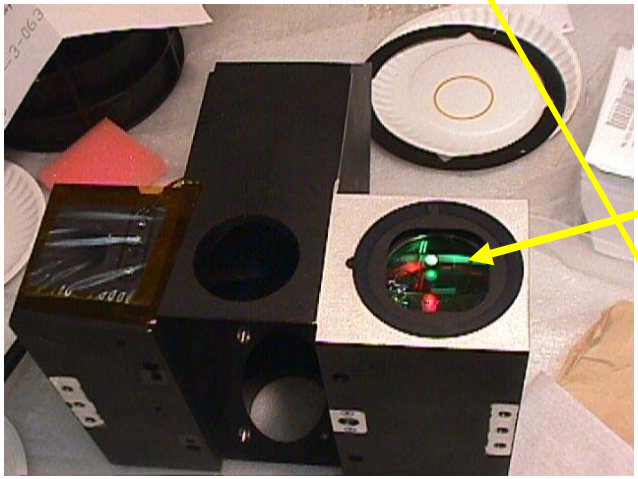
Mounted Lens Cells Installed in Optics Units (Collimator, Camera)

Camera Block





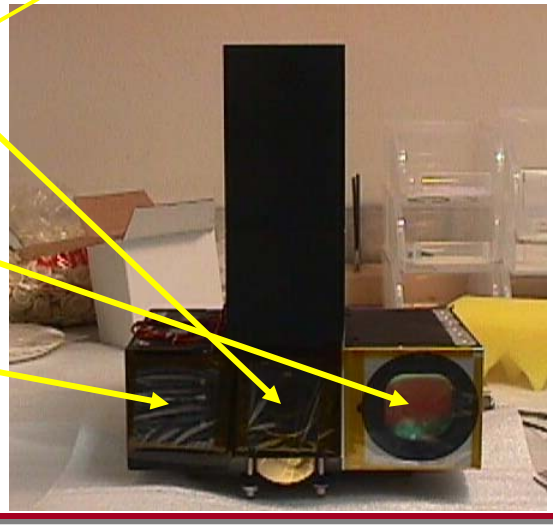




f/17 narrow-field camera

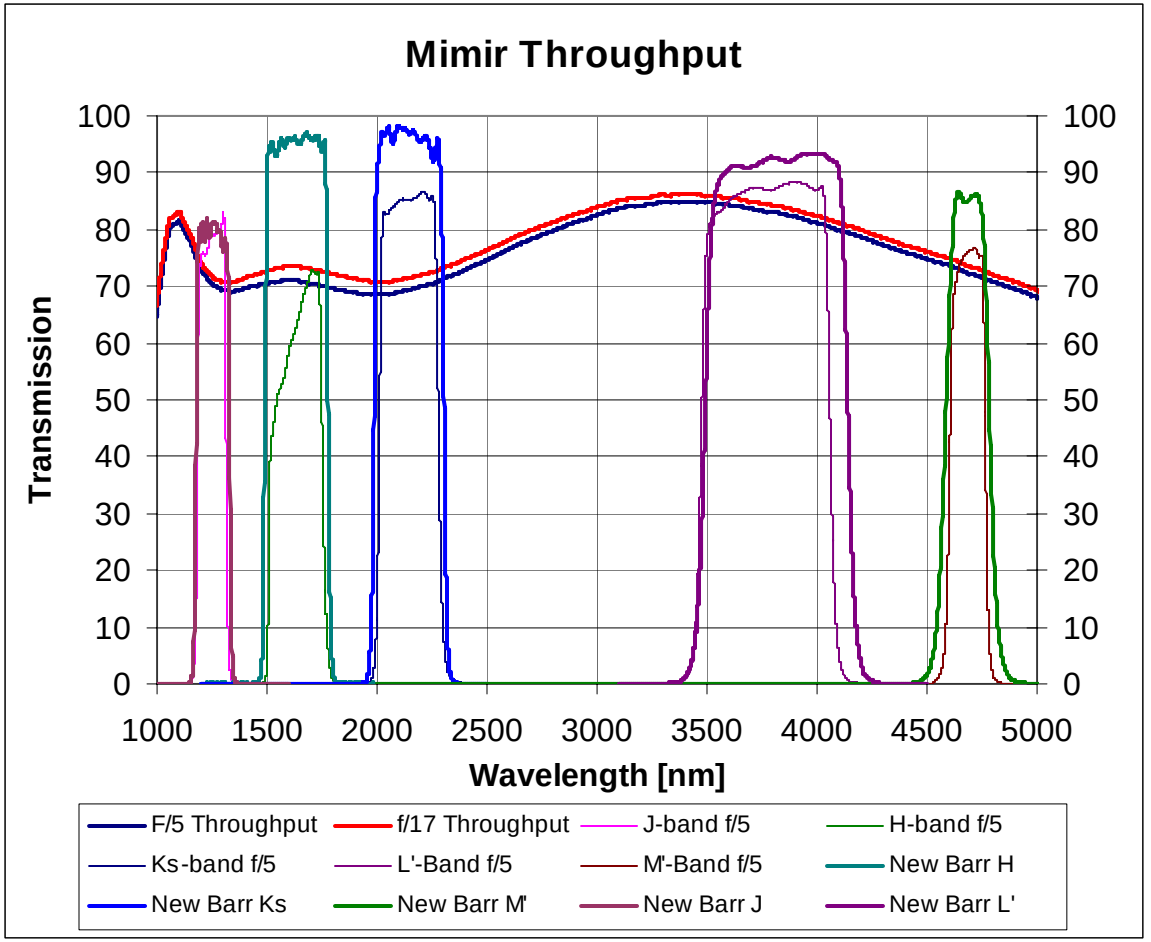
f/5 wide-field camera

Pupil viewer camera



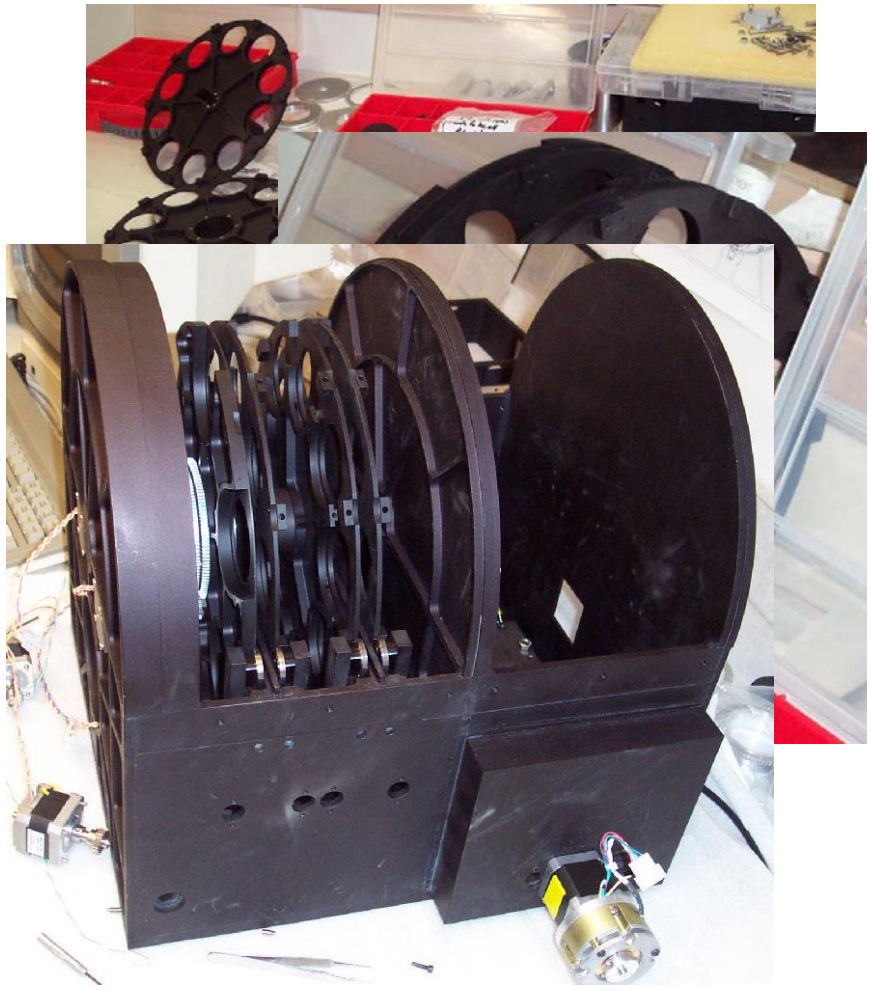
Mimir Direct Imaging Throughput

- Optics throughput for Window, Collimator, F/5 (red curve) or F/17 (blue curve) camera
- Broadband filter transmissions for “classic” JHKL’M’ filters (thin curves) and newly designed and developed filters (thicker, higher, flatter curves)
- Total throughput is product of optics values and filter values



Direct Imaging Filters and Wheels

- 3 Filter Wheels, 1 Half-Wave Plate Wheel
  - –Filter Wheels each have 10 holes
    - 9 filters + 1 open
  - –HWP Wheel has 6 holes
    - 5 HWPs + 1 open
- Can add/move filters and HWPs occasionally (1-2 times per year)
  - –Not for individual runs – warm up time is several days, cooldown time is 4 days
- All wheels are driven by stepper motors located within the cold, vacuum volume



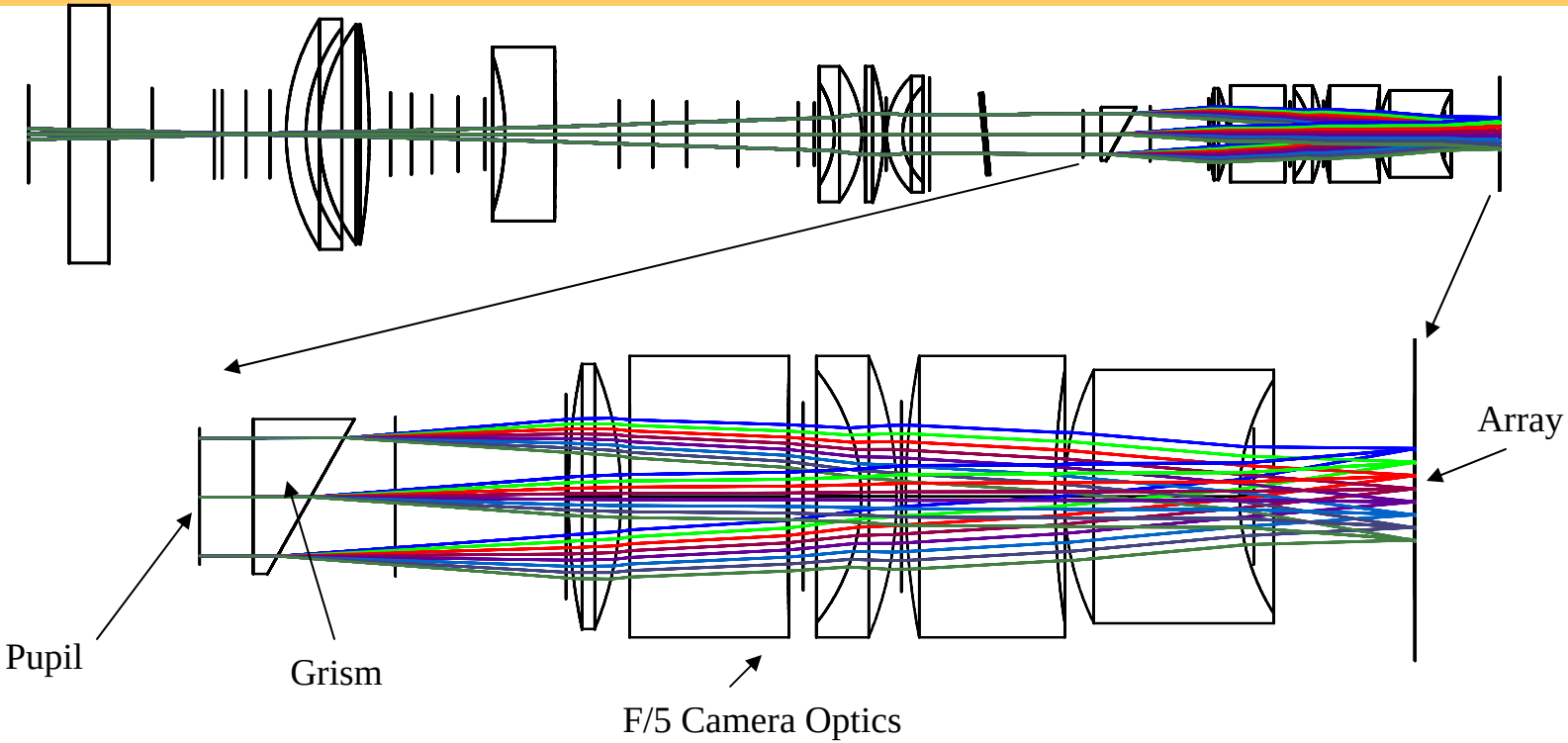
Initial Filter Complement

	Pol	FW1	FW2	FW3
1	dark	dark	dark	dark
2	f/5 baffle	J		JHK Grism
3	f/17 baffle	H	1.17 LP	
4	H-HWP	Ks	1.85 LP	
5	Open-2	L'		SED Grism
6	Open-1	M'	2.8 LP	WireGrid
7		PK50-2	PK50-1	
8				LM Grism
9		H2-Off		
10		Open	J-Corr	Open

- Broadband
  - J, H, Ks, L', M'
- Narrowband
  - H2-On (removed temporarily)
  - H2-Off
- Spectroscopy
  - 1.17LP, 1.85LP. 2.8LP
- Blocking filters
  - PK50 (needed for JHK filters to block light longward of 2.5 microns)
- Dark filters
  - Initially in every wheel
  - For ascertaining dark current, scattered light
- Polarimetry
  - H-band HWP
  - Wire Grid
- Baffles
  - F/5
  - F/17

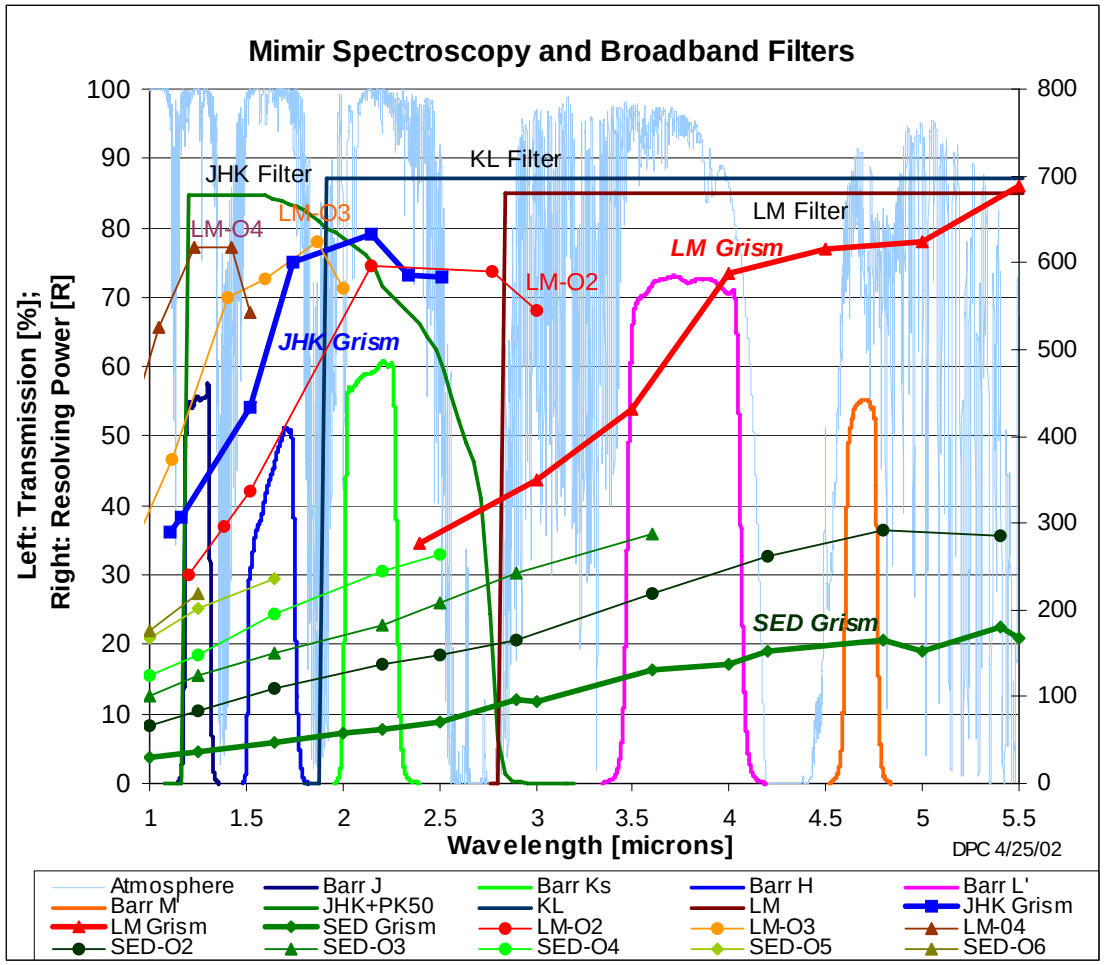
Spectroscopy Layout

- Single Grism to capture up to one full octave within 1-2.5 μm band
- Plenty of slit height (5 arcmin) for planetary observations (30-40 arcsec)
- 3 grism set: JHK, LM, SED



Spectroscopy: R (= $\lambda/\Delta\lambda$) vs λ

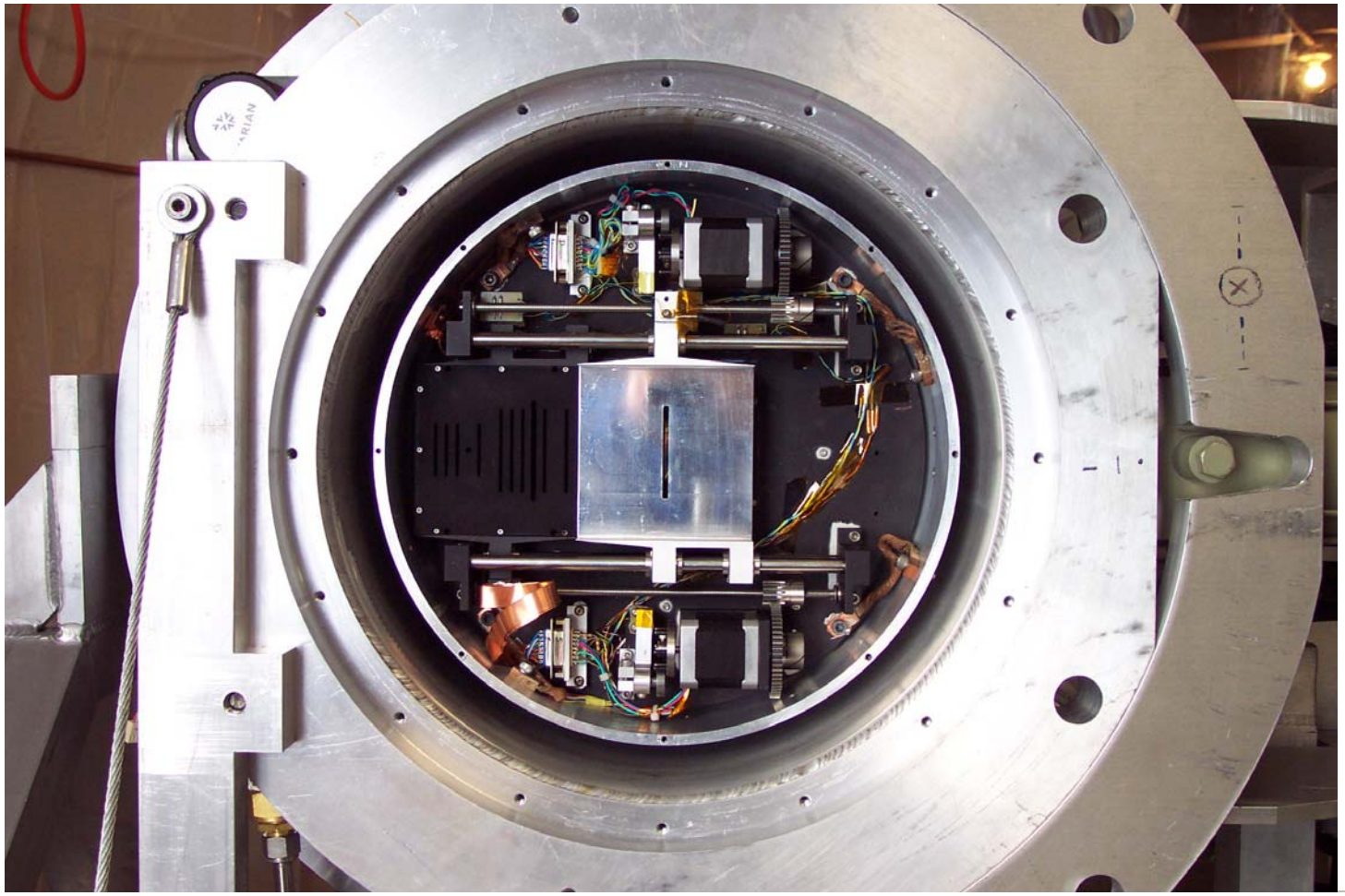
- Single Grisms (not cross-dispersed)
  - –JHK (1.16-2.3um)
  - –LM
  - –SED
- Used with "spectroscopy filters"
  - –JHK = 1.17 LP + PK50
  - –KL = 1.8 LP
  - –LM = 2.8 LP
- Can use in multiple orders with broadband filters
- Minimal spectral overlap on detector



Spectroscopy: Slit Options

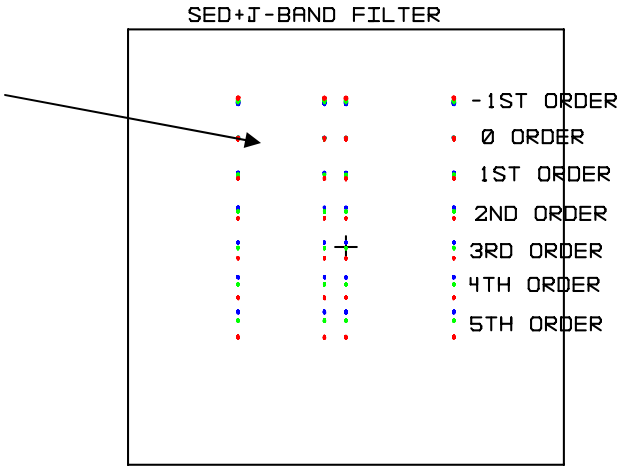
- One slit at a time (single object, unlike PRISM's multi-object)
- Many slit selections in the "Slit Mask" – to match seeing, camera
  - –F/5 camera slits (5' tall, 0.6 arcsec/pixel, 2 pixels/spectral element)
    - "Narrow" – 1.8 pixels wide (1.08")
    - "Normal" – 2 pixels (1.2") [="Buie Slit"]
    - "Medium" – 3 pixels (1.8")
    - "Wide" – 4 pixels (2.4")
    - "Very Wide" – 6 pixels (3.6")
    - "Eared" – 10" wide, with 1.2" tall "ears"
  - –F/17 camera slits (3' tall, 0.18 arcsec/pixel, 3 pixels/spectral element)
    - "Narrow" – 2 pixels (0.36")
    - "Medium" – 3 pixels (0.54")
    - "Wide" – 4 pixels (0.72")
    - "Very Wide" – 5 pixels (0.90")
    - "Super Wide" – 6 pixels (1.08") [same slit as F/5 "Narrow"]
  - –Additional Mask elements: 20" round hole (acquisition), blanks (for dark current), 16x16 grid of pinholes (for optical alignment)

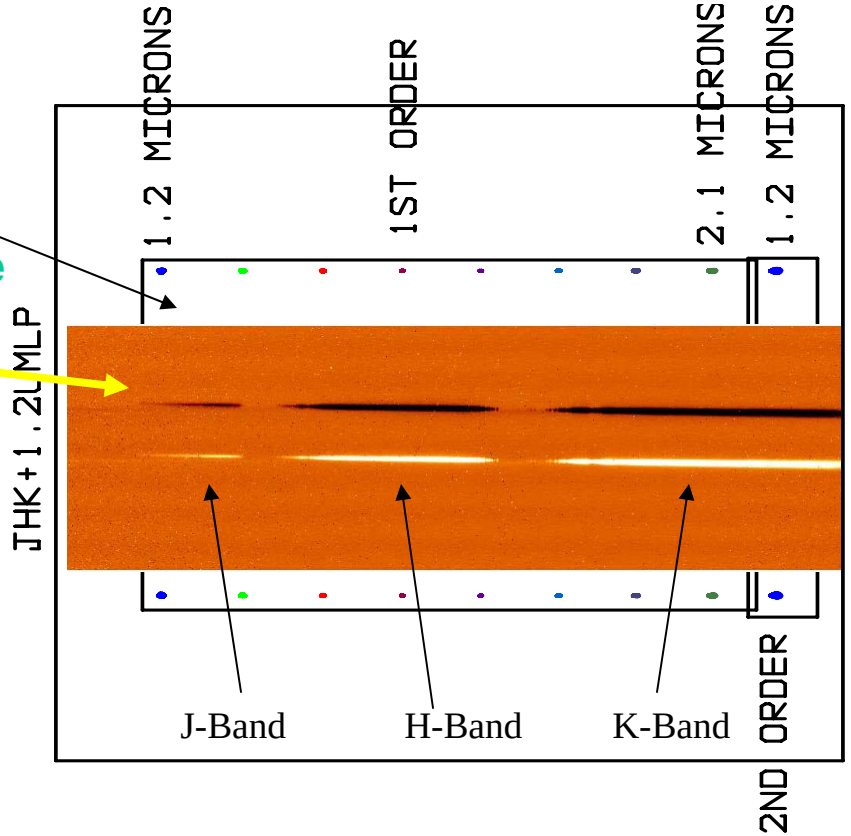
Focal Plane “Slit Decker System”



Spectra as seen on Detector Array

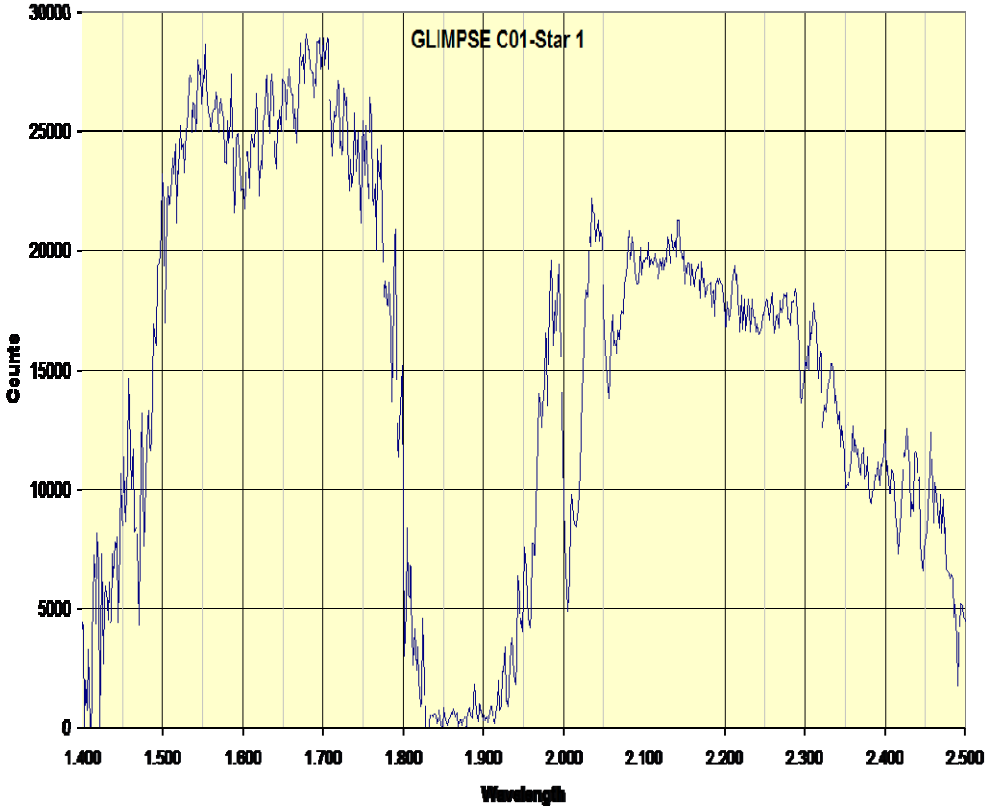
- Tall slit, dispersed, produces 2-D image
- Some grism+filter combinations are mostly free of order overlap
- **Real Mimir spectra from telescope confirm spectroscopy design**
- Other grism+filter combinations can capture all the light in all the orders for narrower wavelength range



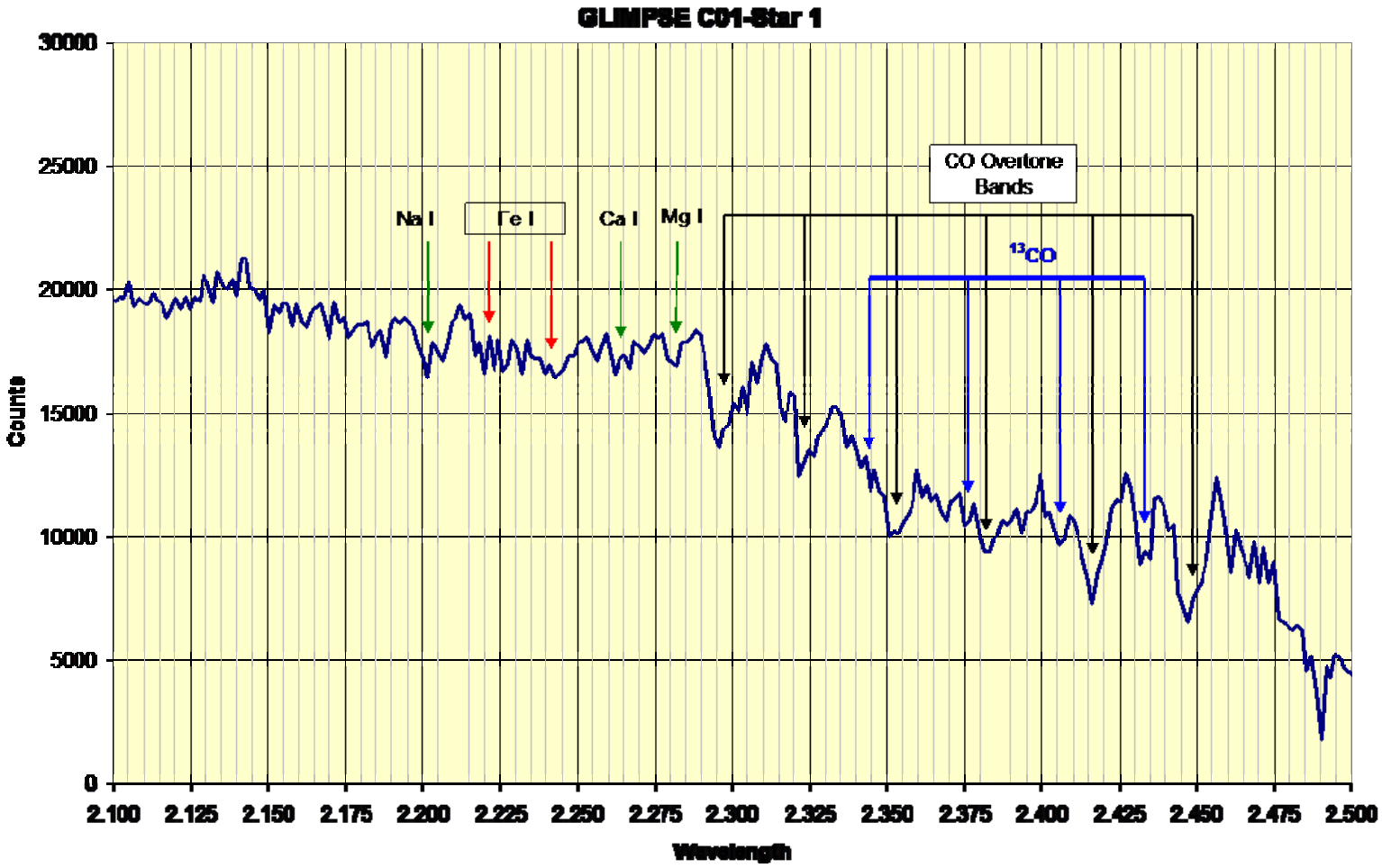


Mimir Spectroscopy Meets Dispersion, Resolution Requirements

- Globular Cluster discovered in Spitzer/IRAC/GLIMPSE data by Kobulnicky et al. (2004) [GLIMPSE team] in June
- L=30, B=0 -> globular or open/galactic with massive stars?
- Mimir spectroscopy of brightest stars in August



Metal-Poor Red Giant

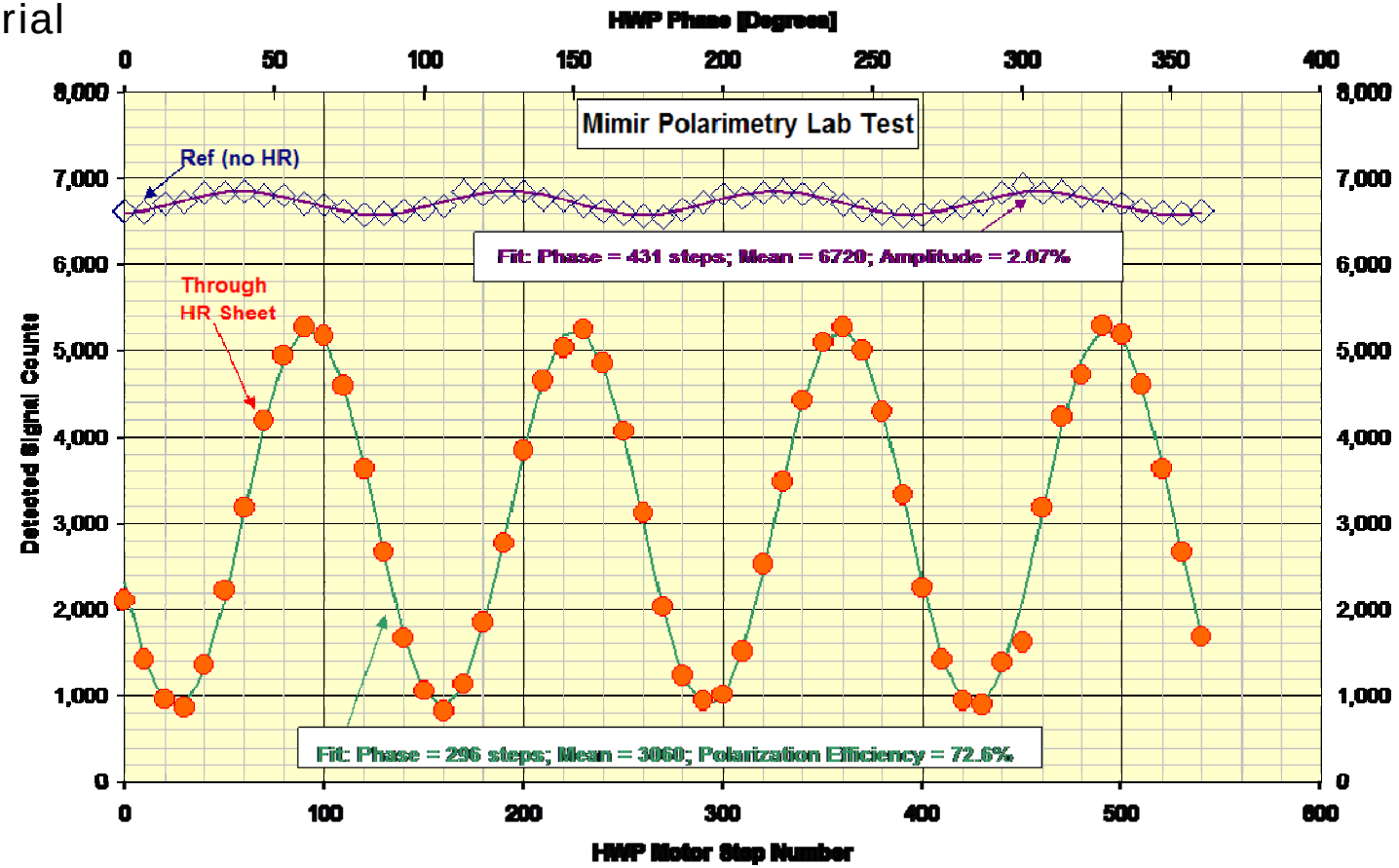


Polarimetry

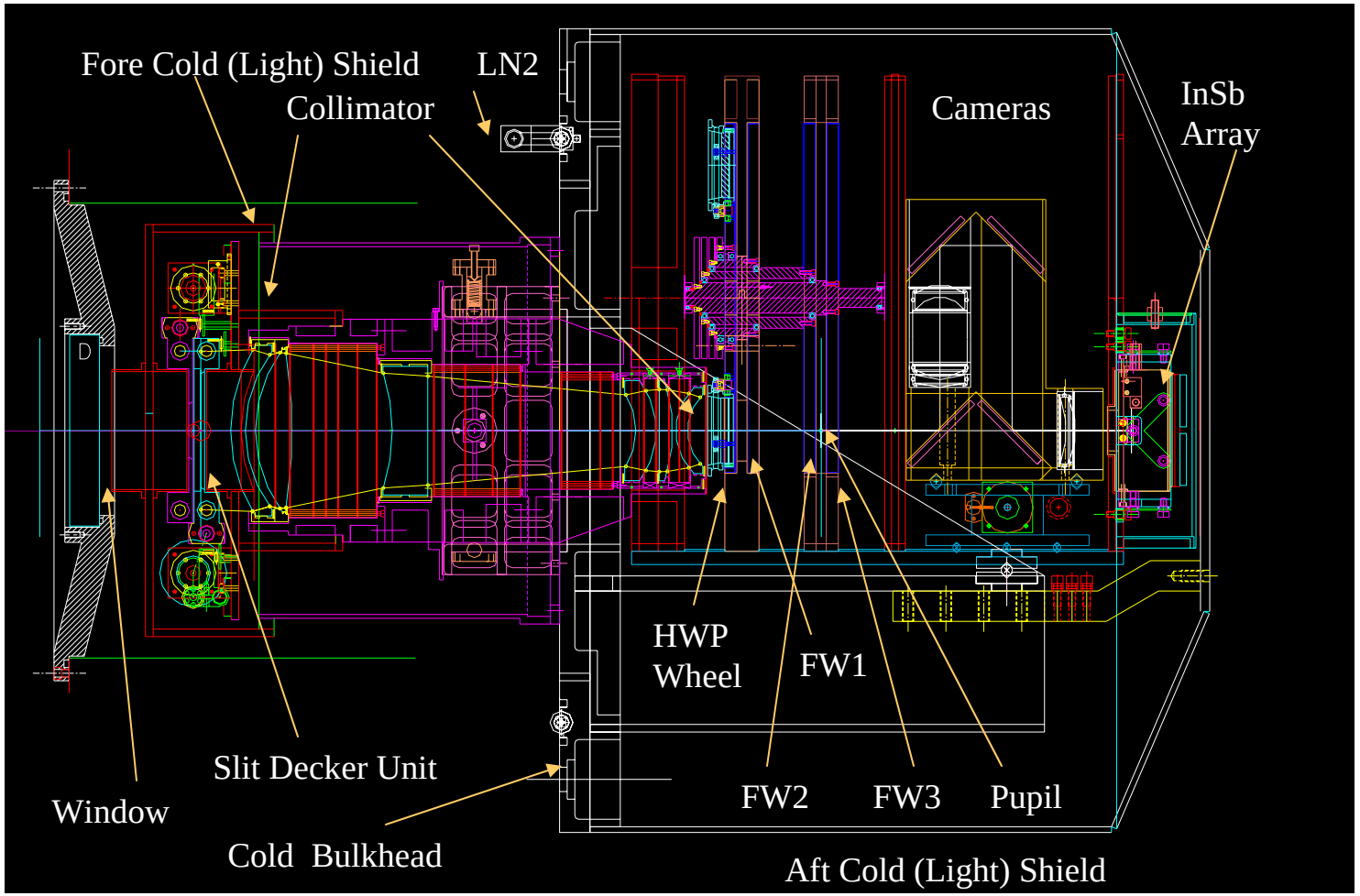
- Designed in from the beginning, not an add-on
  - –No reflective surfaces before polarimetric light analysis
  - –Axial symmetric design, no aspheres
- HWP+Wire Grid polarimetric light analysis
  - –Rotating Half-wave plate
    - Zero-order HWP (single band per plate)
    - H-band HWP fabricated (NovaPhase)
  - –Wire grid polarization analyzer
    - Molectron IG227-38
    - Covers 1-10 microns wavelength
  - –4Θ Modulation of polarization signal with HWP rotation
    - Robust against 1Θ (tilt) and 2Θ systematics
  - –Full Imaging field at once
    - through one HWP angle per image
  - –Collect ~34 images per HWP rotation cycle

Mimir Polarimetry Works

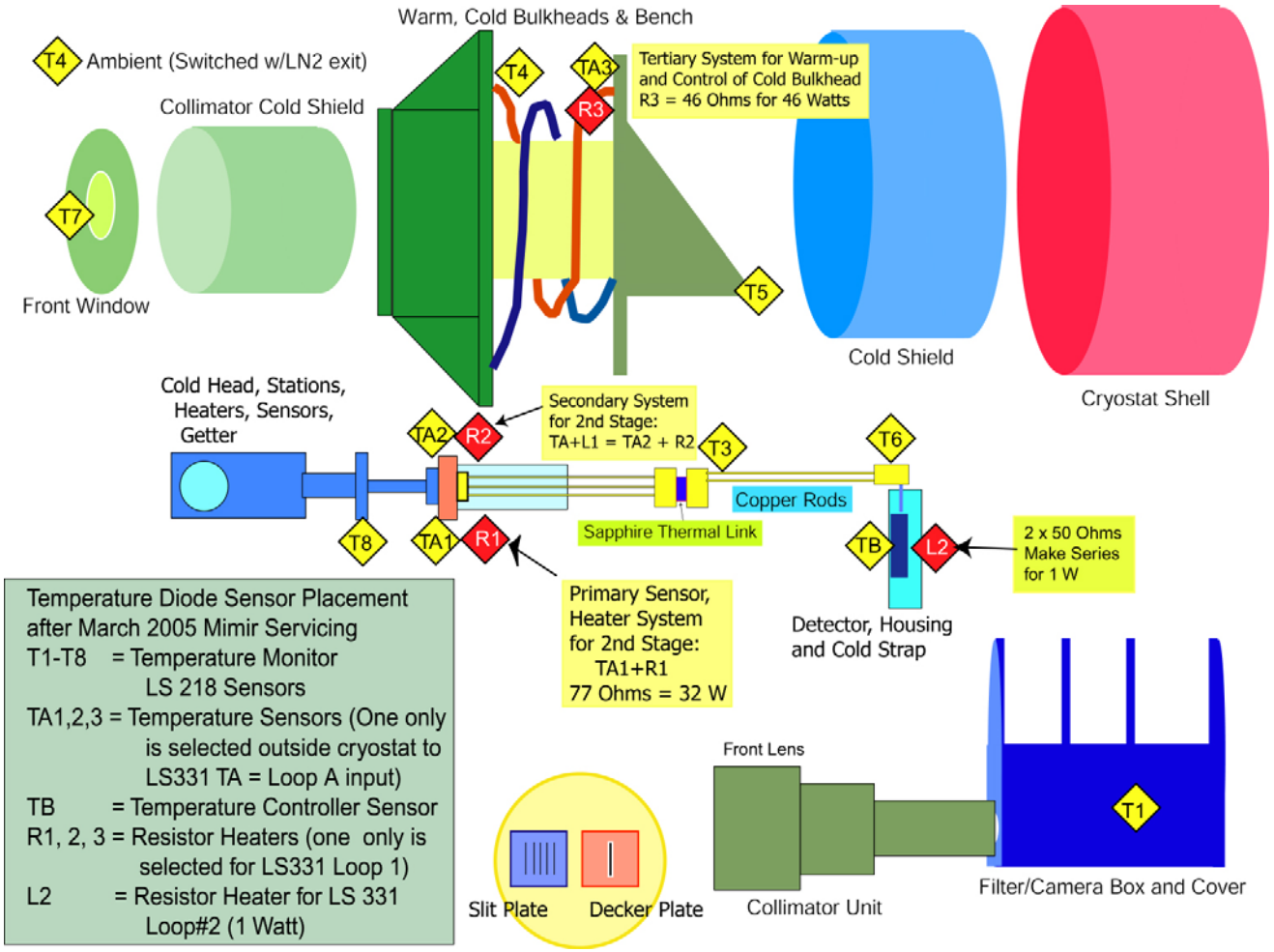
- Lab Test with HR-type NIR polaroid material



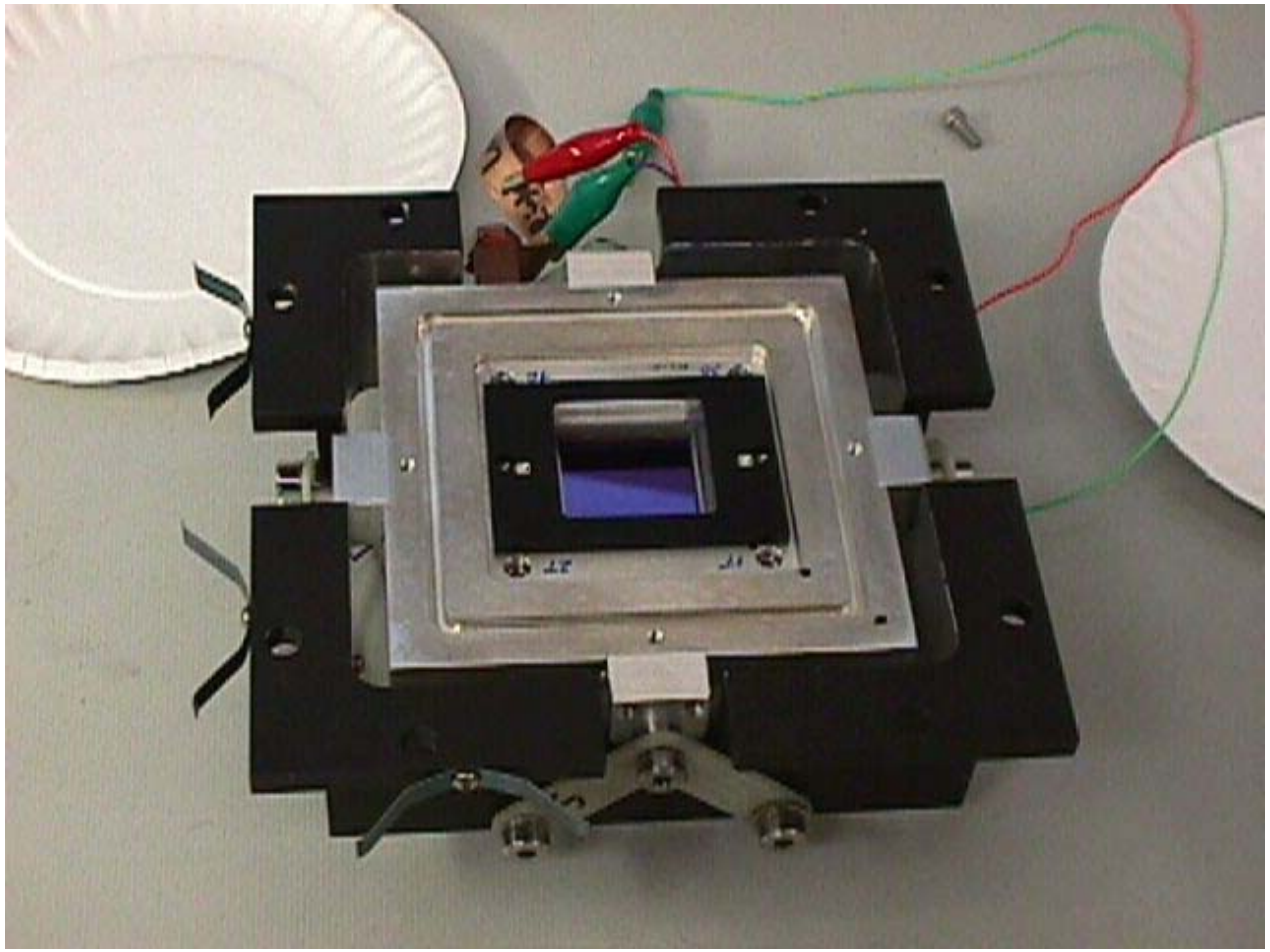
Mimir Cryogenics & Mechanical Overview (Covers removed)



Temperature Monitoring and Control



Detector Package



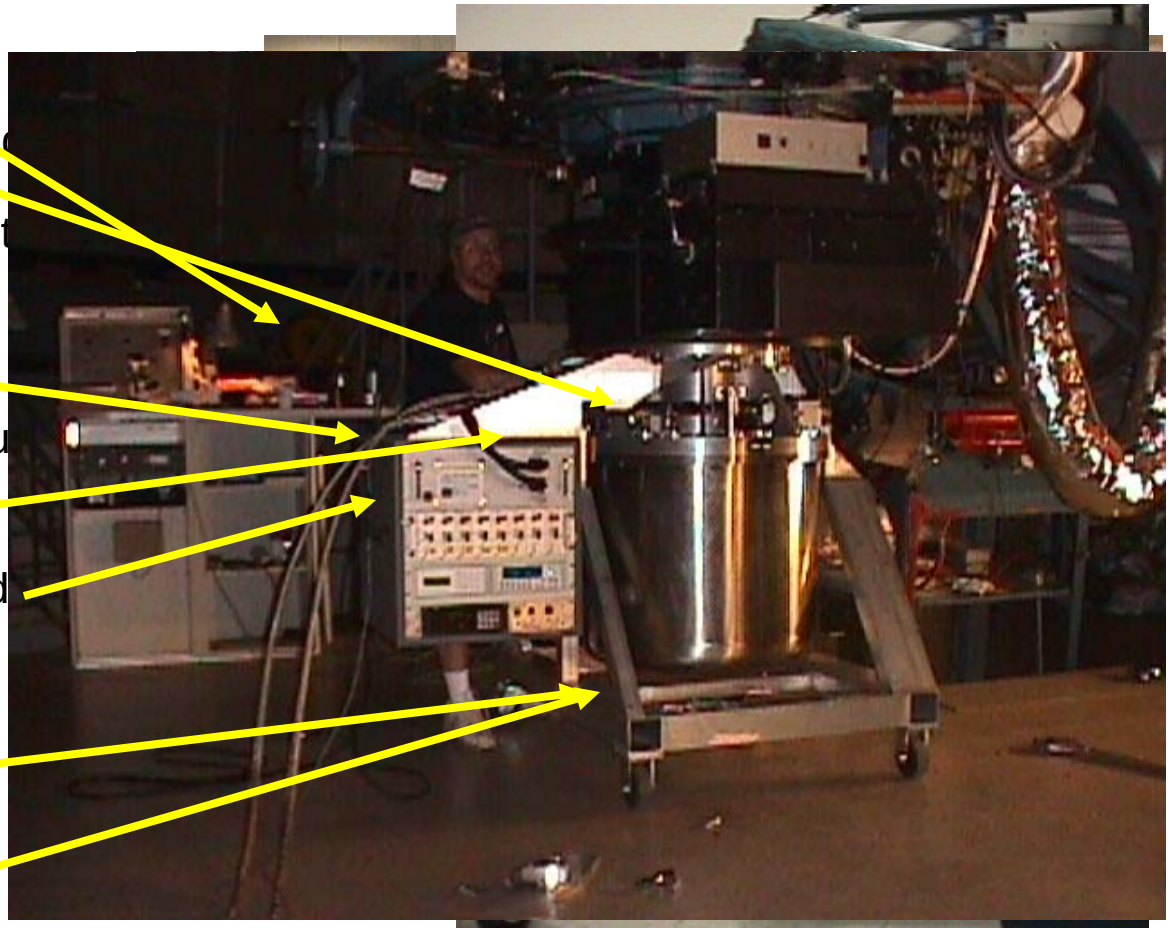
Mimir Detector

- InSb Infrared Light detector “bump bonded” with Indium dots to a silicon signal multiplexer substrate
  - –Not a “CCD” – there is no charge coupling and shifting
  - –Multiplexed readouts – 32 readout channels
    - each reading out every 8th column of each of four 512x512 pixel “quadrants”
    - Full-frame read rates to 12Hz (I/O fiber bandwidth limited)
  - –ALADDIN III technology (latest and greatest)
- Device selection took place in July 2001
  - –Raytheon offered three devices to select from
  - –We picked a great 1024x1024 ALADDIN III device
    - Few bad pixels (< 0.5%)
    - Most uniform response across device
    - Low dark current (< 15 e/pix/sec)
    - High quantum efficiency (> 80%)
    - Low read noise (< 55e/pix)

Assembling Mimir

Mimir goes to Arizona

- Early July – Mimir "Goodbye Party"
- Mid-July – Disassembled Mimir, packed it and almost the entire lab into a large truck
- Late July – Drove truck to Perkins Telescope
- Later July to Early August – rebuilt lab on ground floor of telescope
- Unpacked, reassembled Mimir
- Early August – cooled Mimir with LN2, cryocooler, elevated
- August 16 – Mounted Mimir on Perkins Telescope



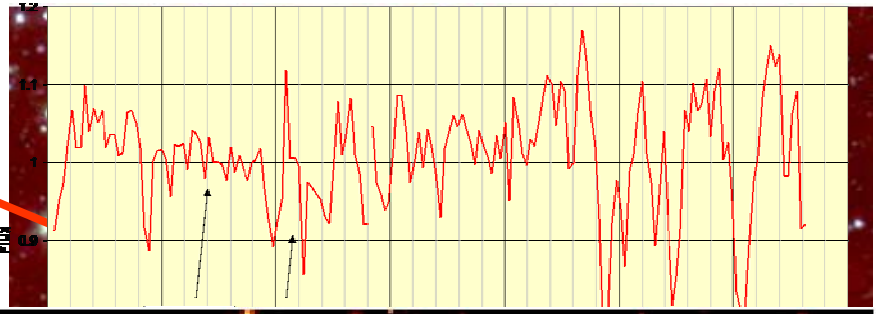
Commissioning Tests

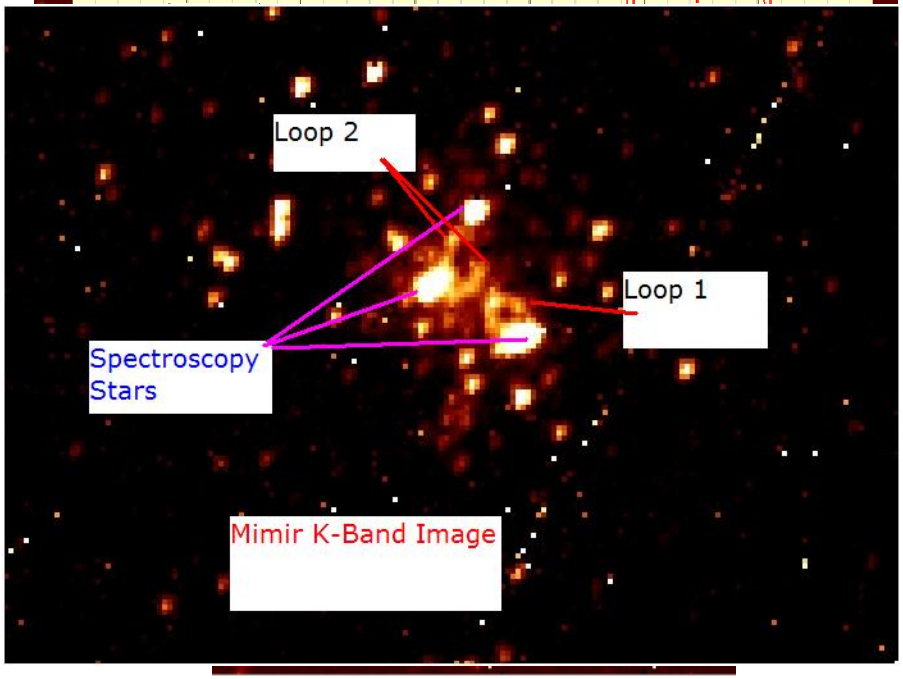
- Mounting on Telescope
- Balancing (2 days!)
- First Light
- Focus, Image Quality Analys
  - Saw sub-arcs
- Direct Imaging
- Spectroscopy
- Polarimetry

First-Light Science Investigations

GLIMPSE Globular Cluster Detection

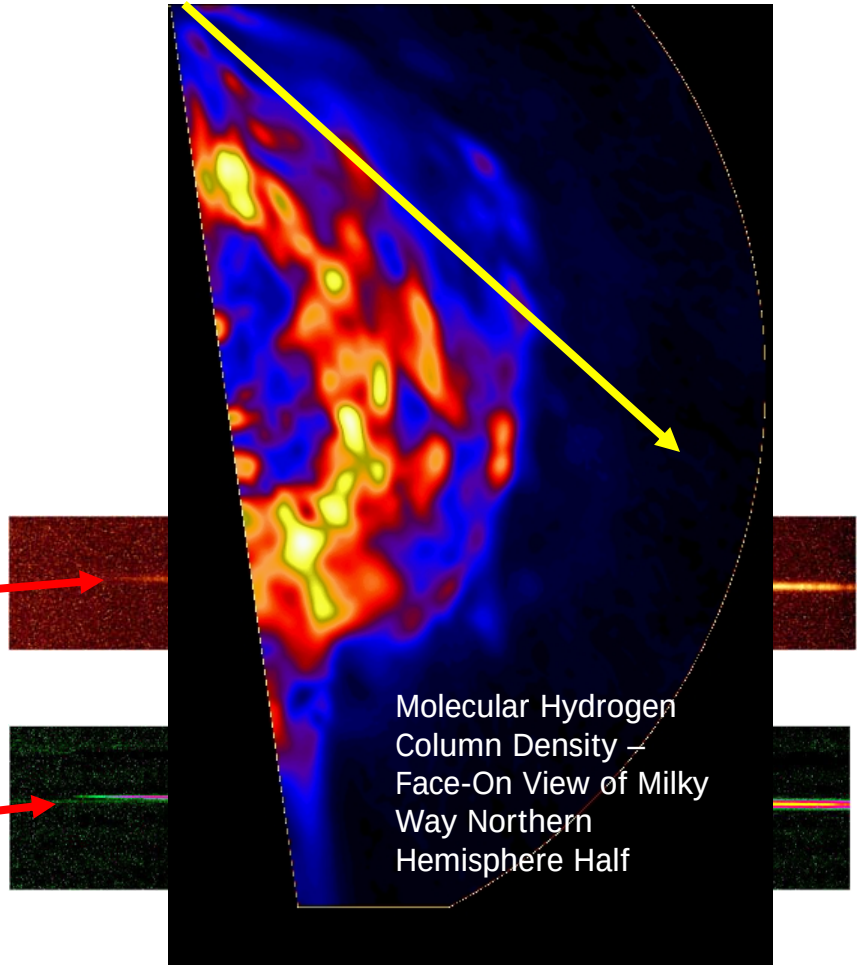
- "C01" at l=30, b=0 – newly discovered cluster, relatively nearby
  - Discovered in Spitzer IRAC Images by Wyoming part of GLIMPSE team
  - Follow up observations with IR cam at WIRO 2.3m telescope
- Mimir Follow-up Observations:
  - JHK Imaging
    - improve color-magnitude diagram
    - larger area than WIRO
    - connect to 2MASS better
  - JHK Spectroscopy
    - Three brightest stars + fortuitous interlopers in tall slit
    - Test whether brightest stars are massive, young or RGs
    - Spectra show deep CO bandheads at 2.3um -> RGs
  - H-Polarimetry
    - Cluster may be plowing through interstellar cloud
    - See bubbles, or cavities associated with brightest stars
    - Polarimetry can tell if highly polarized, single scattering of light off inside cavity walls





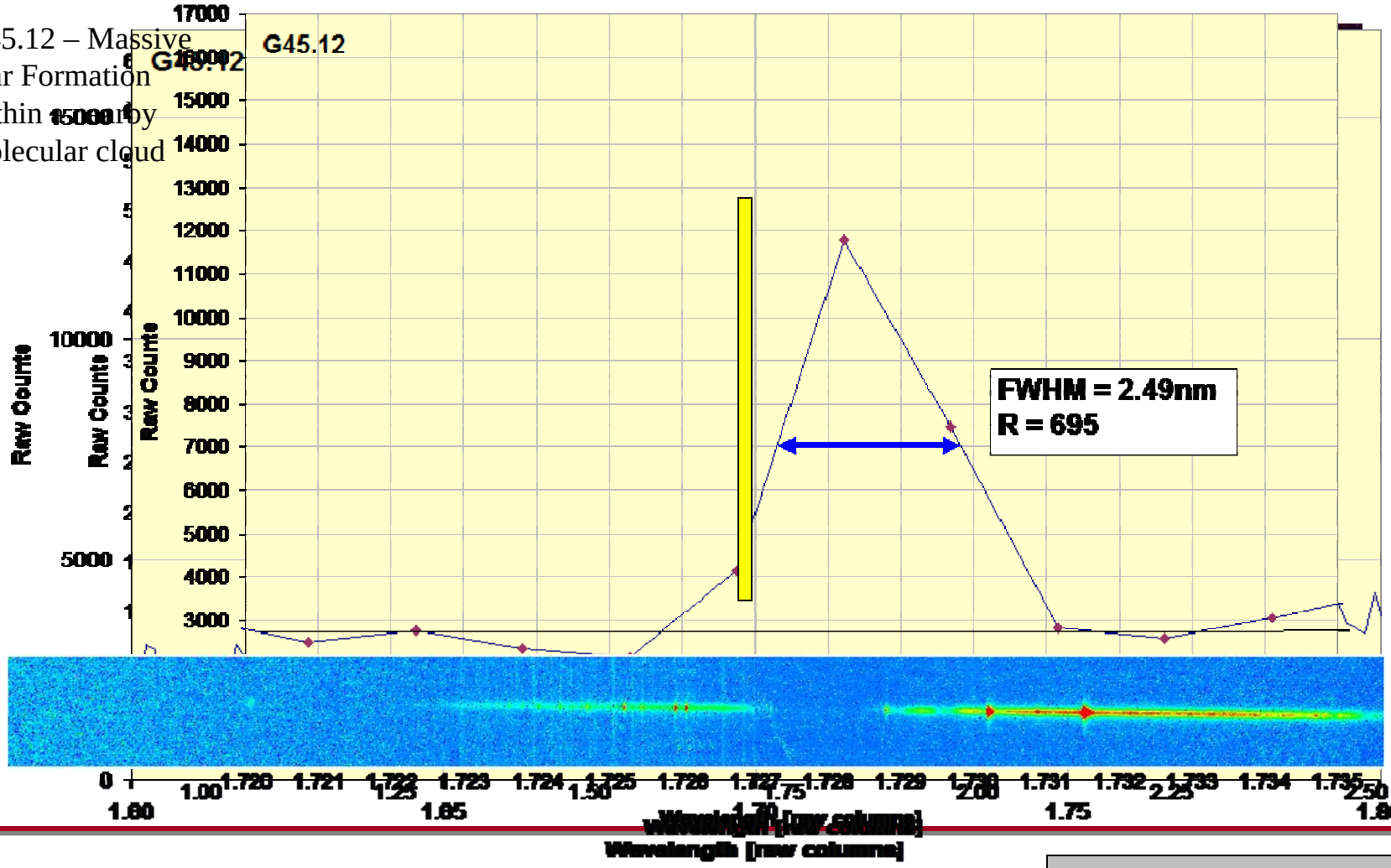
First Light Science - Continued

- Pilot H-Band Polarization Survey
  - –Sagittarius Spiral Arm Tangent Direction
  - –Overlapping fields of 10x5 arcmin size
  - –Total Area ~ 30x10 arcmin
  - –Integration time/pixel ~ 5 minutes
  - –Bright Polarization Standards
- GRS/MIRSI star formation region follow-ups
  - –W51irs2 – JHK imaging + spectroscopy
  - –G45 (Klingon Cloud) objects – JHK imaging + spectroscopy
- PN/MYSO separation project (was a Spitzer Space Tele proposal)
  - –Undergrad J. Shiode
  - –JHK Spectroscopy

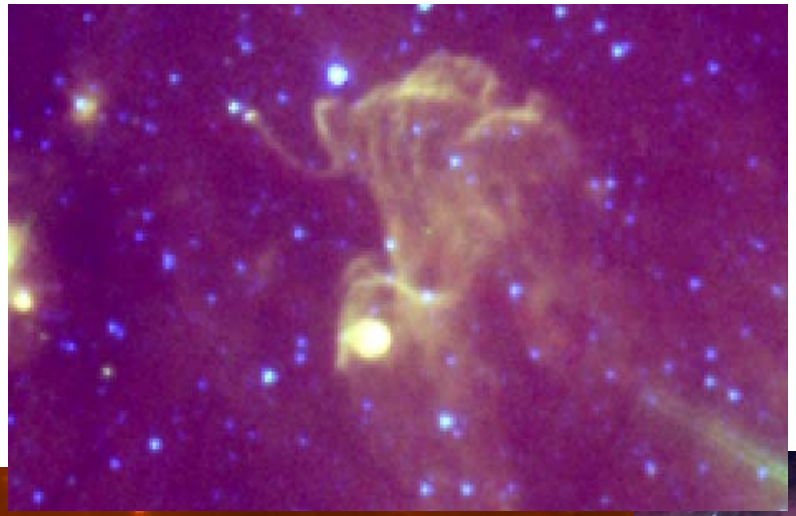
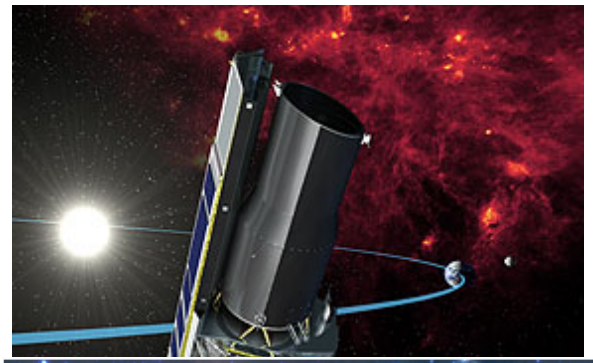
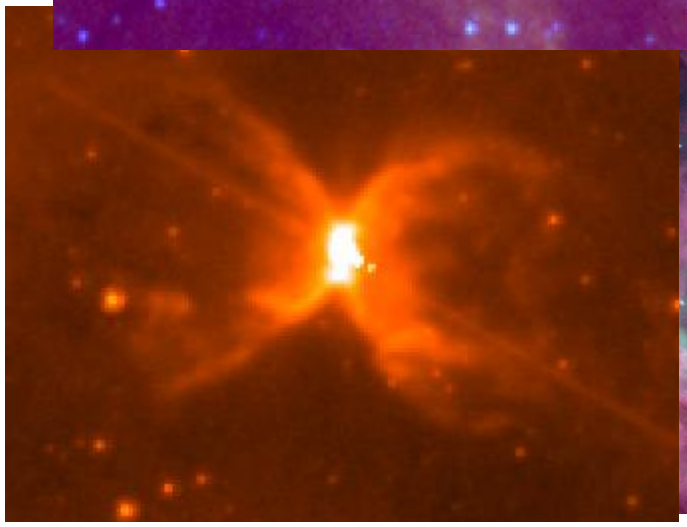
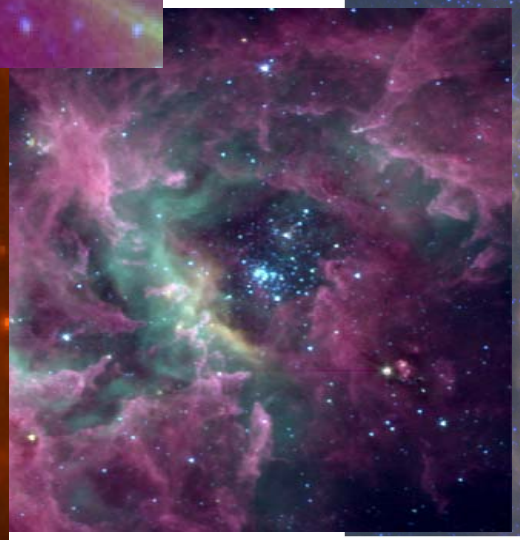


Quick Look Spectroscopy

G45.12 – Massive Star Formation within by molecular cloud



Mimir Projects for the Future: Follow-Up of Spitzer Objects

- 




Mimir's first season (2004/05)

- Engineering/commissioning runs on Perkins telescope (Q3, Q4 2004)
  - **Aug/Sep 04**; **Oct 04**; Dec 04
  - Lots of software to write, tweak, rethink
- Shared risk observing with LO, BU users (Q1, Q2 2005)
  - First draft of "Operating Manual"
- "Routine observing" starting **Q3 or Q4 2005**
  - Open to Lowell and BU observers for regular use
  - Also Vistors under **NSF/PREST** umbrella
- Future, occasional refurbishment, filter complement update
  - Narrow band planetary filters to be added
  - Replace, upgrade grisms
- Acknowledgements & Authorship
  - Publications containing Mimir data from 2004-2005 should list entire Mimir team as authors (not required for data after 2005)
  - All Mimir pubs must include standard line referencing funding agencies (forever)
    - NSF, NASA, W.M. Keck Foundation

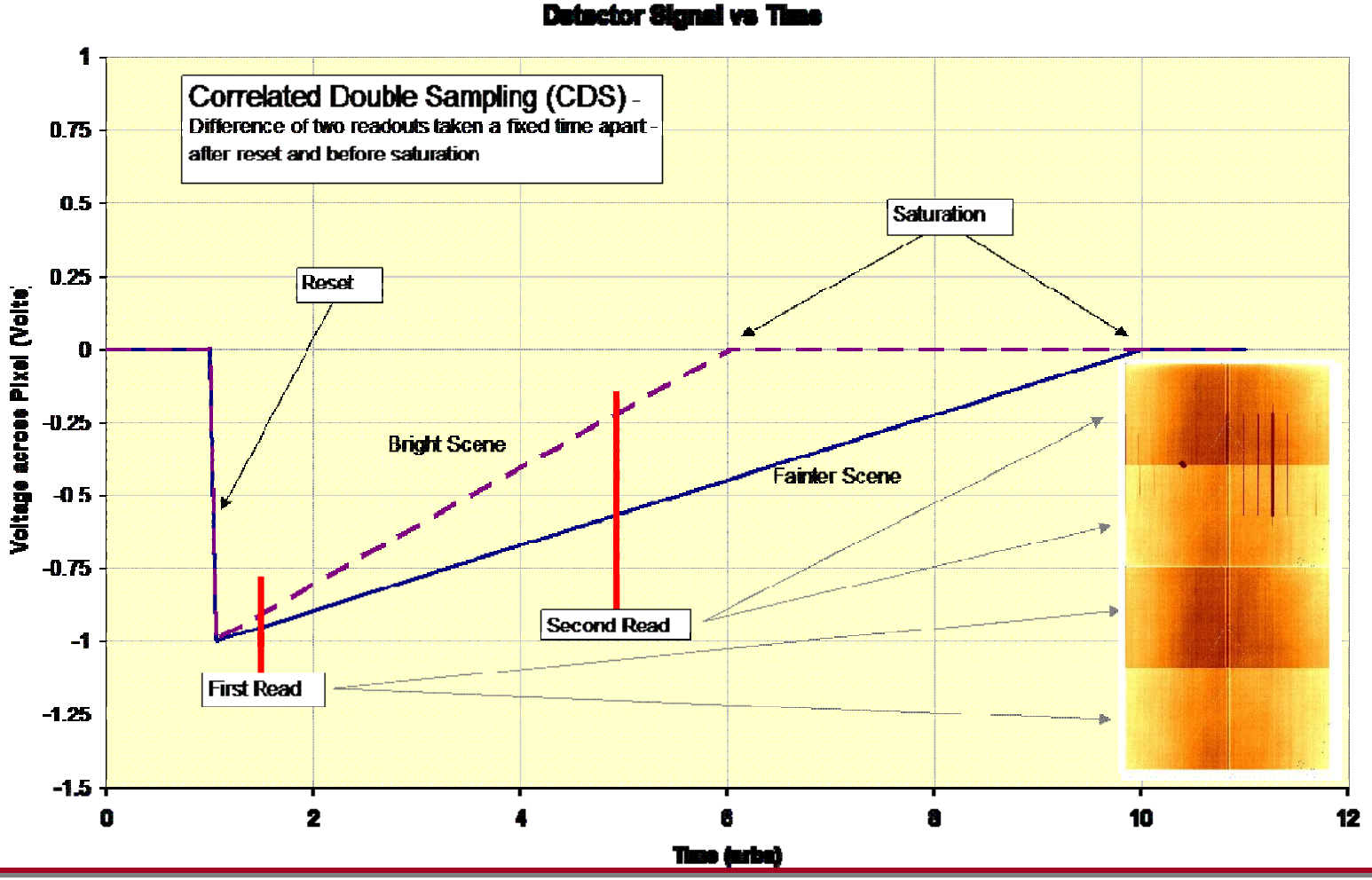
Mimir Summary

- Covers entire 1-5 micron near-infrared region
- Three main instrument modes:
  - **Direct Imaging** (10x10 arcmin FOV @ 0.6"/pix or 3x3' FOV @ 0.18")
    - Broadband, narrowband filters

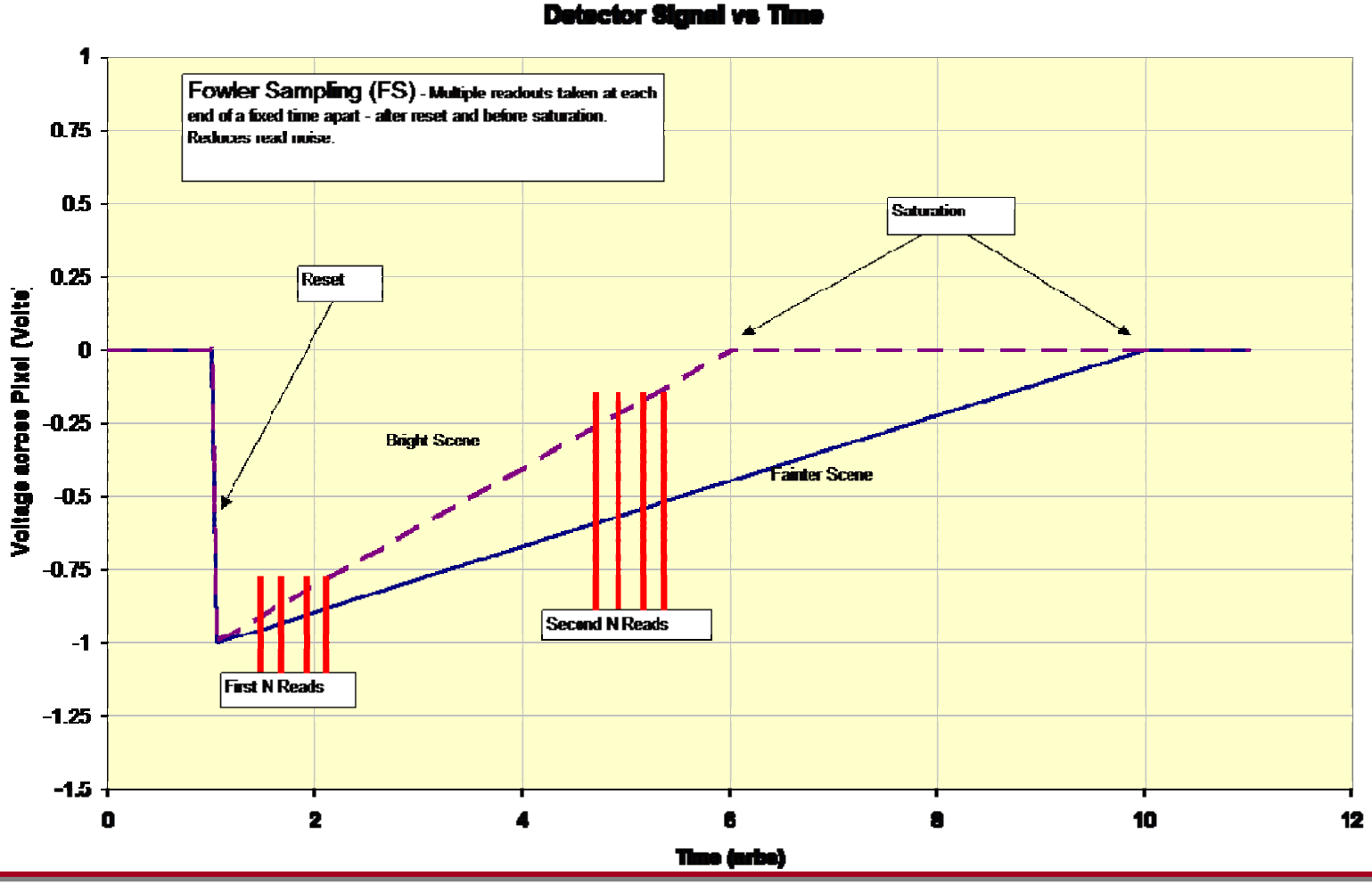
Band	2MASS 10σ	Mimir 10σ in 1 hour	Mimir 3σ in 1 hour
J	15.8	19.65	20.95
H	15.1	19.00	20.29
Ks	14.3	17.40	18.73

  - **Spectroscopy** (single Grism: **JHK**, **LM**, or **SED**)
  - **Imaging Polarimetry** (H-band + wire grid) – ***Unique capability***
- "Facility Class" instrument
  - To be open for use by certified Lowell and BU observers, vistors
  - Lives at the telescope, under vacuum and cold all the time
- First telescope light has taken place
- User access CY2005

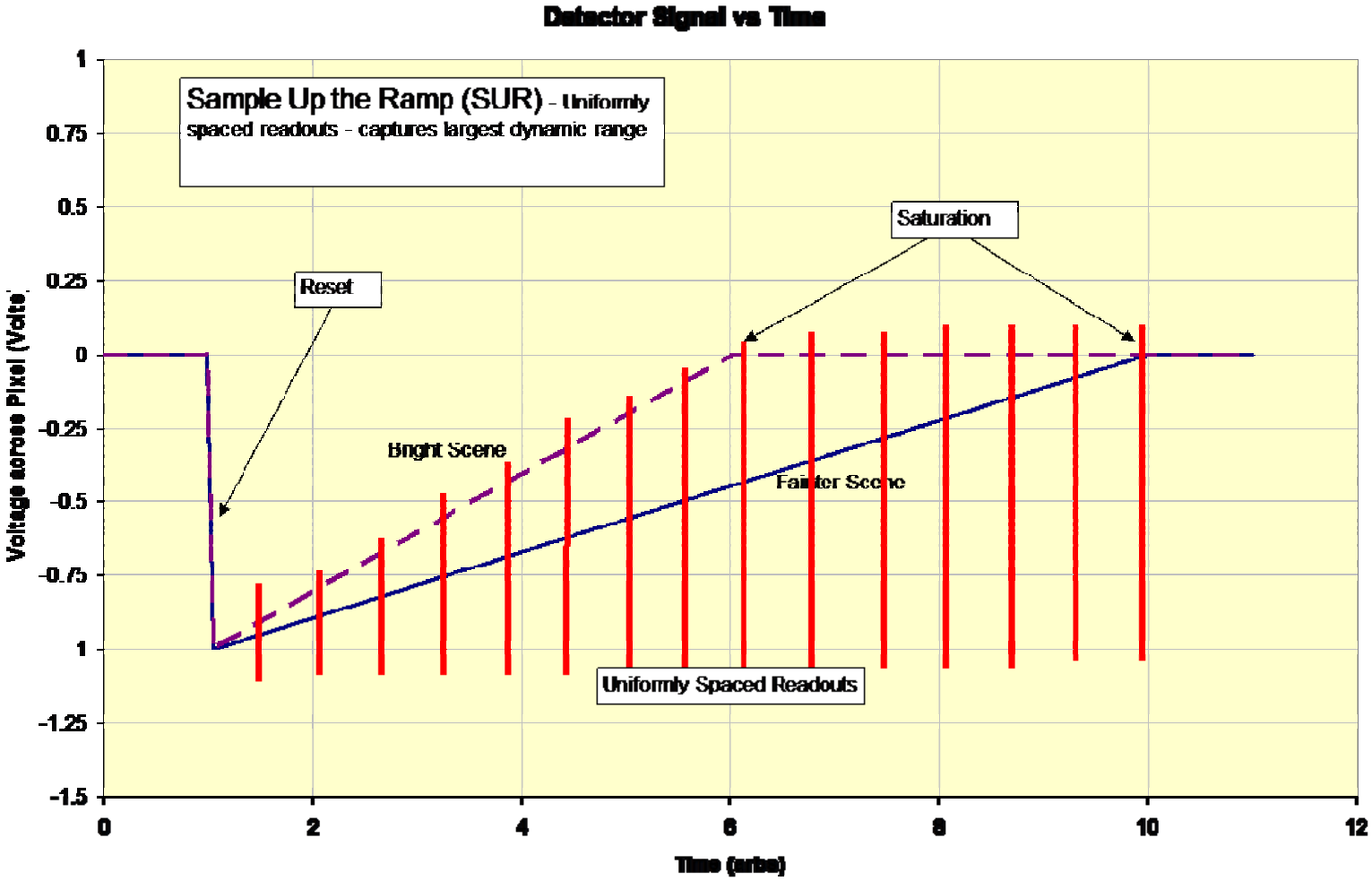
How to Use Mimir: Detector Signal Sampling Methods



Fowler Sampling



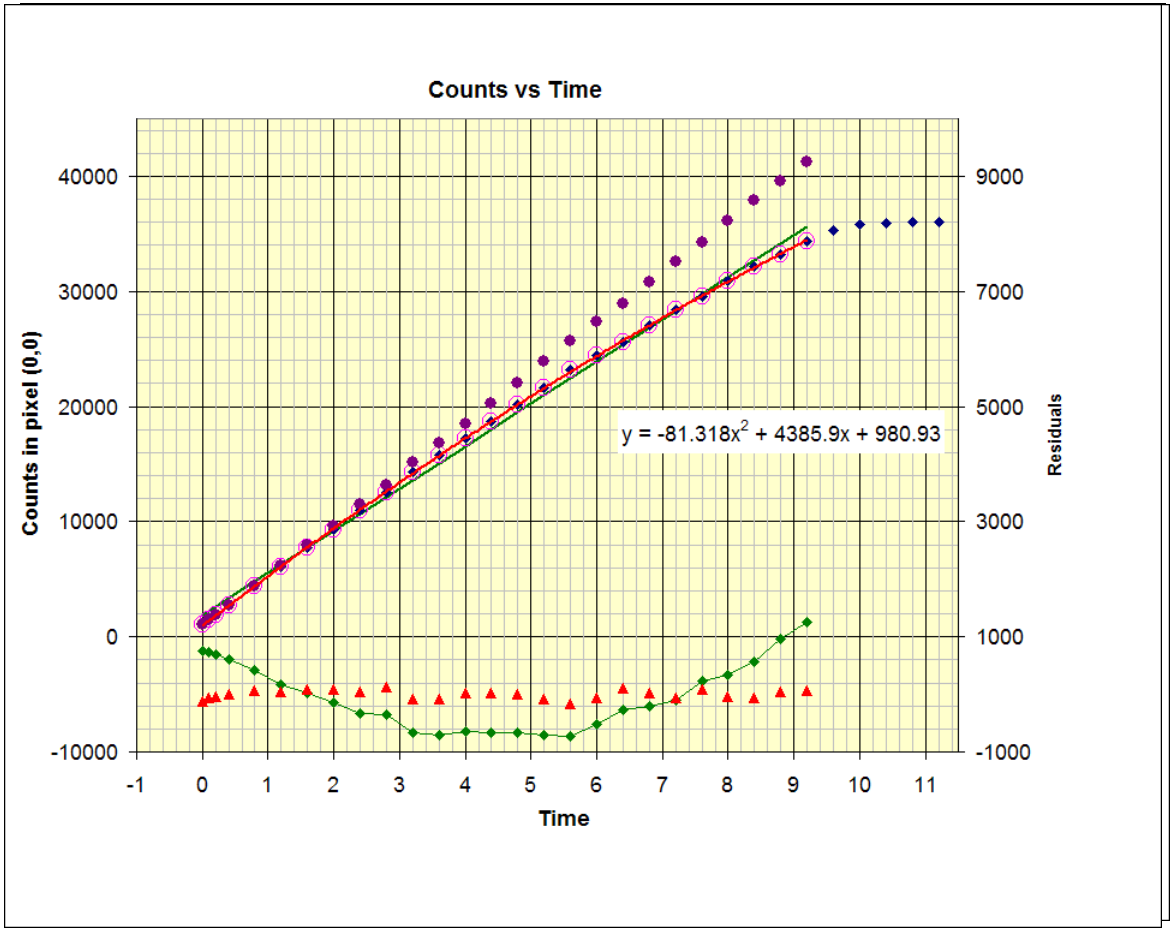
Sample Up the Ramp



Sampling Applications

- CDS – “Normal” Imaging (JHK) - **Implemented**
- Fowler – Short Wavelength (JHK) Spectroscopy – **In Process**
  - Read Noise Limited
  - Long-ish integration times (2-5 minutes)
- SUR – High dynamic range imaging, spectroscopy – **Future**
  - Strong Emission Lines, weak continuum
  - Bright stars, faint companions
- Reset-Read - **Future**
  - High background, full field imaging (L & M)
  - Single read only – must take “bias, darks”
- Other Modes:
  - –Subframe readout – arbitrary sized rectangle, centered – **In Process**
    - Boosts readout speed, sampling interval
  - –Coadding – consecutive CDS or Reset-Reads, accumulated – **In Process**
    - High backgrounds (L & M) or high dynamic range

Linearity Correction
(InSb Detectors are NOT CCDs!)

Dome Flats with exposure times from 0 to 11.2 seconds

- Raw Data
  - Saturation Seen
  - Counts at Zero Time
- Zero Offset = 1 Frame Read Time
  - 0.27s / (1024 x 32) = 8.2us per pixel
- Saturation Detection
  - Major slope change
- Linear Fit & Residuals
  - Not good enough
  - 0-20% deviations
- Quadratic Fit & Residuals
- Corrected (linear) Counts