MYSTIC*

Michigan Young STellar Imager at CHARA

Michigan: John D. Monnier, Jacob Ennis, Ben Setterholm

IPAG: Jean-Baptiste le Bouquin, Laurent Jocou

Arizona: Narsireddy Anugu

Exeter: Stefan Kraus

CHARA: Theo ten Brummelaar, Cyprien Lanthermann

*funded by the National Science Foundation

Science Motivation

Primary Science goal is to image the inner disks of Young Stellar Objects

- K band sensitivity better for T Tauri Stars and will allow "temperature mapping" of the inner disk when combined with MIRC-X

	MWC275 (Herbig Ae)	V1295 Aql (Herbig Be)	SU Aur (T Tauri)
J/H/K uncorrelated	6.2 / 5.5 / 4.8	7.2 / 6.6 / 5.9	7.2 / 6.6 / 6.0
Visibility (V) on longest baseline	0.3? / 0.2 / 0.1	0.5? / 0.3 / 0.2	0.6? / 0.5? / 0.4
J/H/K correlated	7.5 / 7.2 / 7.3	8.0 / 7.9 / 7.6	7.8 / 7.3 / 7.0

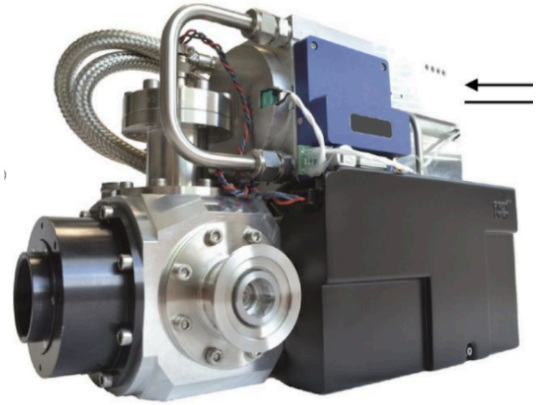
Secondary Science goal is to detect exoplanets with precision closure phases

Tertiary Science goal is to explore Spectro-Interferometry

- YSOs, Be stars (Br-gamma); cool stars (CO)

Requirement: MYSTIC integration with MIRC-X and SPICA for simultaneous V+R+J+H+K observing with all 6 telescopes (!)

MYSTIC Instrument Architecture



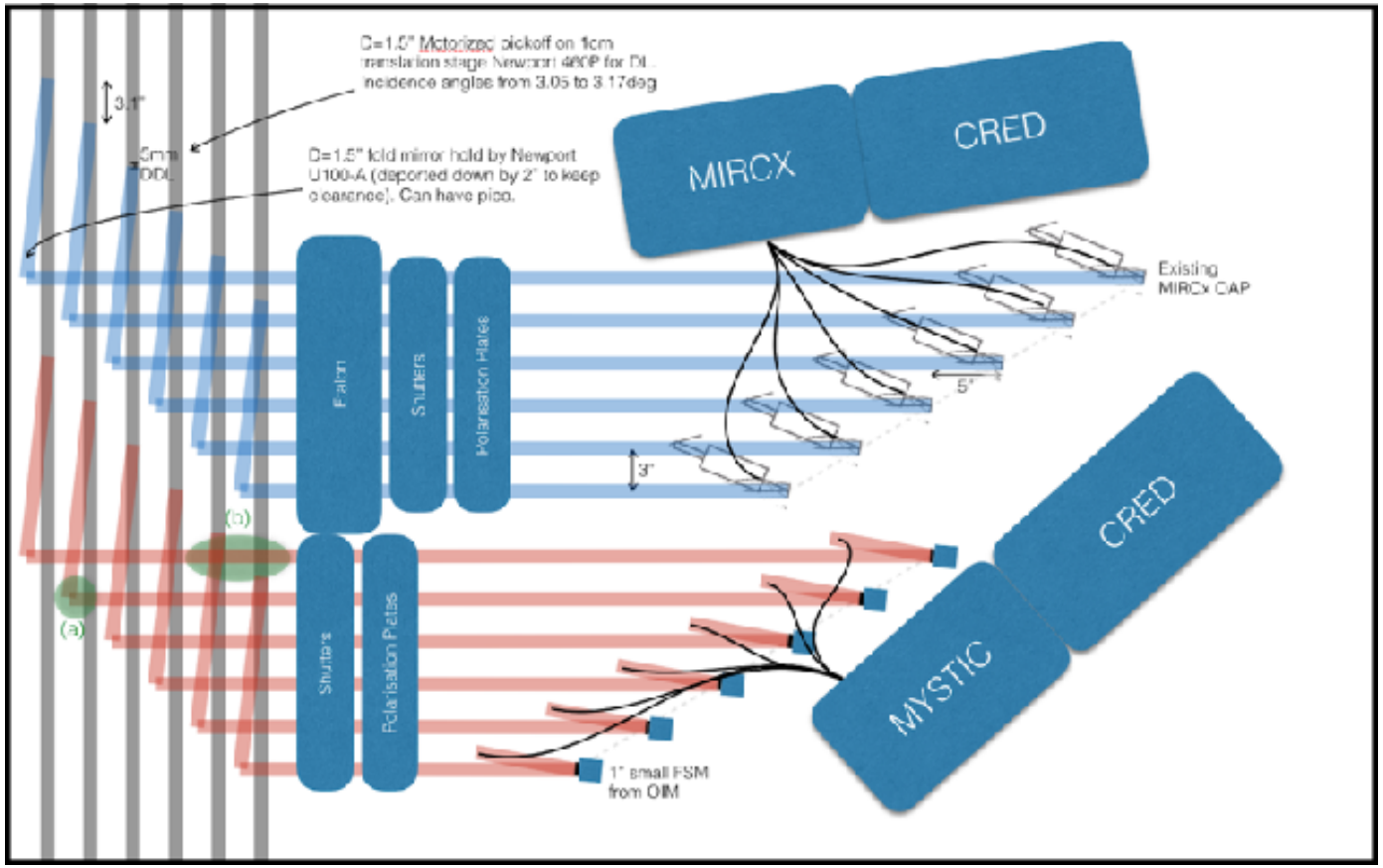
- CRED-One e-APD Camera (80K)
  - Low readnoise (yes!), low background (not so much)
- Custom Cryostat (200K, cryocooled) for Combiners/Spectrograph
  - Fed by single-mode fibers
- TWO COMBINERS:
  - 4-beam mode for high sensitivity
    - Using spare GRAVITY IO chip, No cross talk
  - 6-beam mode for snapshot imaging
    - Using “classic” MIRC-style combiner
- Wollaston mode for polarization experiments
- Many options for prisms/grisms for spectroscopy

PRISMS	GRISMS
R=20	R=278
R=50	R=981
R=100	R=1726 (CO + Br-γ)

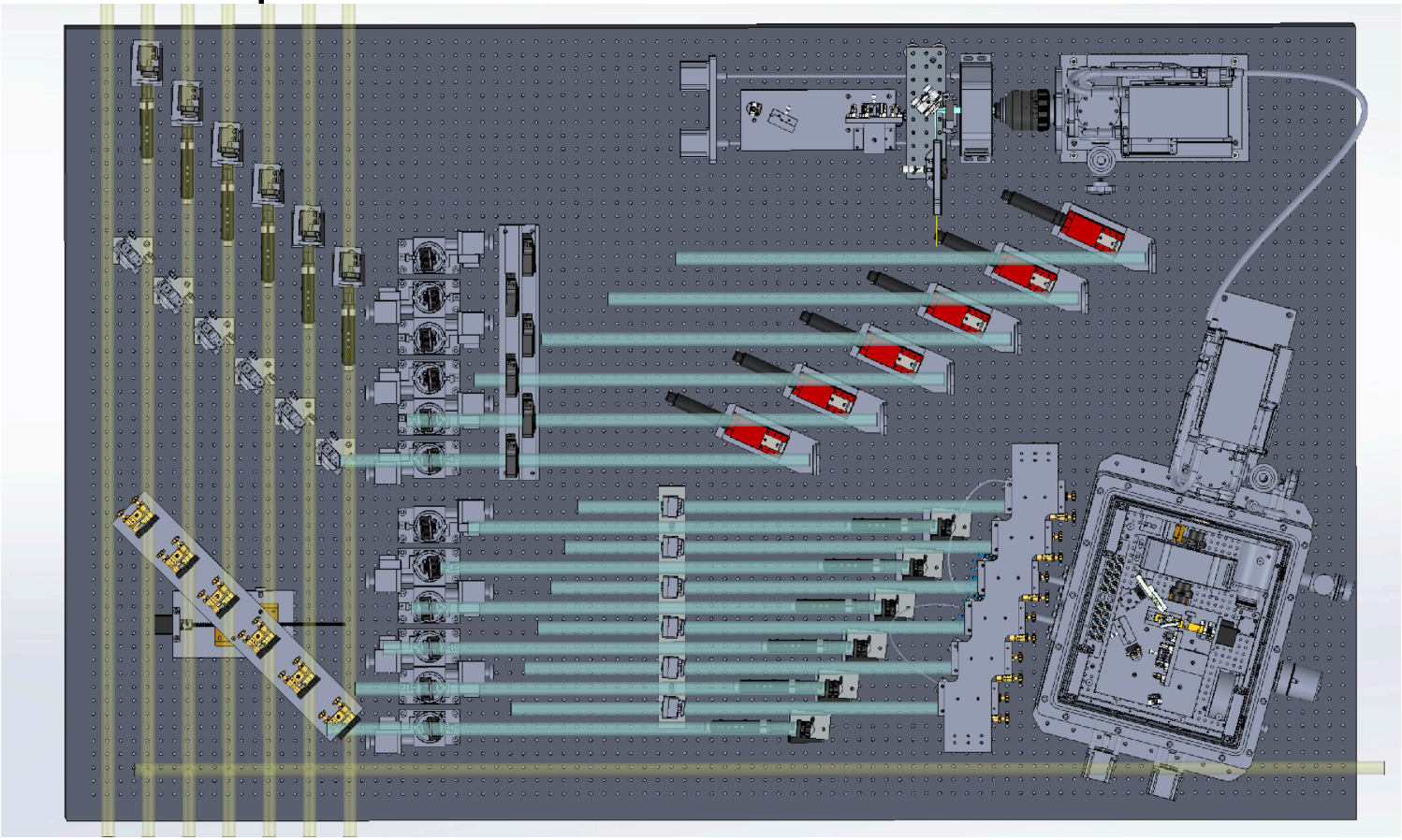
Amazing Team Effort

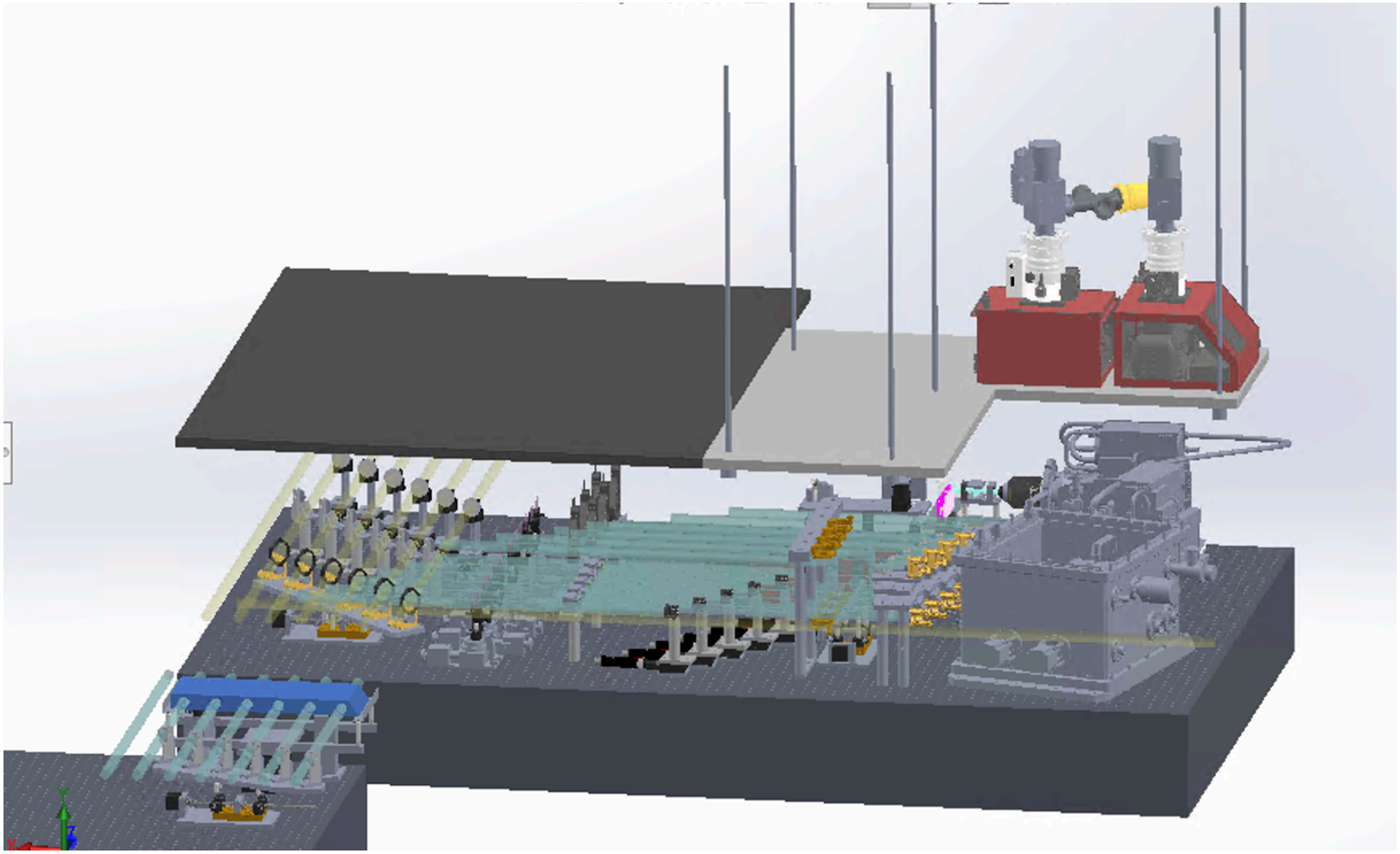
- John Monnier (PI, UM)
- Jean-Baptiste le Bouquin (IPAG -> UM -> IPAG)
- Narsireddy Anugu (Exeter -> Arizona)
- Stefan Kraus (Exeter)
- Ben Setterholm (UM graduate student)
- Jacob Ennis (UM undergraduate -> UM alum)
- Cyprien Lanthermann (IPAG -> Leuven -> CHARA)
- Laurent Jocou (IPAG)
- Theo ten Brummelaar + whole Mountain team

Progress Report – How we started



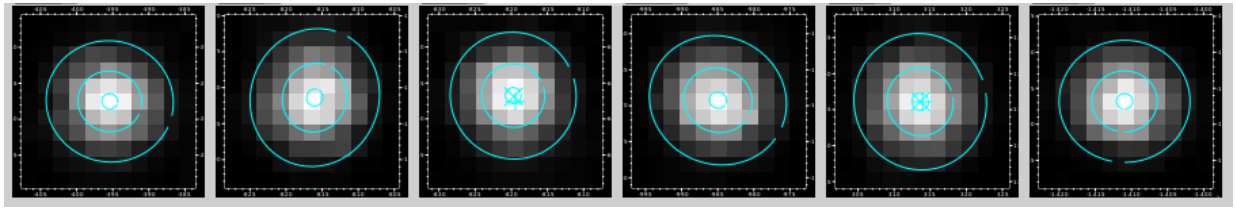
Progress Report – Where we are!





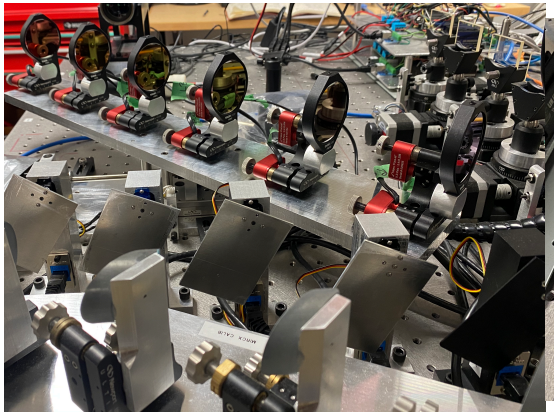
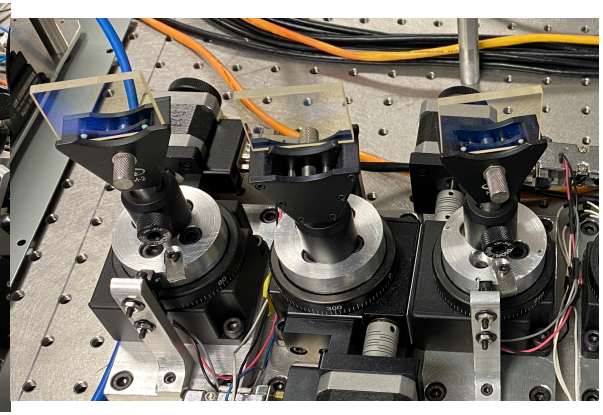
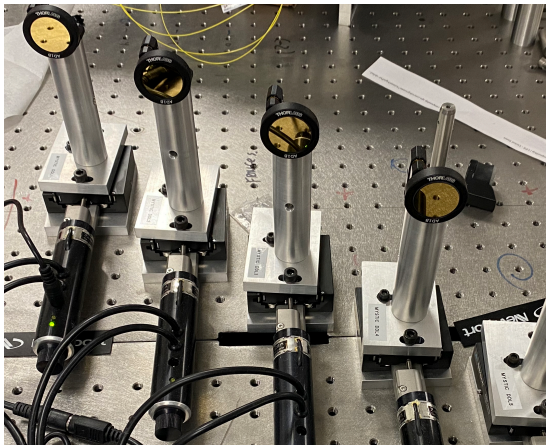
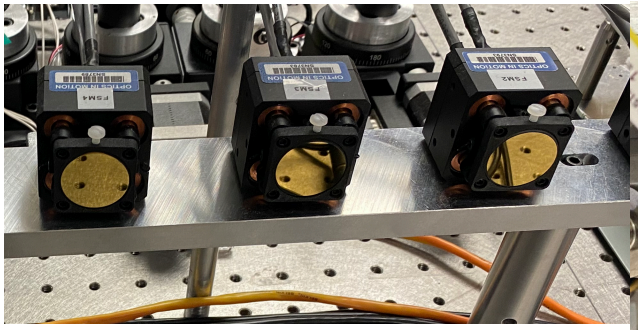
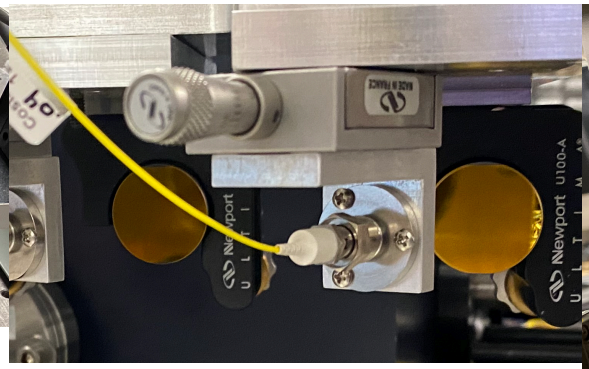
Warm Optics Status

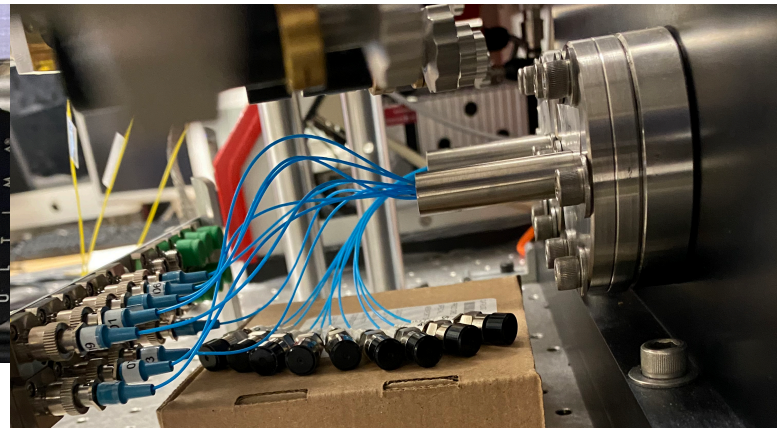
- Lab 6-beam Star Simulator — Installed, motorized, and tested
- Updated Arduino-based Shutters — Installed, motorized, and tested
- New Custom Dicroics to pick-off MYSTIC light — Installed, motorized, and tested
- New Lithium Niobate Plates for Polarization Control — Installed, motorized, and tested
- Folded differential delay lines w/ stepper motors
- Voice-coil actuated tip-tilt mirror for fiber injection — Installed, motorized, and tested.
- Custom diamond-turned Off-axis Parabolas
  - Original plan to use Edmund Optics OTS mirrors failed



Full system working end-to-end

Quick Tour of Warm Optics



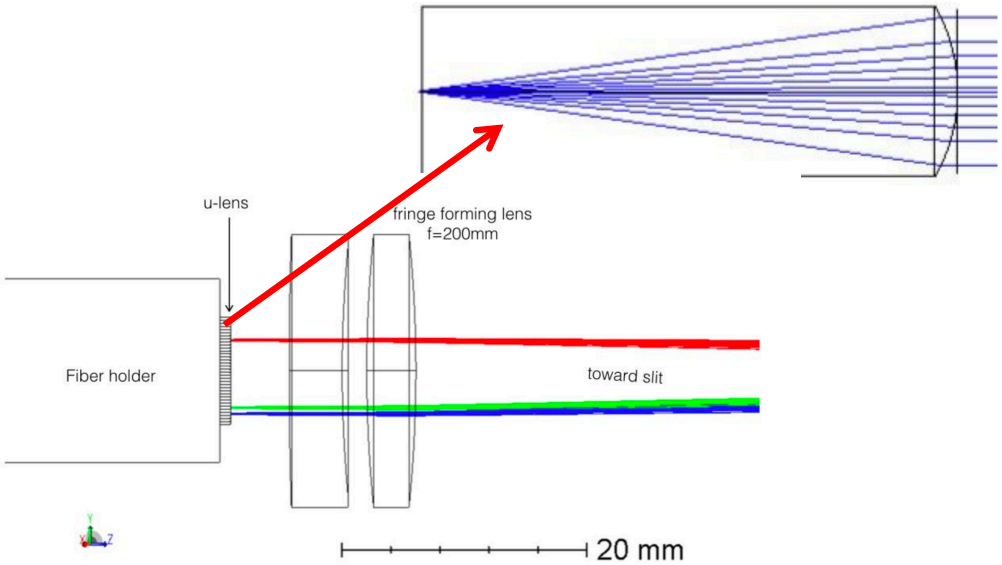
Fibers

- Extensive testing of PM1950 fiber (silica, not fluoride)
  - NA 0.2, cutoff 1.7mu
  - Large NA required custom lenslet arrays $$$$
- 3 fibers: OAP Patch (0.45m), Feedthrough (0.4m), V-groove (0.2m)
- Throughput between 80%-60% (1.9->2.4mu)
- Coastal Connections was a great vendor to work with for length matching and feedthrough
- We measured of every fiber length (using Luna backscatter reflectometer)
  - Mixing/matching: <75mu Combiner1, <0.5mm GRAVITY
- Late addition: Adding 4 'extra' OAPs on moving periscope so we can switch between the GRAVITY and V-groove combiners w/o unplugging fibers
  - We should develop a similar system for MIRC-X IO fringetracker

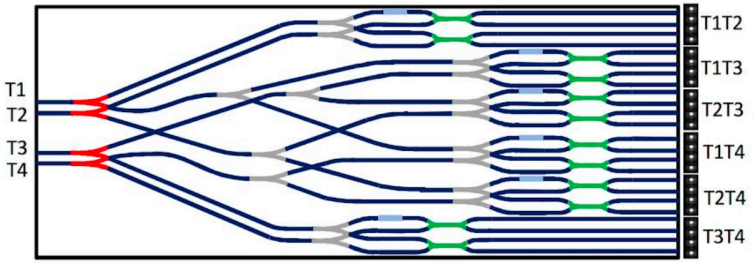
MYSTIC 1	1	2	3	4	5	6			
Patch 1	3	1	7	6	4	2	MAX-MIN	1165	µm
Feedthrough 1	6	3	7	2	1	9	RMS	441	µm
Patch 2	1	3	5	4	2	8	MAX-MIN	515	µm
Feedthrough 1	6	2	3	7	1	9	RMS	158	µm
Patch 1	3	8	7	2	4	1	MAX-MIN	497	µm
Feedthrough 2	1	7	5	3	8	9	RMS	160	µm
Patch 2	***3***	***4***	***2***	***8***	***7***	***5***	***MAX-MIN***	***73***	µm
Feedthrough 2	***3***	***2***	***7***	***1***	***8***	***9***	***RMS***	***23***	µm
Patch 1	5	1	7	6	4	2	MAX-MIN	1103	µm
FT 3 w/o #6	5	2	8	9	3	4	RMS	392	µm
Patch 2	3	5	6	4	2	1	MAX-MIN	568	µm
FT 3 w/o #6	5	9	2	7	3	1	RMS	194	µm

Two COLD combiners:

- MIRC-Style
  - 6 beams = 15 fringes
  - w/ photometric channels split with custom pol-neutral BS

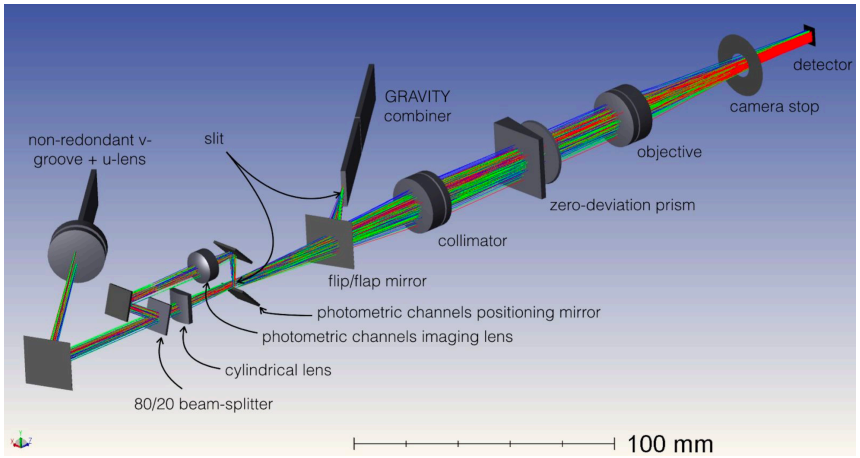


- GRAVITY
  - 4 beams = 6 fringes
  - 4 outputs/fringe ABCD => 24 outputs
  - 180 mu separation
  - MORE SENSITIVE: fewer pixels, lower spectral resolution

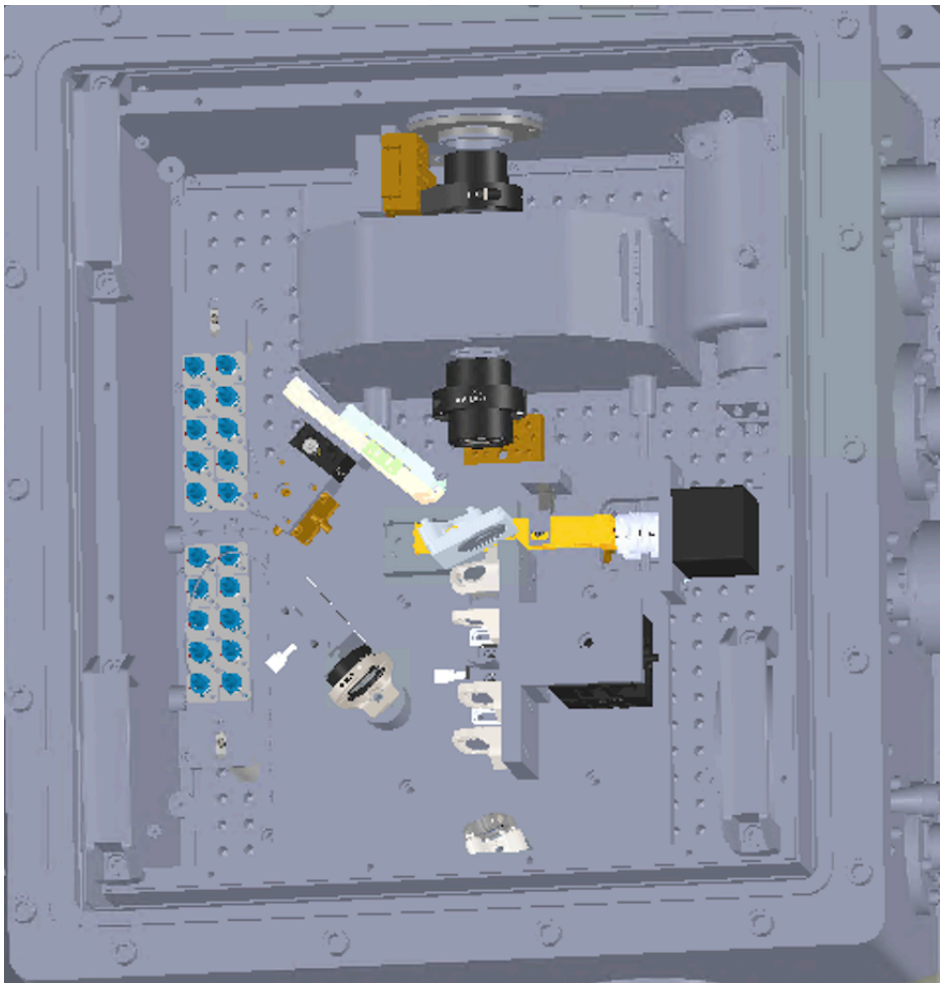


MYSTIC Cryostat

- From Design to Build

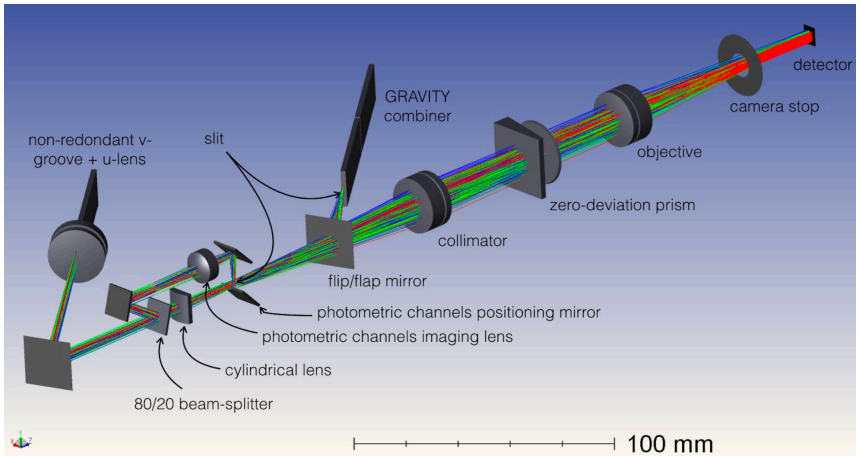


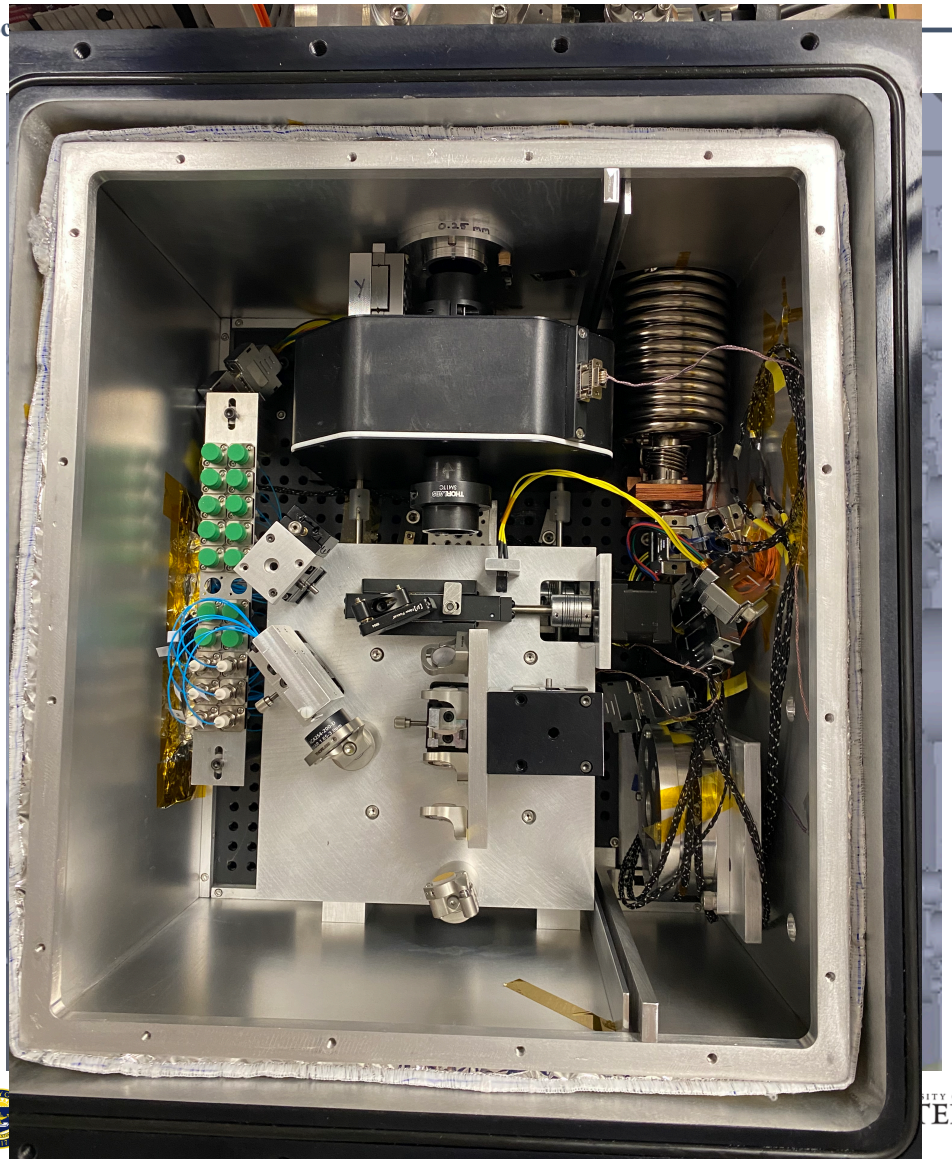
- GRAVITY combiner not installed



MYSTIC Cryostat

- From Design to Build

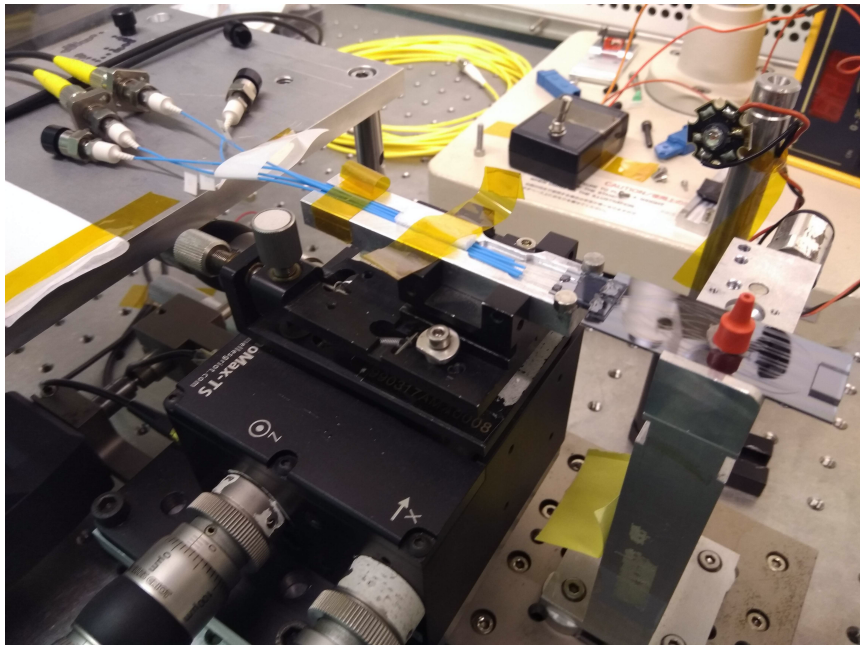


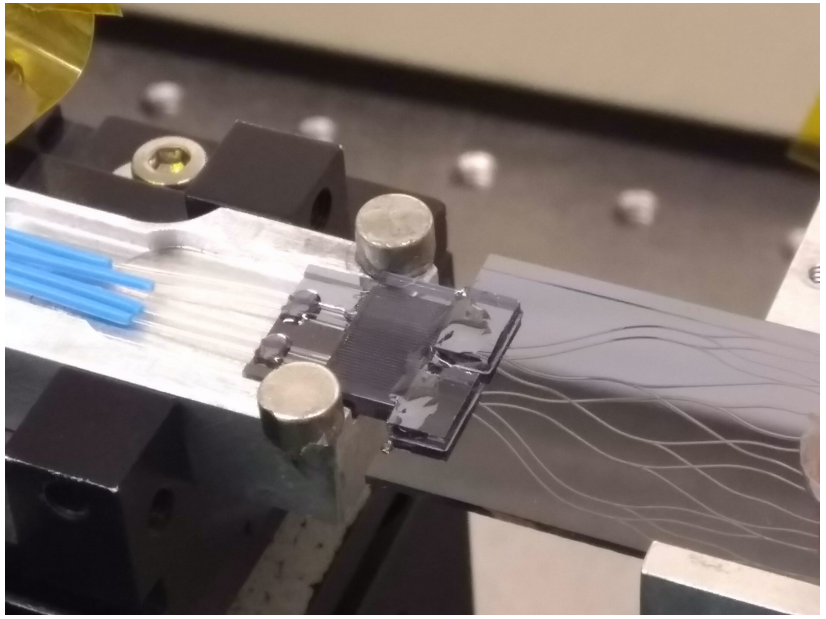


- GRAVITY combiner not installed

Preparing the GRAVITY Chip in IPAG

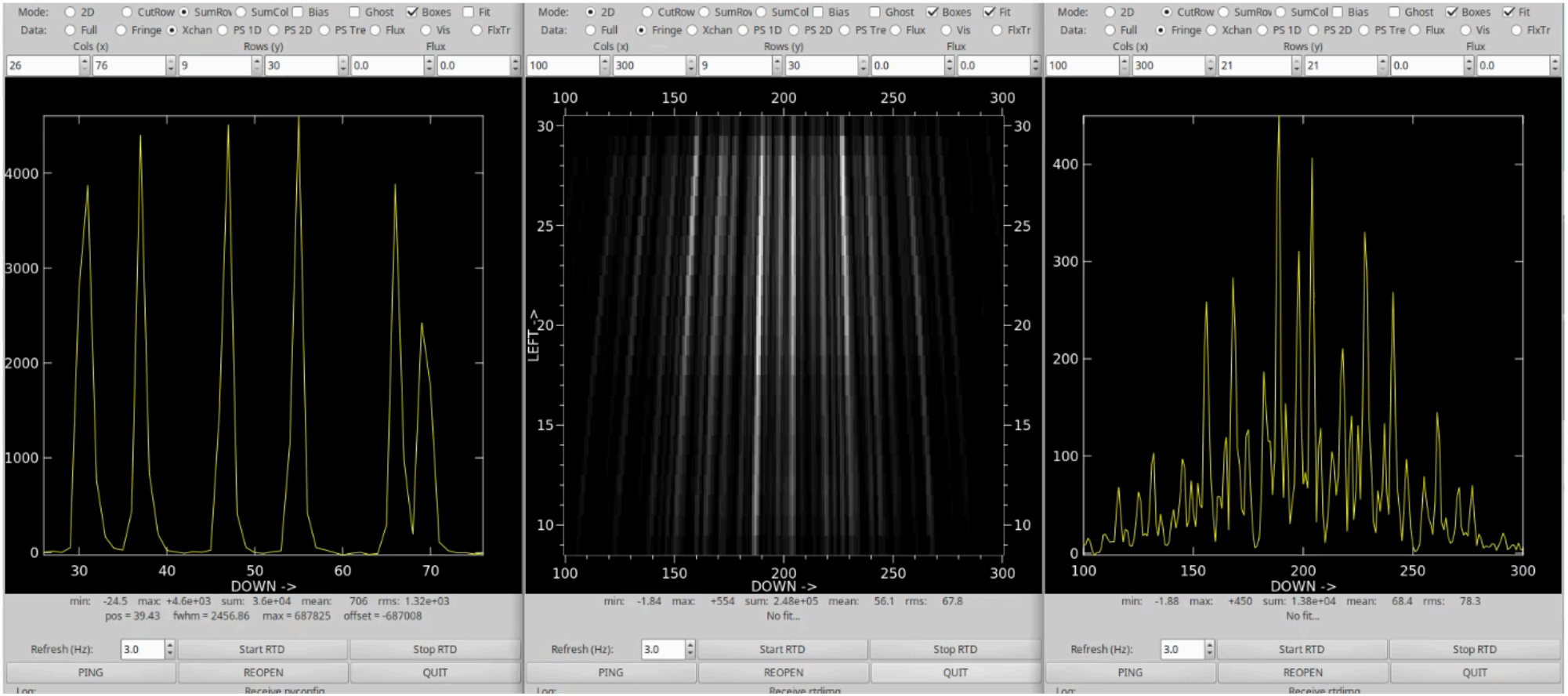
- Gluing v-groove to integrated optics chip
- Gluing beam-shiping micro-lens arrays to output of chip
- Robust packaging and mounting for shipping and cryogenic shrinkage





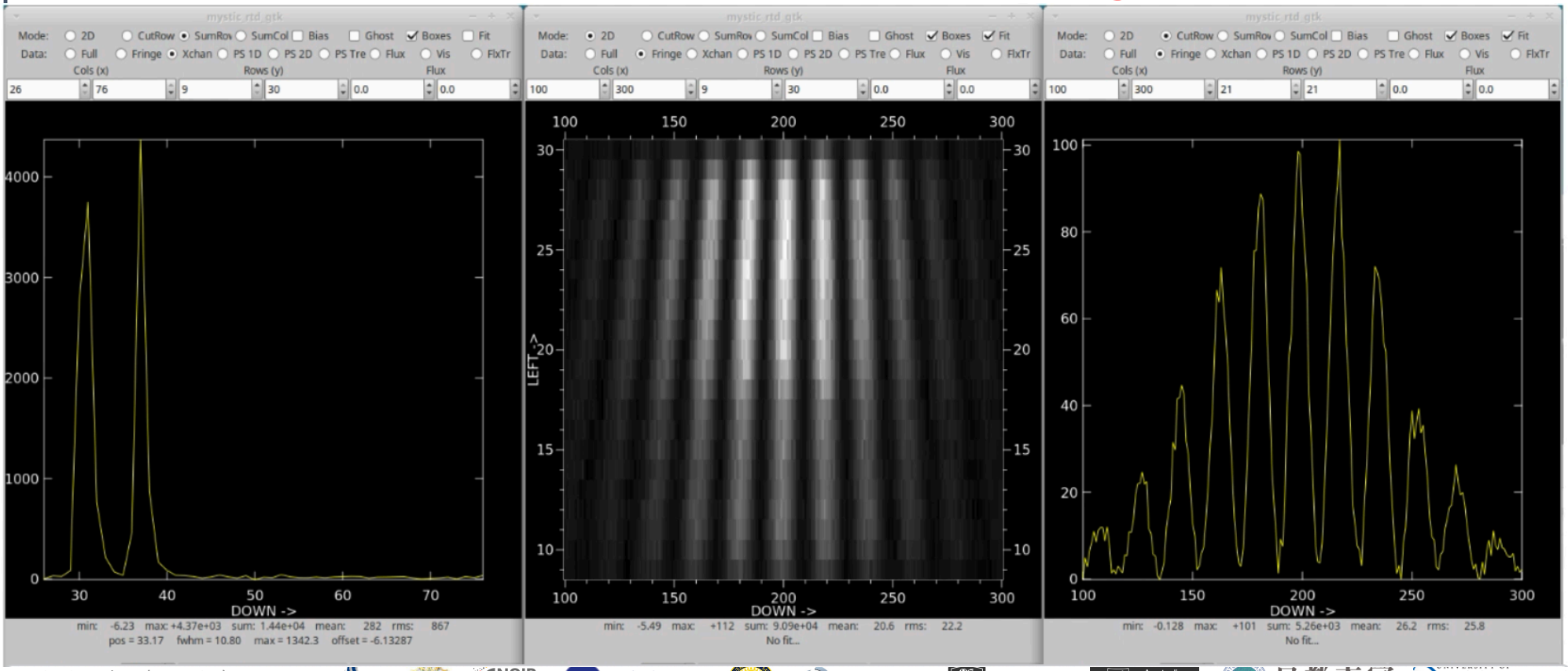
System is fully tested end-to-end (WARM)

All 6 beams

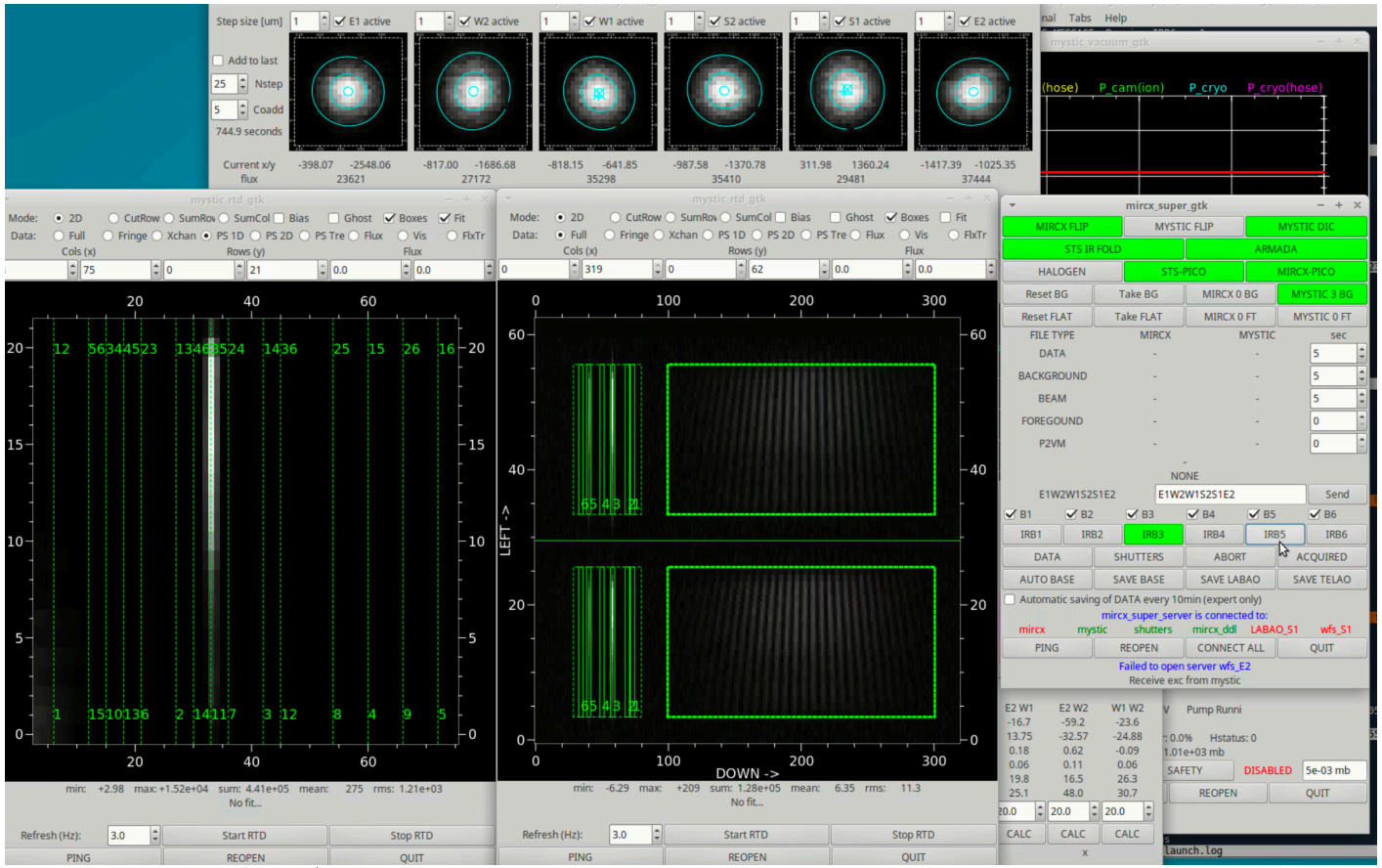


System is fully tested end-to-end (WARM)

Just 2 beams to see nice fringes!

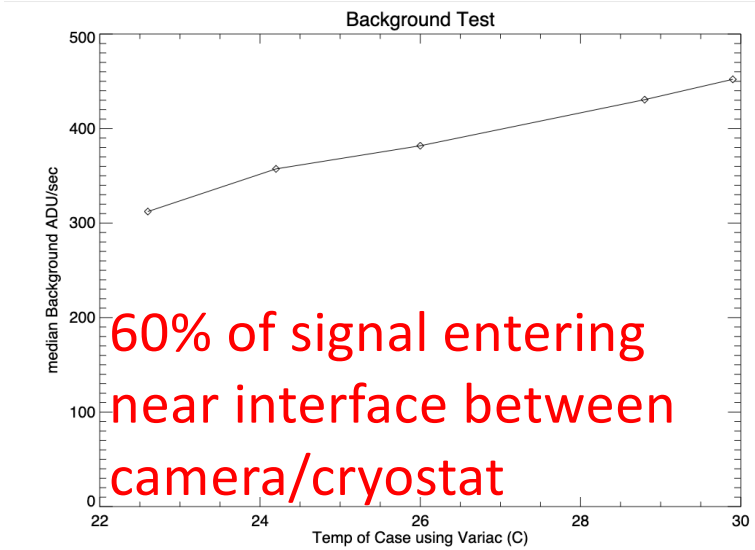


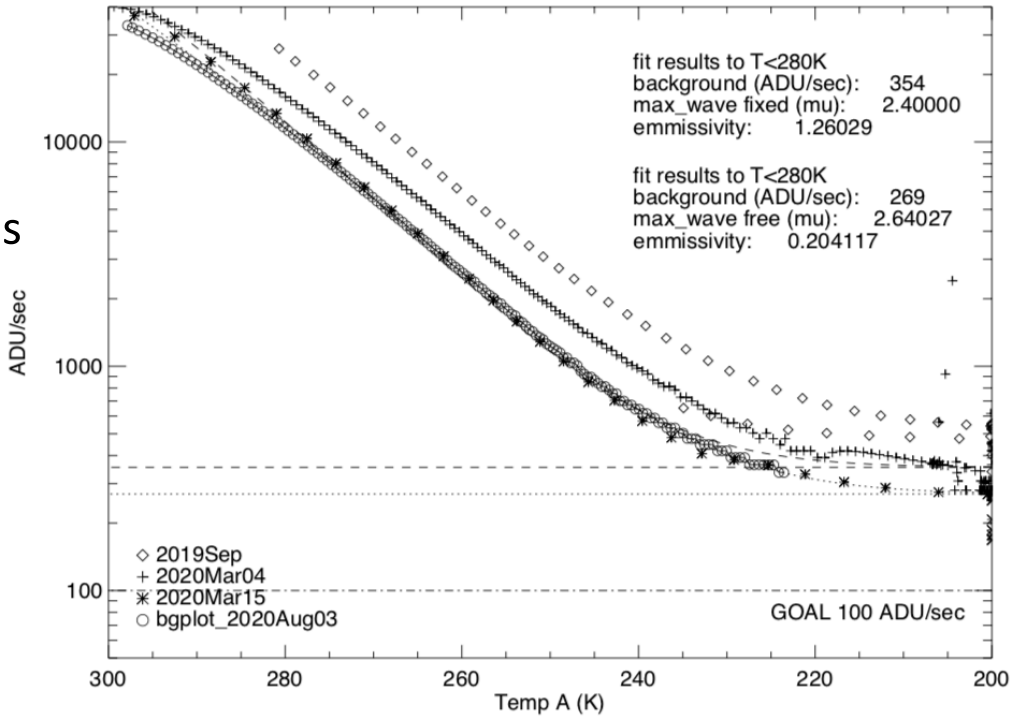
Software is mature, based on MIRC-X



Thermal Background

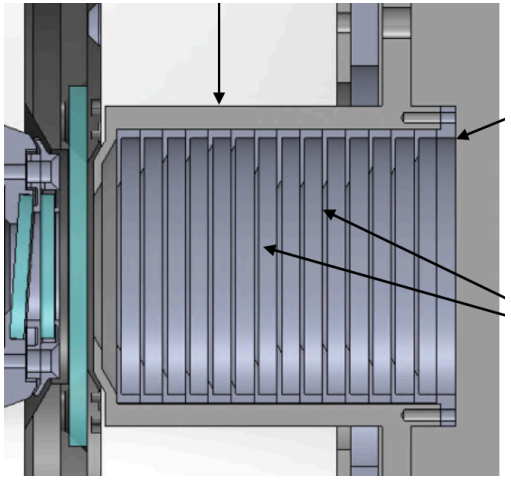
- At first we had 1200 e-/sec background
  - Originally expected <50 e-/sec
  - Higher than MIRC-X 150 e-/sec
- Now: 350e-/sec background
  - Equivalent to rms 4e- read noise t= 50ms



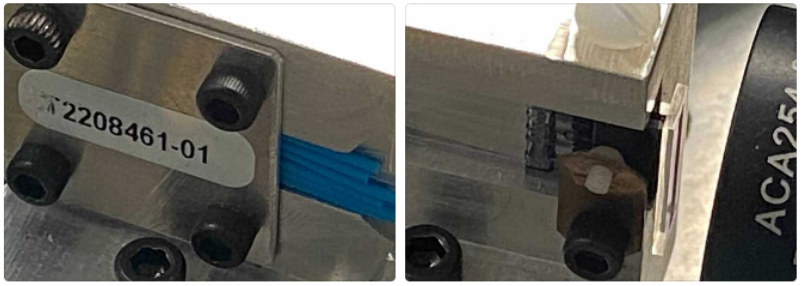


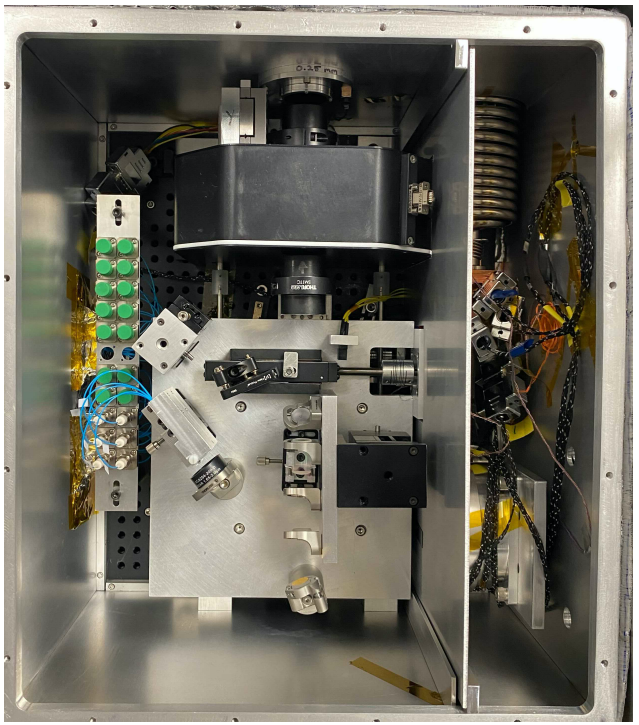
Interventions to lower background

- New Sapphire window
- Added cold cutoff filter to remove flux >2.38 microns
- Custom “Singularity Black” Baffle
- Custom-designed Baffling w/ Singularity Black Coating
- Extensive cryostat baffling of warm entry points
- Remaining options to get last factor of 2 in noise
  - Carefully clean sapphire window
  - Optimize size of cold stop in camera
  - Cool camera body (problem with vacuum sensor)
  - Take window out completely



Remaining Steps





- Test science combiner cold
  - There is risk something will break ☹
  - First cryo Test next week ☺
- Finish mounting then install/test GRAVITY chip
- *GRAVITY OAP Periscope Subsystem*
- *IR guider with new "STS" (stretch goal)*
  - *Need enw funding for decent commercial IR camera*
- Carefully ship/drive to CHARA and install
  - Best case 2021 June (??)

Final words

Huge Acknowledgment to the amazing TEAM EFFORT to build MYSTIC

- Looking forward to moving out of lab and getting on-sky as soon as we can!

Preliminary Design Review Lookback (marked in red have indeed impacted development)

Warm Optics Risk Matrix

Risk	Impact	Probability	Mitigation
Tolerance analysis insufficient	medium	Low	Lose some spectral resolution; crosstalk
Cryogenic mounting	medium	Low	Gravity experience
Poor thermal baffling for camera	medium	Medium	Detector placed as close to dewar as physically possible
Gluing lenslets	high	Medium	Extra prototype work
OTS optics fail when cold	medium	Medium	Custom optics and mounting
Alignment strategy difficult	low	Medium	Many warm/cooling cycles; add cryomotors
Accumulation of delays	high	High	Prototype with MIRCx, meet schedule...

Cold Optics Risk Matrix

Risk	Impact	Probability	Mitigation
Equalisation of fibre length	Medium	High	We will use 3-sections of fibres. Second mitigation: glass plates
Image quality of parabola	Medium	High	Buy better quality parabola. Make stiff mount of fiber.
Vignetting in the warm optics	Medium	High	Help CHARA to control the pupil shear
Impact on CHARA beams (vignetting, heat)	High	Low	Motor do not dissipate heat when not moved. Vignetting will be avoided by design.
Vibration from cryostat	High	Medium	Pre-sale discussion with provider.