Commissioning Gemini Planet Imager 2.0 (GPI 2.0) at the Gemini North Observatory

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Garima Singh, Ph.D.
GPI 2.0 Project Scientist at Gemini North
Gemini North Observatory, Hilo, Hawaii

garima.singh@noirlab.edu
ORCiD: 0000-0001-8224-9106
equanimouscorner.com
Office Ph: +1 (808)-974 2544

Land Acknowledgement - "He ali'i ka 'āina, he kauā ke kanaka"
We as scientists and educators are most fortunate to have the opportunity to conduct observations from Maunakea.

Gemini Planet Imager (GPI) Team

GPI 1.0

Bruce Macintosh, Dave Palmer, Lisa Poyneer, Brian Bauman, James Graham, Jason Wang, Paul Kalas, Quinn Konopacky, Jerome Marie, Max Millar-Blanchaer, Don Gavel, Daren Dillon, Jim Ward, Sloane Wiktorowicz, Kent Wallace, John Angione, Bijan Nemati, Chris Shelton, Fred Vescelus, James Larkin, Jeff Chilcote, Jason Weiss, Mike Fizgerald, Evan Kress, Stephen Goodsell, Markus Hartung, Kayla Harding, Brian Wolf, Carlos Quiroz, Fredrik Rantakyro, Pascale Hibon, Andrew Cardwell, Markus Hartun, Les Saddlmyer, Jennifer Dunn, Dan Kerley, Kris Kaputa, Andre Anthony, Christian Marois, Zach Draper, Darren Erikson, Jenny Atwood, Malcolm Smith, Alexis Hill, Vlad Reshitov, John Pazder, R. Oppenheimer, Remi Soummer, Anand Sivaramakrishnan, Lauret Puyeo Marshall Perrin, Schuyler Wolfe, Alex Greenbaum, Patrick Ingraham, Dmitry Savransky, Sandrine Thomas, Franck Marchis, Katie Morzinski, Rene Doyon, Simon Thibaut, Abi Rajan, Joanna Bulger, Jennifer Patience, Rob DeRosa

GPIES

PIs: Bruce Macintosh, James R. Graham, Lead Co-Is: Travis Barman, Rene Doyon, Daniel Fabrycky, Michael Fitzgerald, Paul Kalas, Quinn Konopacky, Franck Marchis, Mark Marley, Christian Marois, Jennifer Patience, Marshall Perrin, Rebecca Oppenheimer, Inseok Song, Stephen Goodsell, David Palmer, Leslie Saddlemyer, Co-Is: Etienne Artigau, Brian Bauman, Steve Beckwith, Mike Bessel, Doug Brenner, Adrian Brunini, Adam Burrows, Andrew Cardwell, Carolina A. Chavero, Christine Chen, Eugene Chiang, Jeffrey Chilcote, Robert de Rosa, Daren Dillon, Zack Draper, Gaspard Duchêne, Jennifer Dunn, Darren Erikson, Jonathan Fortney, Donald Gavel, Raphaël Galicher, Alexandra Greenbaum, Markus Hartung, Pascale Hibon, Sasha Hinkley, Patrick Ingraham, Robert King, David Lafrenière, James Larkin, Jérôme Maire, Brenda Matthews, James McBride, Ian McLean, Stanimir Metchev, Max Millar-Blanchaer, Katie Morzinski, Erik Petigura, Lisa Poyneer, Laurent Pueyo, Fredrik Rantakyro, Ramiro de la Reza, Emily Rice, Patricio Rojo, Maria Teresa Ruiz, Naru Sadakuni, Didier Saumon, Gene Serabyn, Adam Schneider, Mike Shao, Remi Soummer, Anand Sivaramakrishnan, Sandrine Thomas, Carlos A. Torres, Gautam Vasisht, Jean-Pierre Veran, Jason Wang, J. Kent Wallace, Sloane Wiktorowicz, Schuyler Wolff, & Ben Zuckerman

GPI 2.0

Jeffrey Chilcote, Quinn Konopacky, Robert J. De Rosa, Joeleff Fitzsimmons, Randall Hamper, Bruce Macintosh, Christian Marois, Marshall D. Perrin, Dmitry Savransky, Remi Soummer, Jean-Pierre Veran, Guido Agapito, Arlene Aleman, S. Mark Ammons, Sheila Balu, Marco Bonaglia, Marc-Andre Boucher, Maeve Curliss, Clarissa Do O, Jennifer Dunn, Simone Esposito, Guillaume Filion, Trevor Foote, Isabel Kain, Dan Kerley, Jean-Thomas Landry, Olivier Lardiere, Duan Li, Mary Anne Limbach, Alex Madurowicz, Jerome Maire, Max Millar-Blanchaer, Mamadou N'Diaye, Eric Nielsen, Dillon Peng, Saavidra Perera, Lisa Poyneer, Laurent Pueyo, Fredrik Rantakyrö, Eckhart Spalding, Joel Burke, Garima Singh, Christy Ricardo, Teo Mocnik, Oyku Galvan, Andreas Seifahrt

Exoplanet Survey

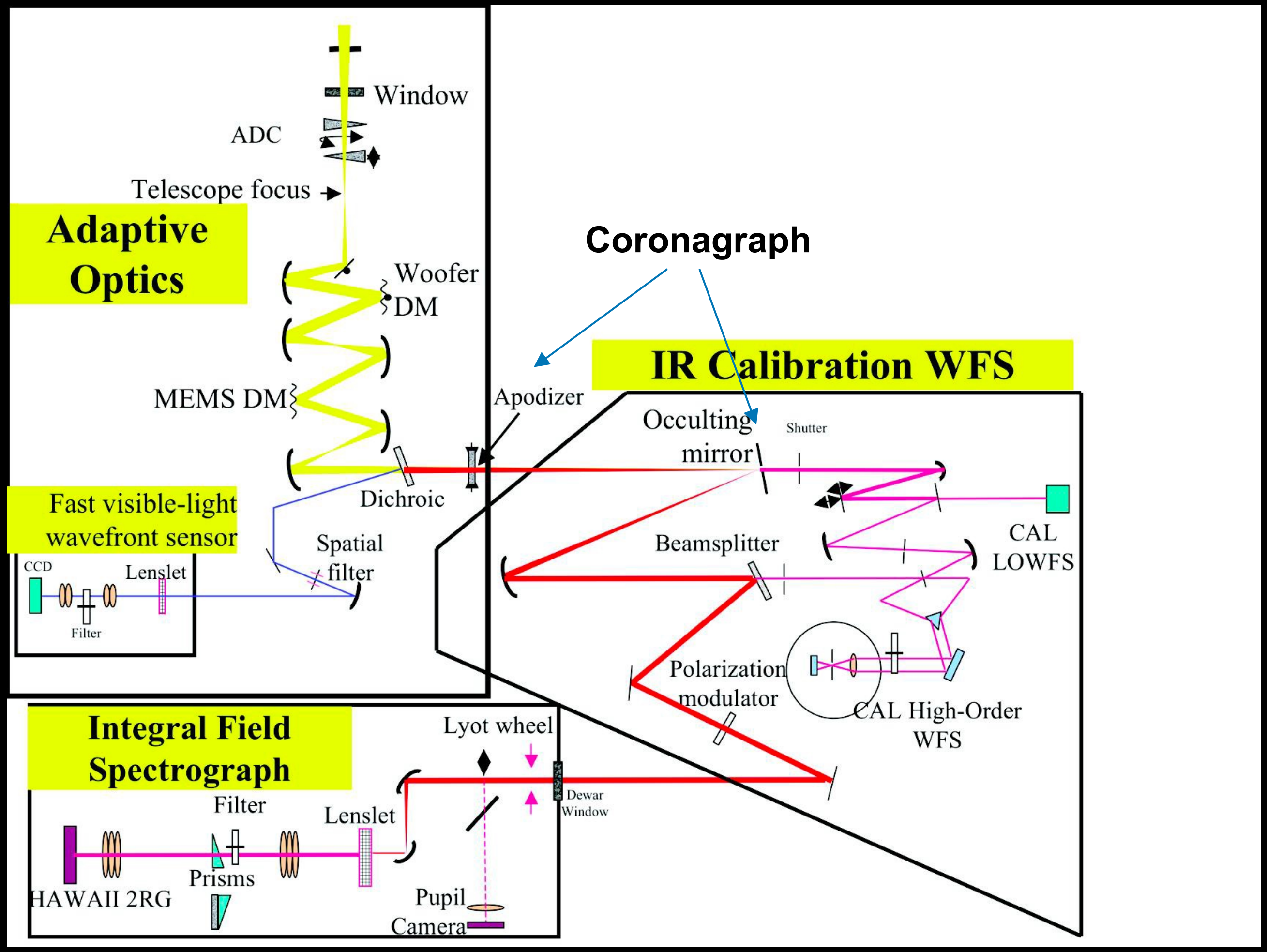
Gemini Planet Imager (GPI)
GPI 1.0 – Gemini South, Chile (2014B – 2020A)
GPI 2.0 – Gemini North, Hawaii (commissioning ~ early-2026)

- Gemini Planet Imager 1.0 (GPI 1.0), Gemini South, Chile.
- Gemini Planet Imager 2.0 (GPI 2.0), Gemini North, Hawaii.
- Commissioning of GPI 2.0 at Gemini North.

Lisa Poyneer (left) and Bruce Macintosh (right)
GPI 1.0 (instrument at the bottom port)

Cassegrain focus of Gemini South

Optical layout of GPI 1.0



Macintosh et al., 2008

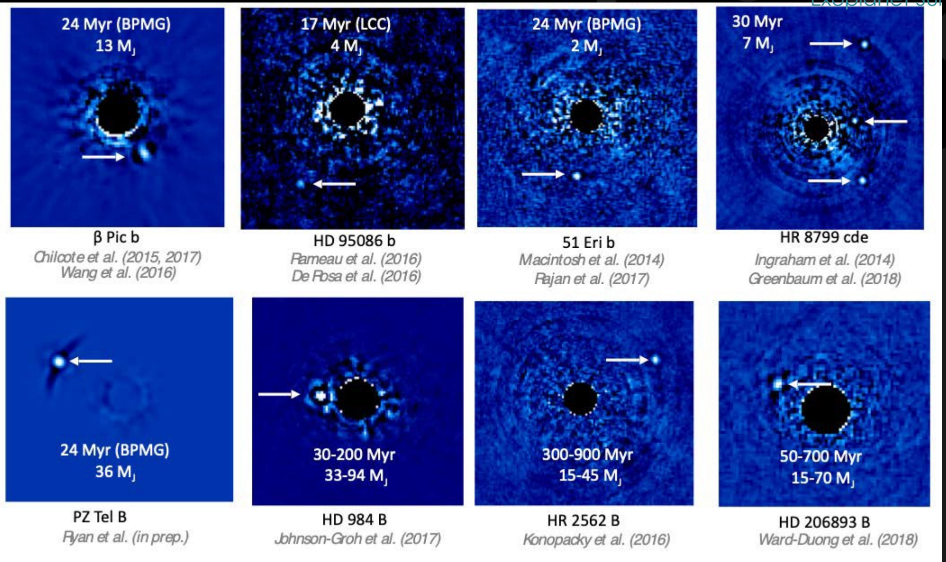
- The first light was on November 11, 2013.
- Six years in operation (2014B- 2020A).
- Wavelength range 0.97-2.4μm
- A high-order Adaptive Optics system, MEMS 4096-actuator Deformable Mirror and a Piezo Woofer System (5 bad actuators).
- Spatially-filtered Shack-Hartmann Wavefront Sensor, 160 x 160 pixel Lincoln Labs CCD.
- 1 kHz update rate on bright targets (I < 8), 500 Hz on fainter stars. ~ 1.4 ms delay.
- I < 9-10 mag limit (due to detector read-out noise).
- Coronagraphs, and an interferometric calibration, feeding a 1 - 2.4 μm Integral Field Spectrograph (IFS) with a 2.7” x 2.7” Field of View.
- Excellent data reduction pipeline.

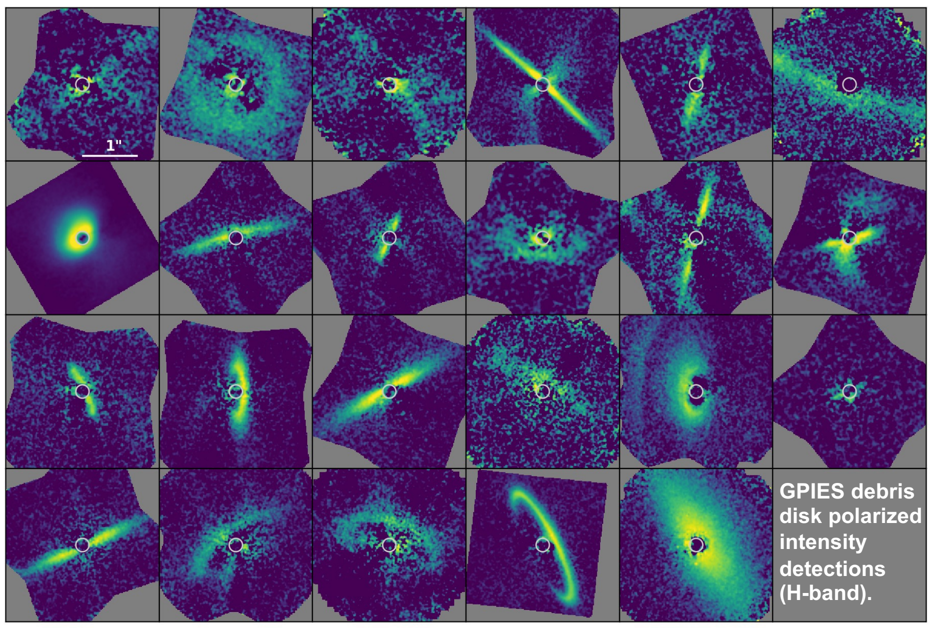
Gemini Planet Imager 1.0: Science Yield

GPIES survey: 300 stars survey (8 – 300 Myr age),
Detected 3 brown dwarfs, and 6 giant planets

- Wide-separation giant planets (5-13 M_{Jup} at 10 – 100 au) had higher occurrence rates around higher-mass ($\gtrsim 1.5 M_{\odot}$) stars compared to Solar-type stars.

- Most Jupiter-mass planets are located at < 10AU.

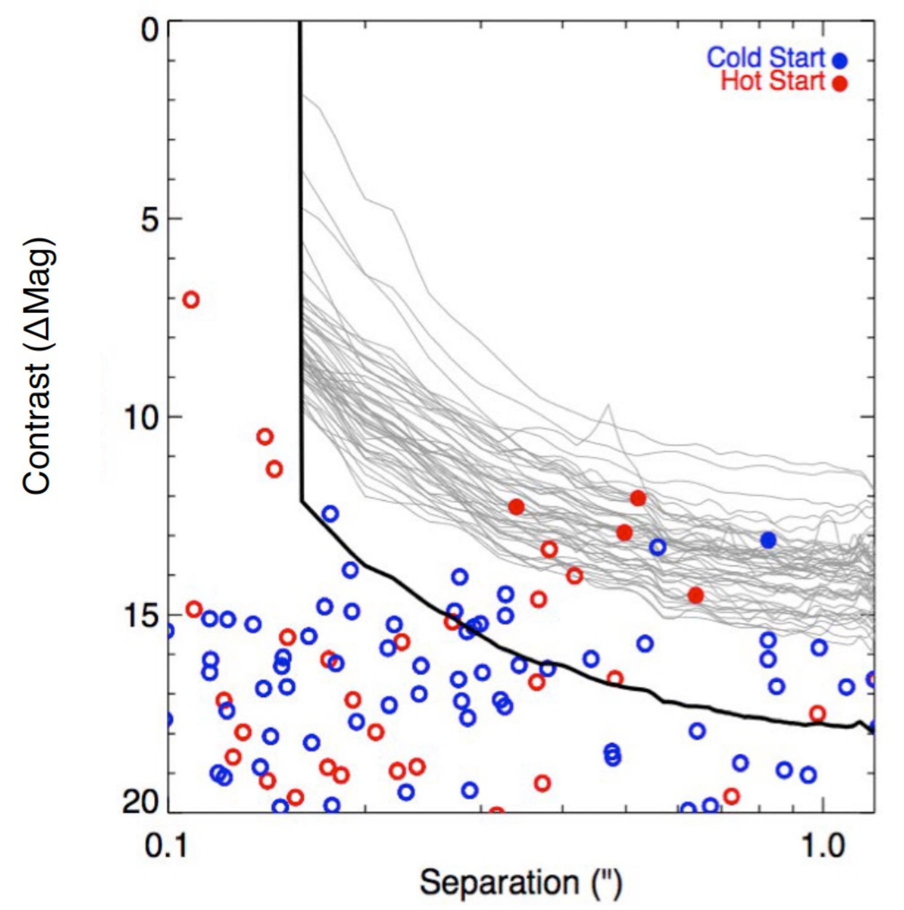




GPIES debris disk polarized intensity detections (H-band).

Neilson et al., 2019 http://planetimager.org/ Esposito et al., 2020

Gemini Planet Imager 2.0: Science Motivation

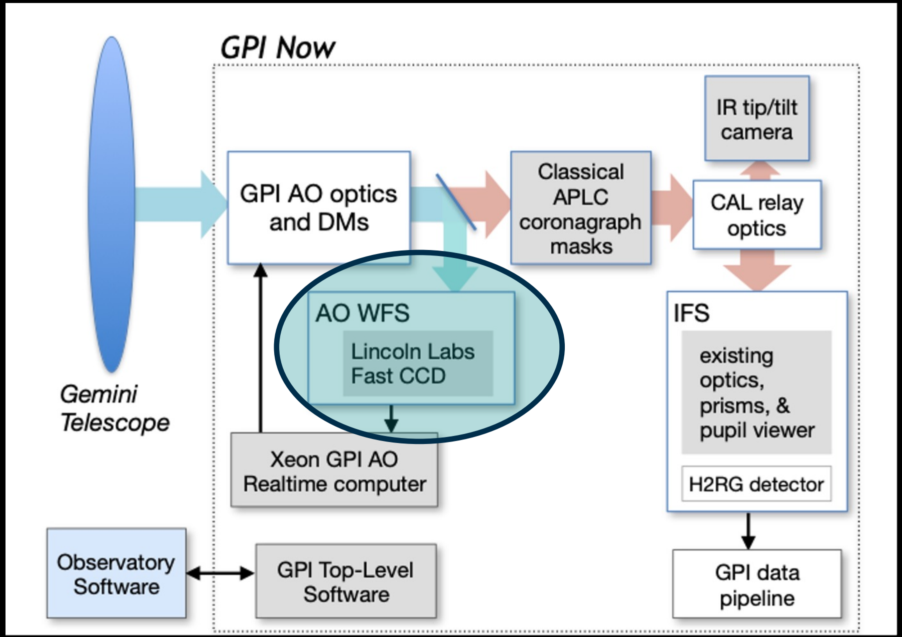


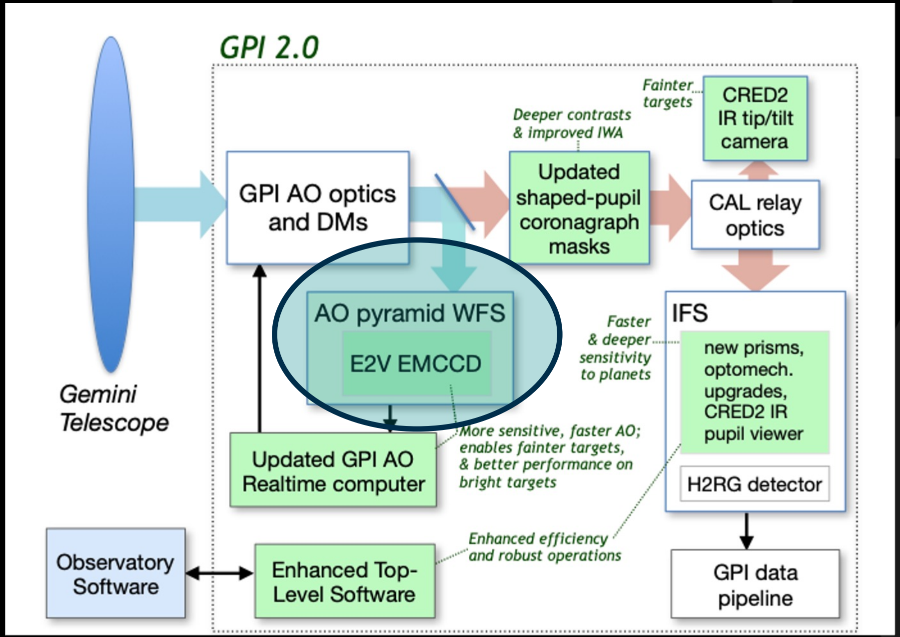
Monte Carlo Simulations of the Universe

Science Cases	WFS I Mag Limit	Inner Working Angle	Contrast Improvement
Large scale survey / cold-start planets	10	0.15″	2+ mag
Very young stars + transitional disks	13 (or IR WFS)	0.1″	0
Asteriods & solar system objects	13-14	-	0
Debris Disks	9	0.2″	0
Planet Variability & abundance charcterisation	6	0.2″	1% photometry, high-res
Evolved Stars	9	0.1″	0
Nearby AGN	14	-	Only modest contrast required

- Exoplanets around nearby low-mass M-stars. Constrain giant-planet distribution as a function of the semi-major axis around nearby young stars.
- Search for higher-mass planets around older stars (300-500 Myr) within 30 parsecs
- Protoplanets around young, bright, nearby stars and imaging their transition disks
- High-resolution spectropolarimetry of planetary atmospheres
- Characterize the physical properties of the Solar system objects (such as Asteroids)
- Study outflows from evolved stars, and inner regions of nearby Active Galactic Nuclei

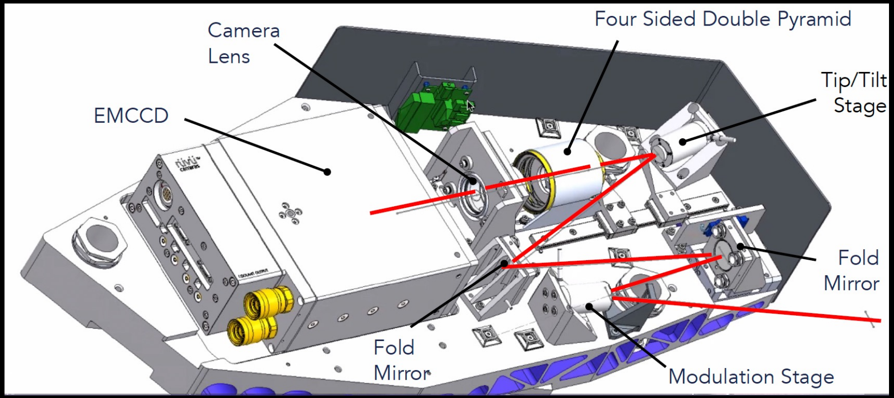
Chilcote et al., 2018, 2020, 2022





Upgrades

- Pyramid Wavefront Sensor using an EMCCD: More sensitive → better AO performance on bright stars (faster) / allowing access to fainter targets (I<14).



Based on the TMT NFIRAOS AO system

Design HAA, Canada,
Build Univ. of San Diego

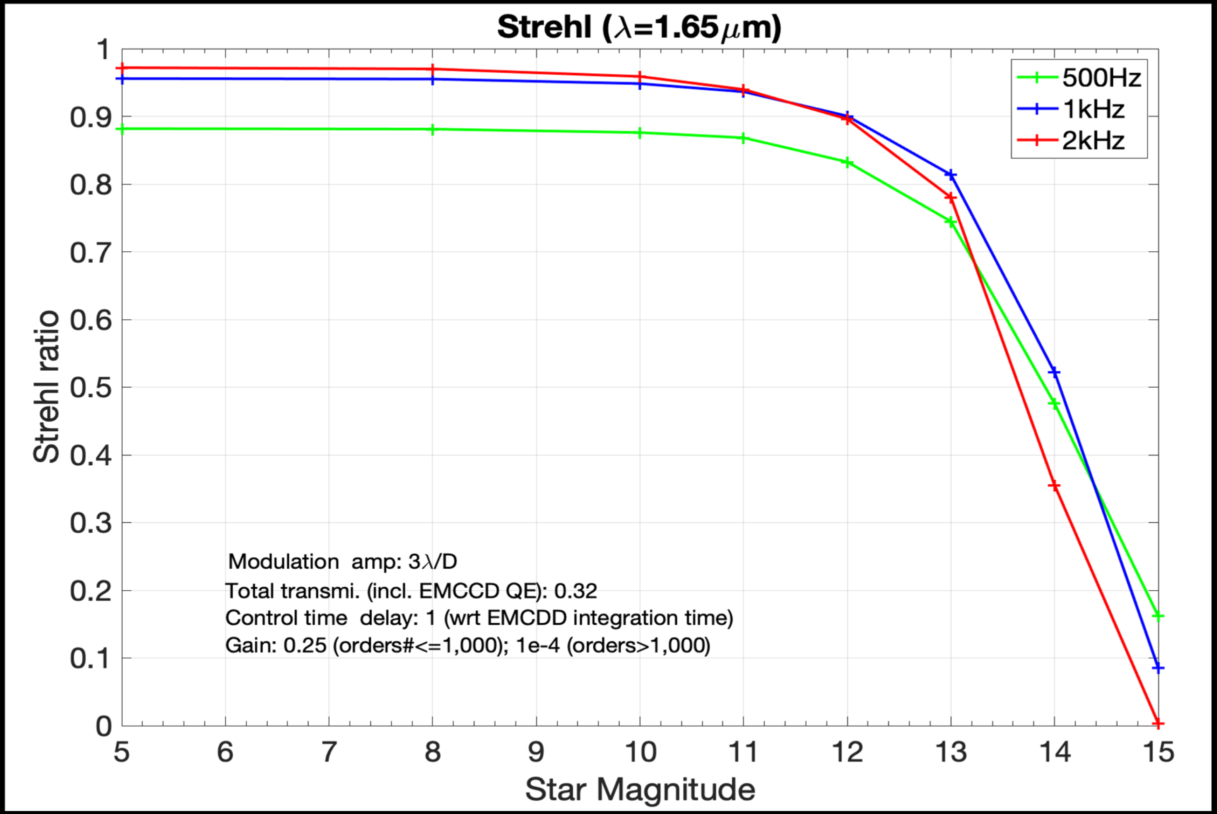
Simulations Stanford University

Integrated on the GPI2-AO bench at Univ. of Notre Dame, May, 2024

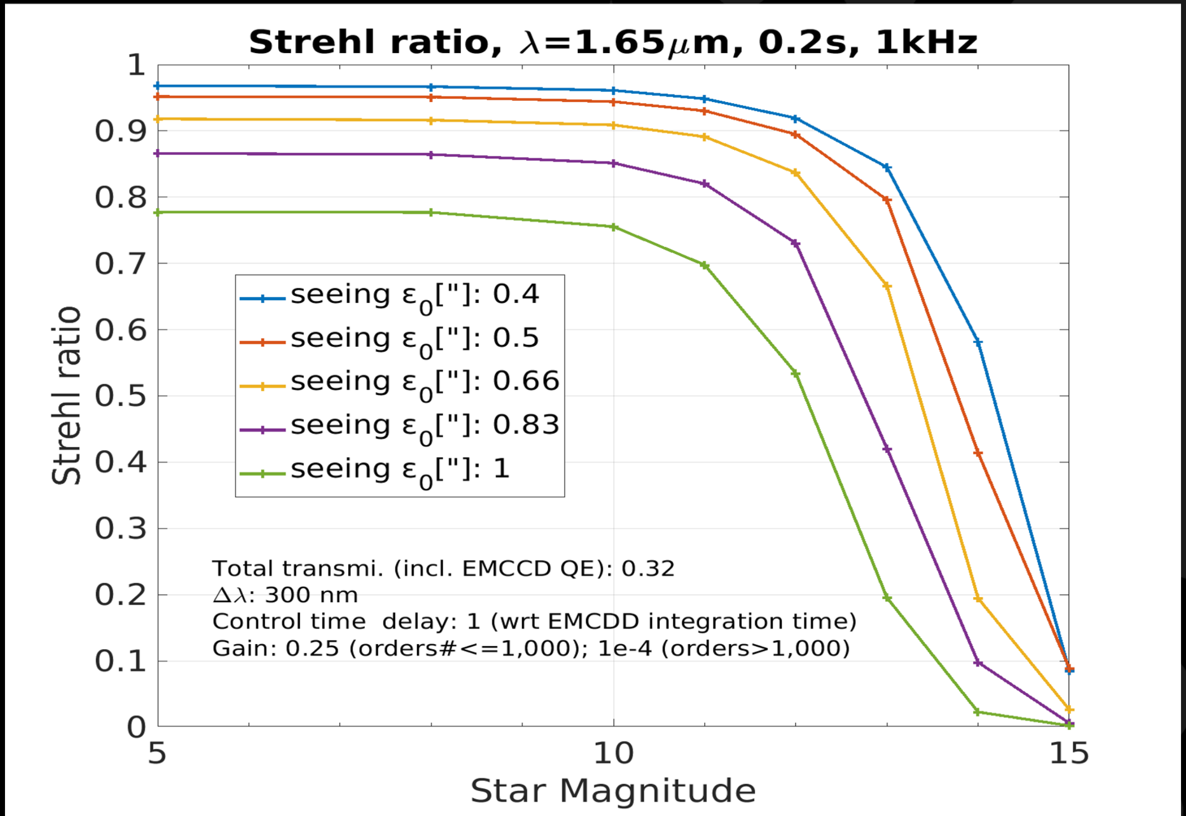
Chilcote et al., 2020, 2022

GPI2 will be able to operate on stars between I=0 and I=14

Strehl ratio versus magnitude for different closed-loop frequencies.



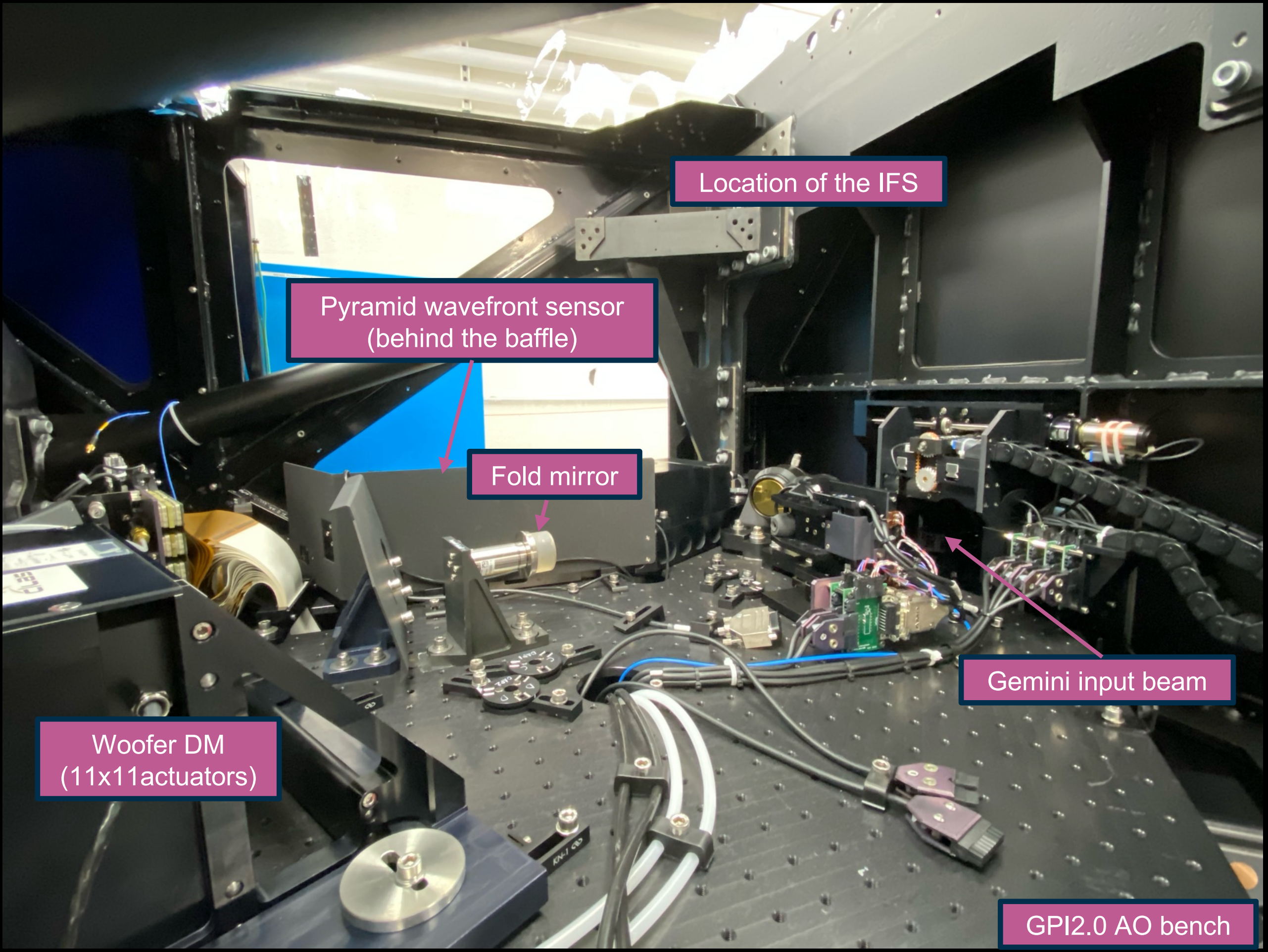
Strehl ratio versus magnitude for different seeing conditions

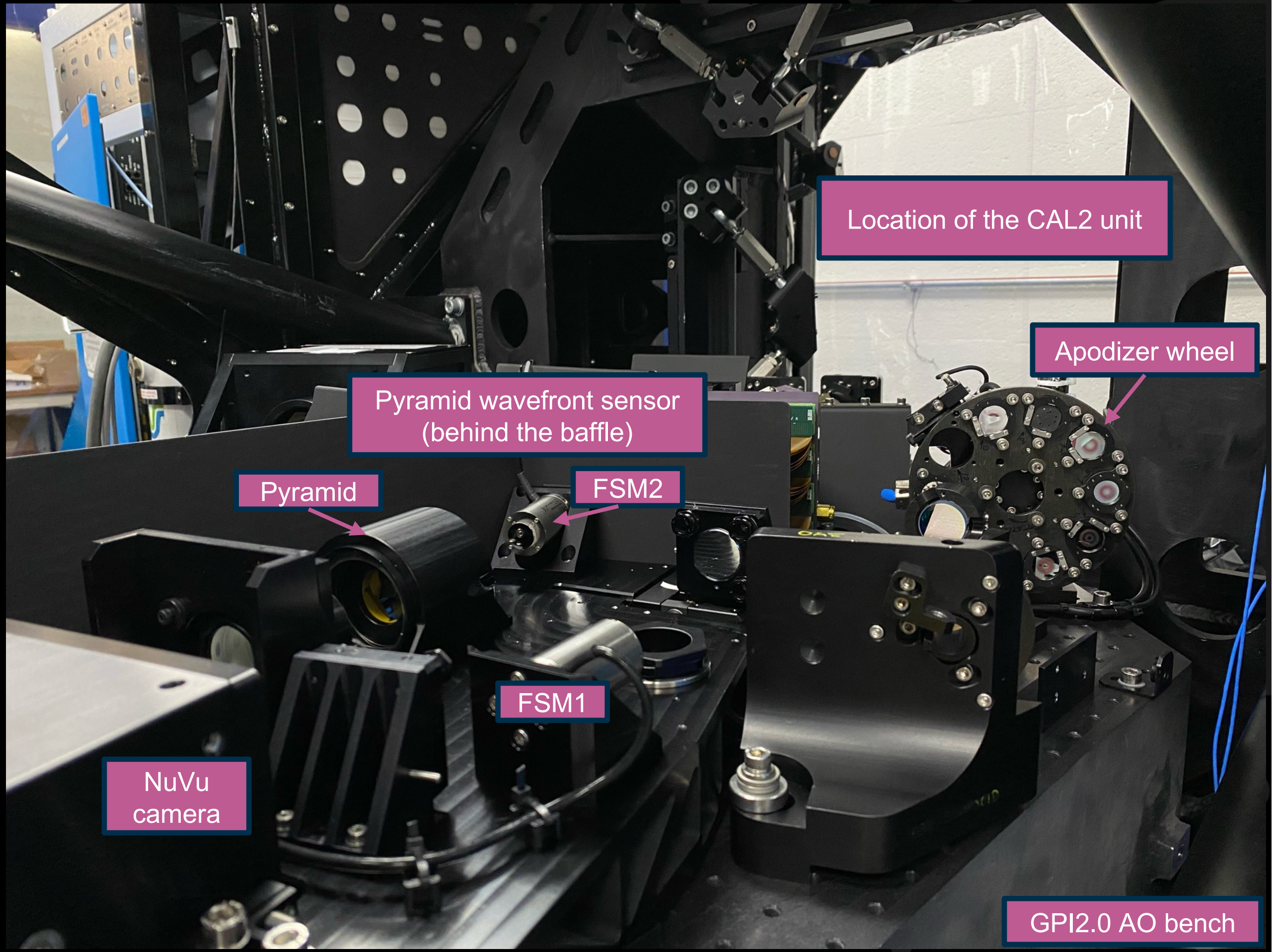


Fitzsimmons et al. SPIE (2020)

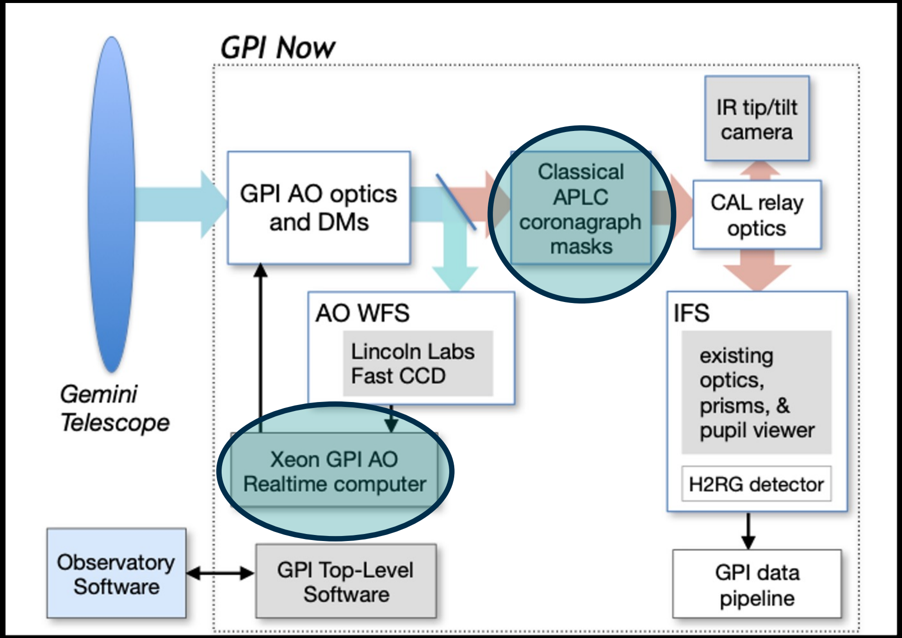
Gemini Planet Imager 2.0: AO Status

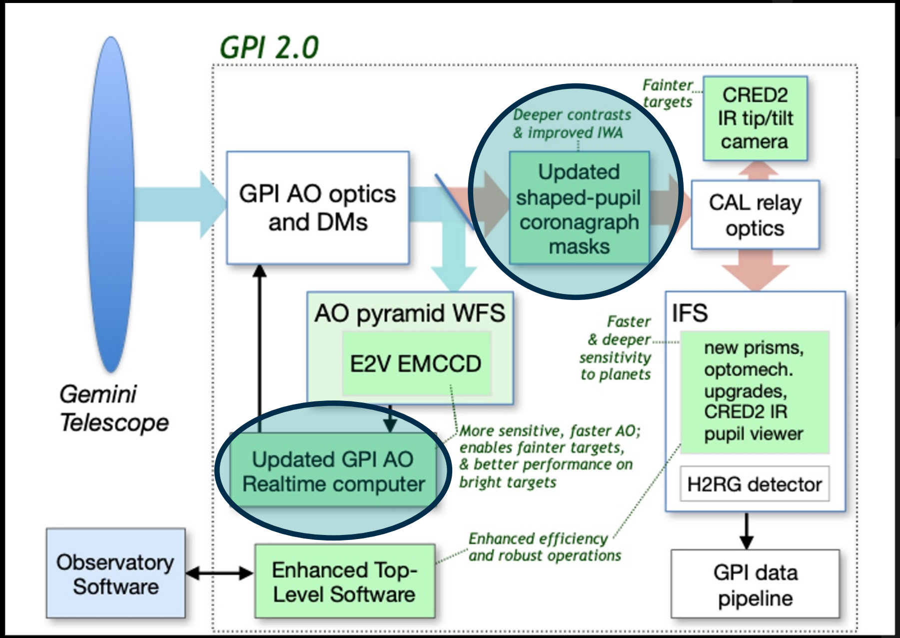
GPI2.0 AO bench at the University of Notre Dame, 5 November 2024





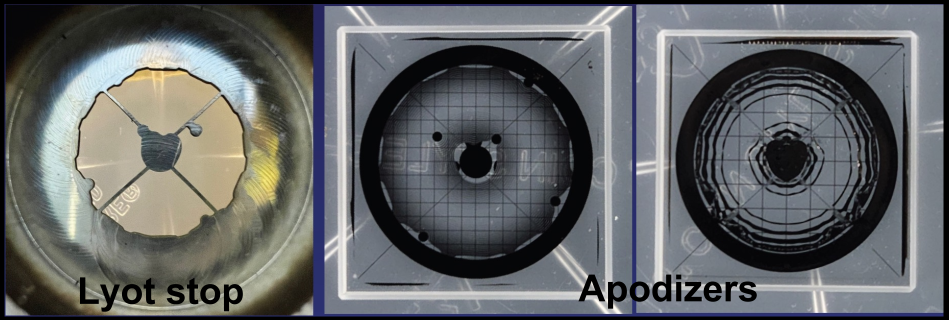
GPI2.0 Instrument: New Technical Capabilities





Upgrades

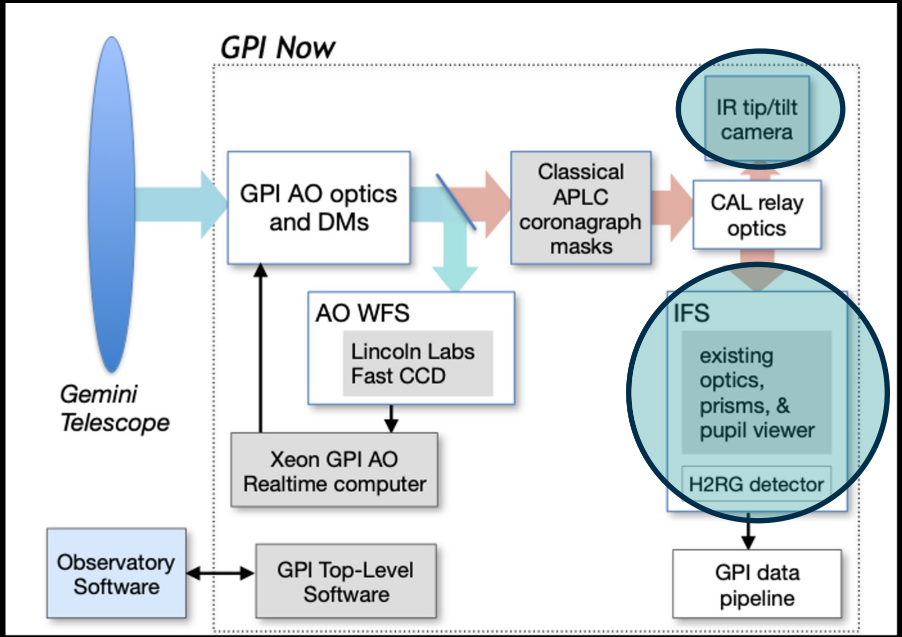
- Pyramid Wavefront Sensor using an EMCCD: More sensitive → better AO performance on bright stars (faster) / allowing access to fainter targets (I<14).
- Low-latency RTC with better GPI science execution rate – "**Herzberg Extensible Adaptive Real-Time Controller (HEART) algorithm**" Dunn et al., 2022
- New Apodizers and Lyot stops: more robust to vibration, higher throughput allowing deeper contrast and improved inner working angle.

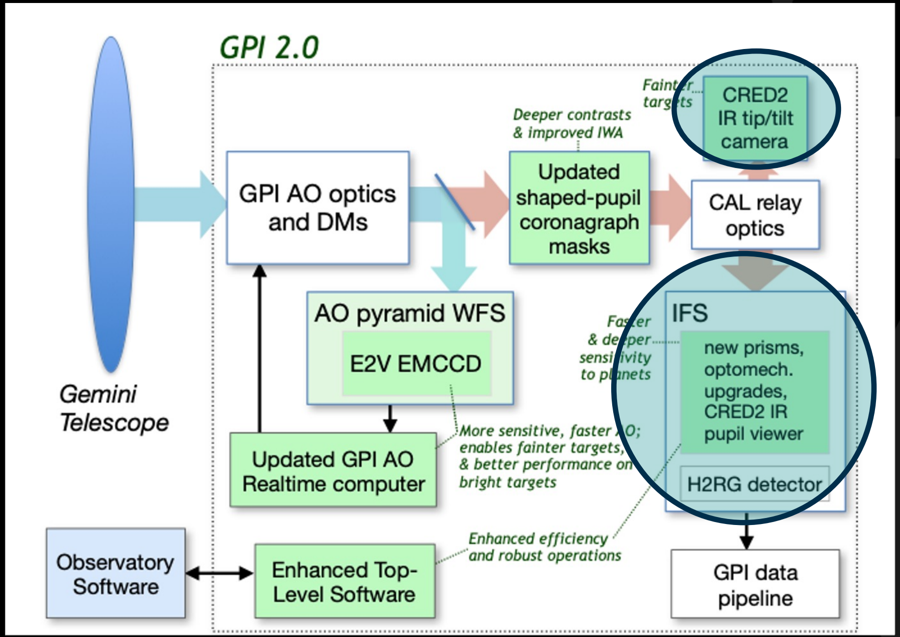


Retain old focal plane masks (IWA radius ~ 3 λ/D, ~127 mas (H-band))
Design Space Telescope Lab
Build Univ. of Notre Dame
(N'Diaye et al. 2016).

Chilcote et al., 2020, 2022

GPI2.0 Instrument: New Technical Capabilities





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- Low-latency RTC with better GPI science execution rate.
- New Apodizers and Lyot stops: more robust to vibration, higher throughput allowing deeper contrast and improved inner working angle.
- CAL1: New IR tip-tilt camera enabling tip-tilt correction on fainter targets (H mag of >12).
- IFS: 192x192 spatial pixels, R=~30-100, 0.95 - 2.4 μm. New low-resolution mode in broadband, new pupil-viewing camera (C-RED2).

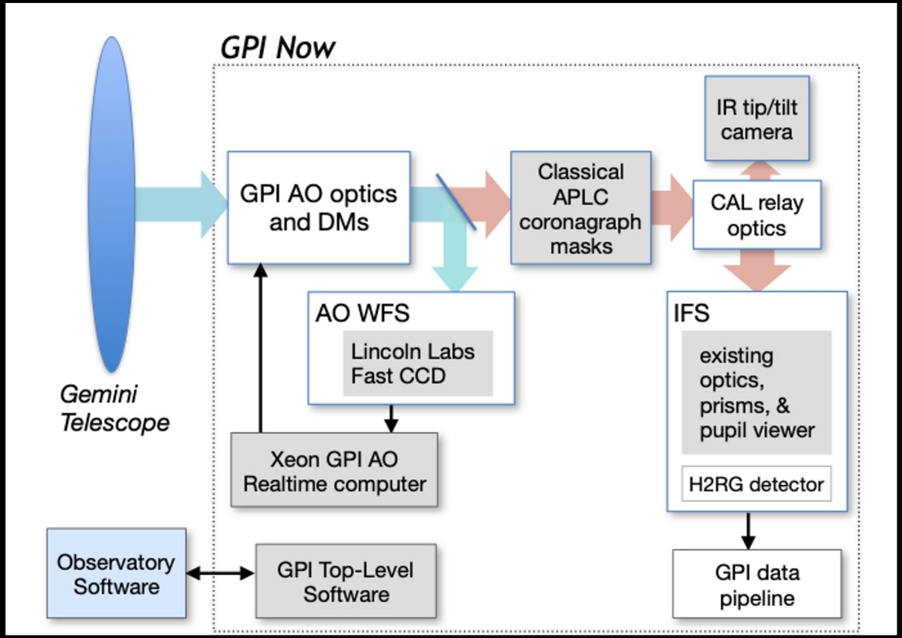
Design Texas A&M University
Design and Build Univ. of Notre Dame

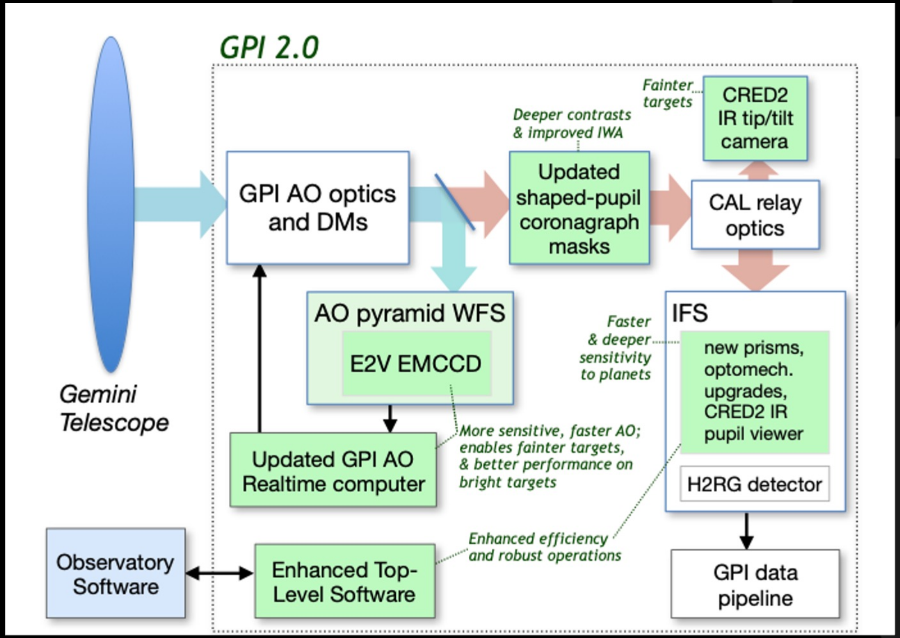
GPI2.0 Spectral Mode Parameters

Band	Cut-on/off (μm)	Length (pixels)	R = $\lambda/\Delta\lambda$
Y	0.95-1.07	14.7	61.9
J	1.13-1.34	17.5	47.9
H	1.498-1.796	15.4	42.7
K	2.00-2.40	20.0	55.1

Chilcote et al., 2020, 2022

GPI2.0 Instrument: New Technical Capabilities





Upgrades

- Pyramid Wavefront Sensor using an EMCCD: More sensitive → better AO performance on bright stars (faster) / allowing access to fainter targets (I<14).
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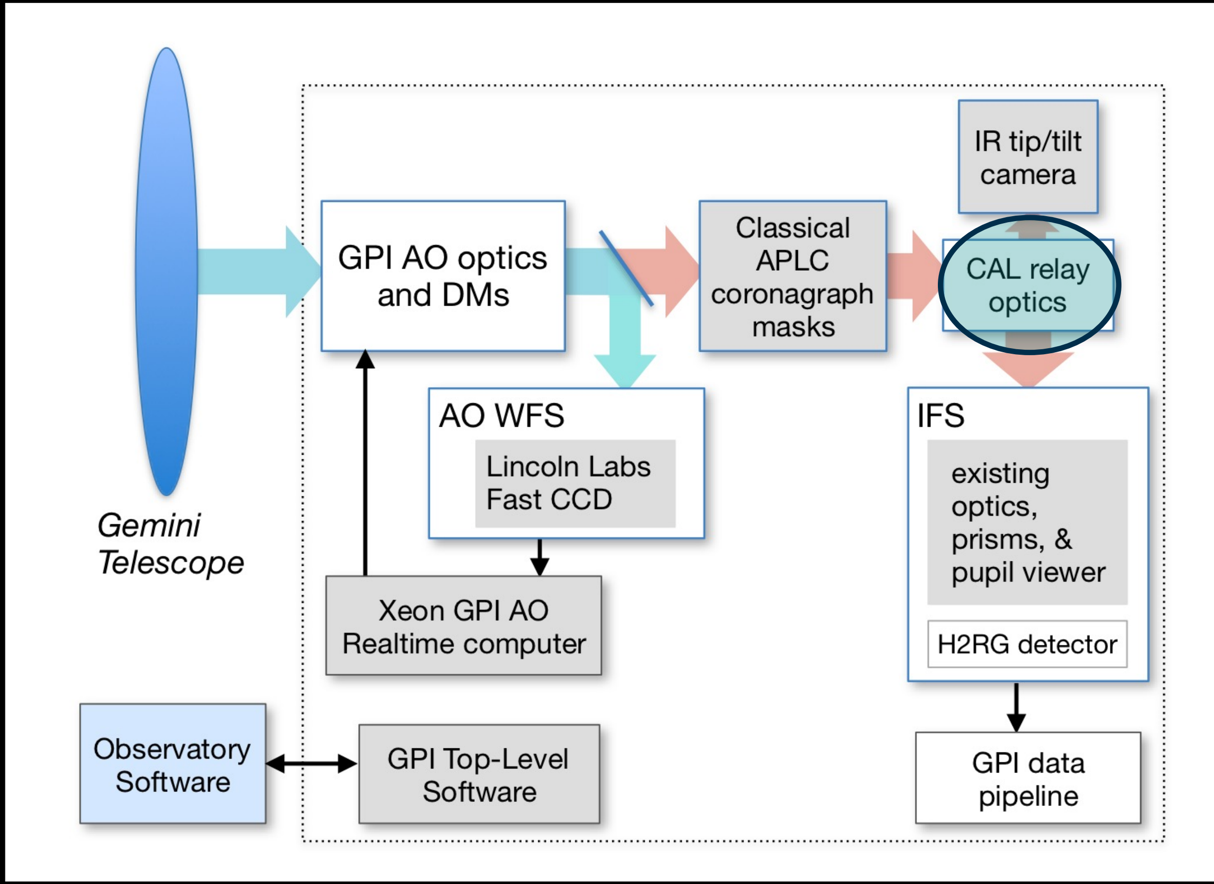
- New Apodizers and Lyot stops: more robust to vibration, higher throughput allowing deeper contrast and improved inner working angle.
- CAL1: New IR tip-tilt camera enabling tip-tilt correction on fainter targets (H mag of >12).
- IFS: New low-resolution mode in broadband, new pupil-viewing camera (C-RED2).
- Zernike wavefront sensor for the initial static high-order non-common path aberration (NCPA) calibration during the star acquisition phase (operation is not simultaneous with the science operations).

Chilcote et al., 2020, 2022

GPI2.0 Instrument: New Technical Capabilities

GPI 1.0 at Gemini South, Chile (2013 - 2018)



Chilcote et al., 2020, 2022

GPI 2.0 at Gemini North, Hawaii
(Installation on GPI2.0 and Commissioning ~mid-2026)

CAL 2.0

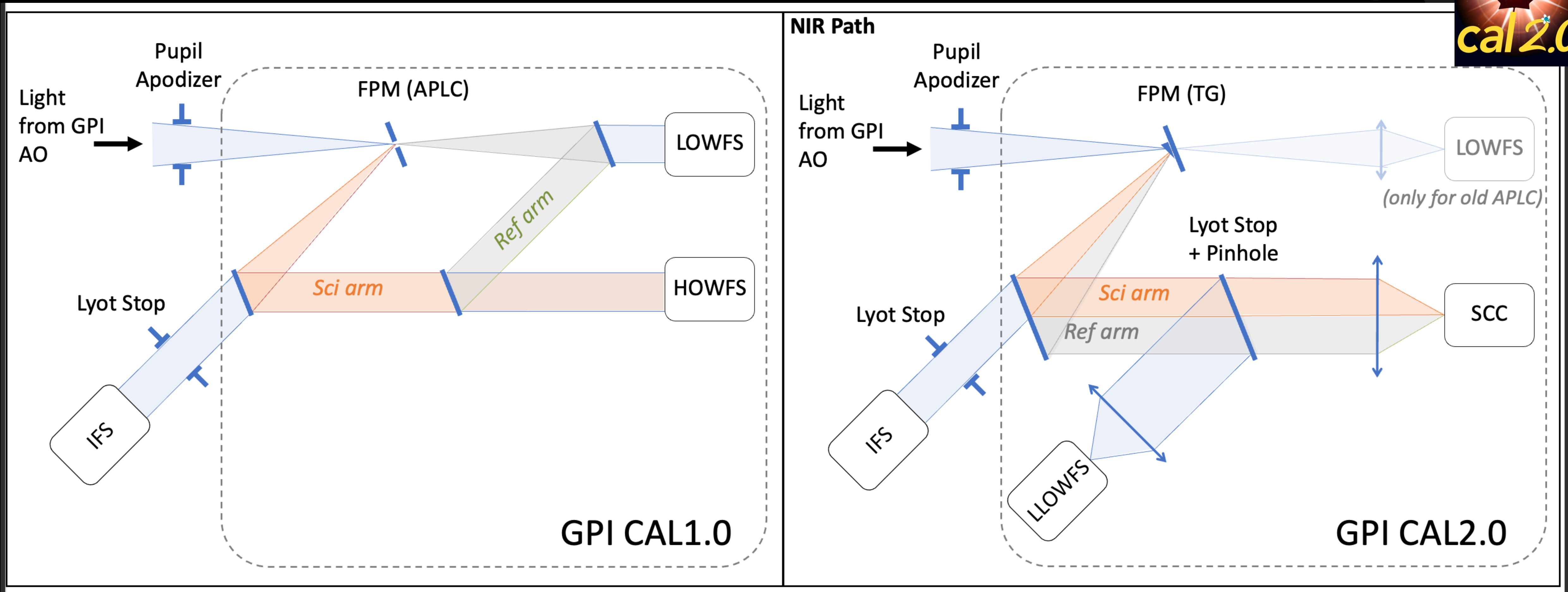
Developer HAA, Victoria BC, Canada
PI **Christian Marois**

Expected to leverage GPI2.0 sensitivity by at least a factor of 100 at small angular separations and on bright stars.

SPIDERS at Subaru is a prototype of CAL2.0 for Gemini.

Marois et al, 2020, 2022, 2024

Commissioning ~2026



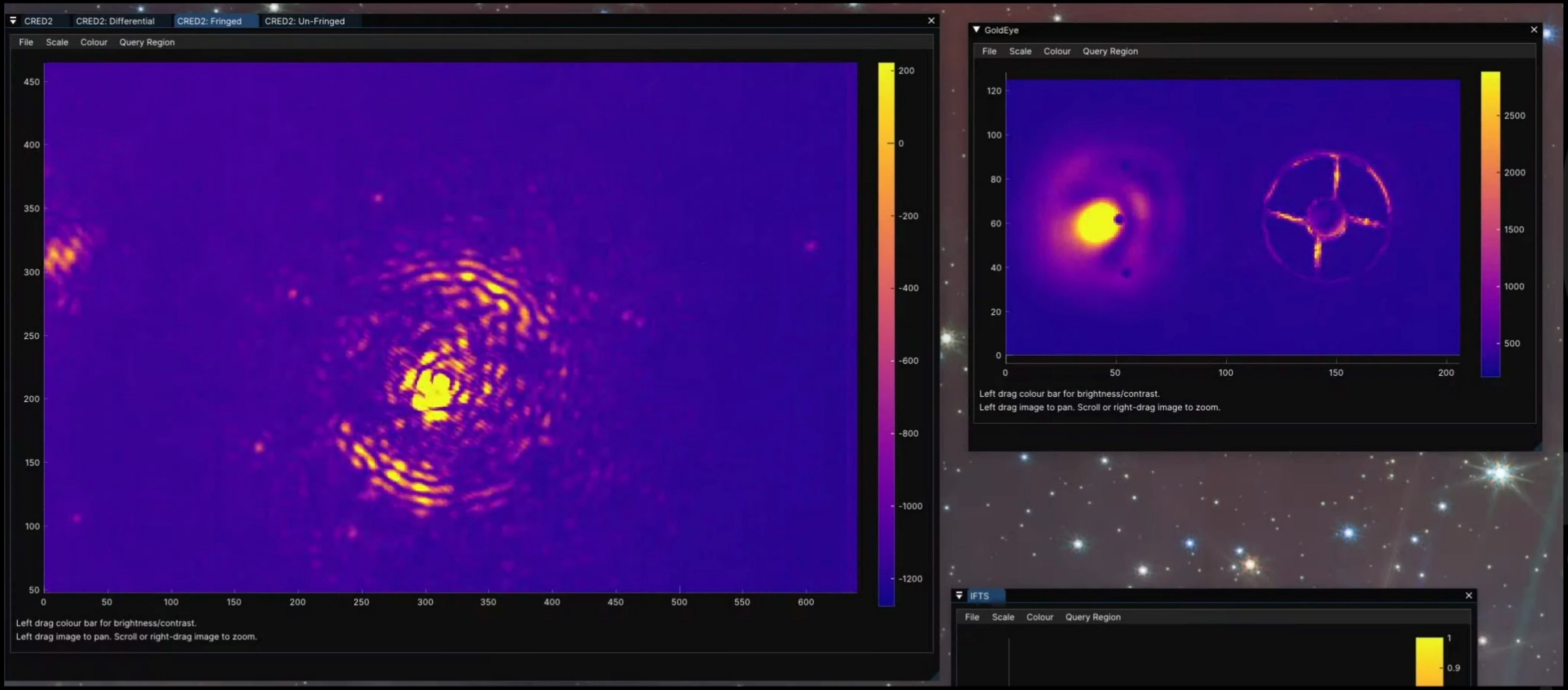
Marois et al, 2020

Gemini Planet Imager 2.0: Calibration Unit 2.0

SPIDERS (Prototype of CAL2) testbed at NRC/HAA. To be commissioned at Subaru Telescope in ~2025.

Self-Coherent Camera (SCC)
(actively measuring and correcting quasi-static speckles directly in the focal plane)

Lyot-stop Low-order Wavefront Sensor (LLOWFS, actively measuring and correcting low-order aberrations)

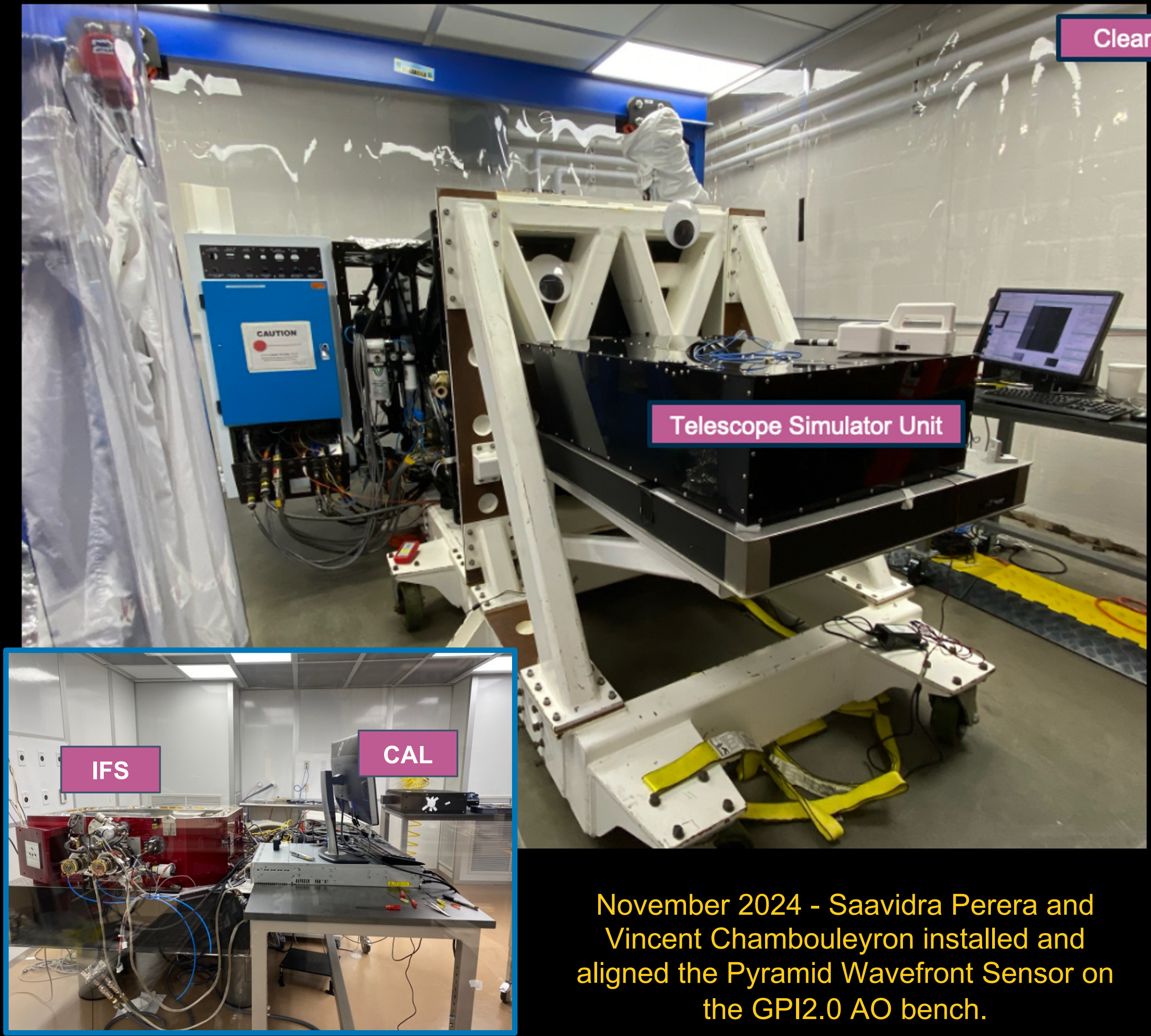


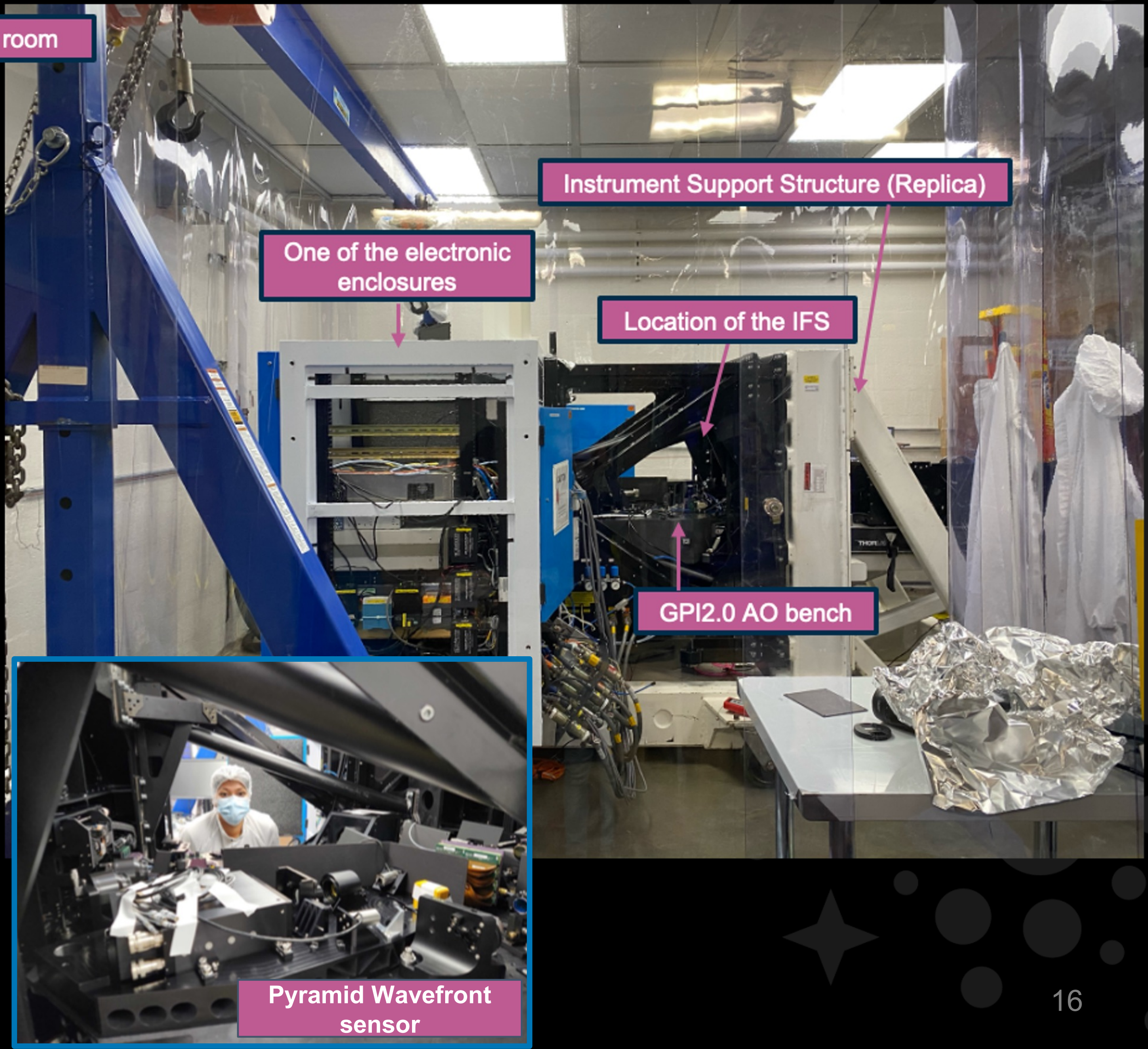
Contrast gain in the half-dark hole is ~ 100 times better on GPI2 post-AO residuals in the lab (as expected).
~1e7 contrast levels with GPI spare optics.

Credit – C. Marois, W. Thompson, A Johnson, O Lardiere

GPI2.0 Instrument: Current Status

GPI2.0 instrument at the University of Notre Dame, November 2024





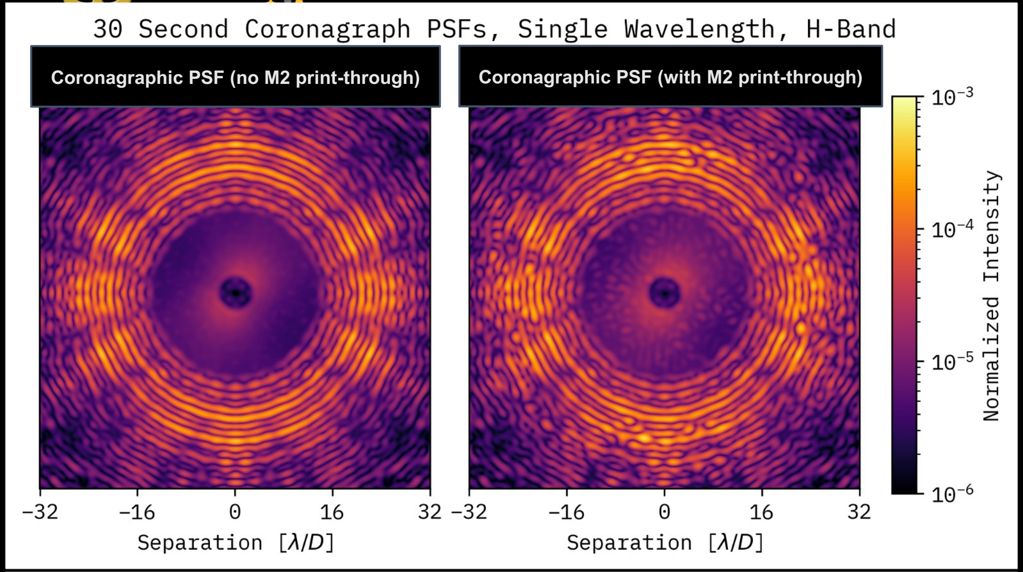
November 2024 - Saavidra Perera and Vincent Chambouleyron installed and aligned the Pyramid Wavefront Sensor on the GPI2.0 AO bench.

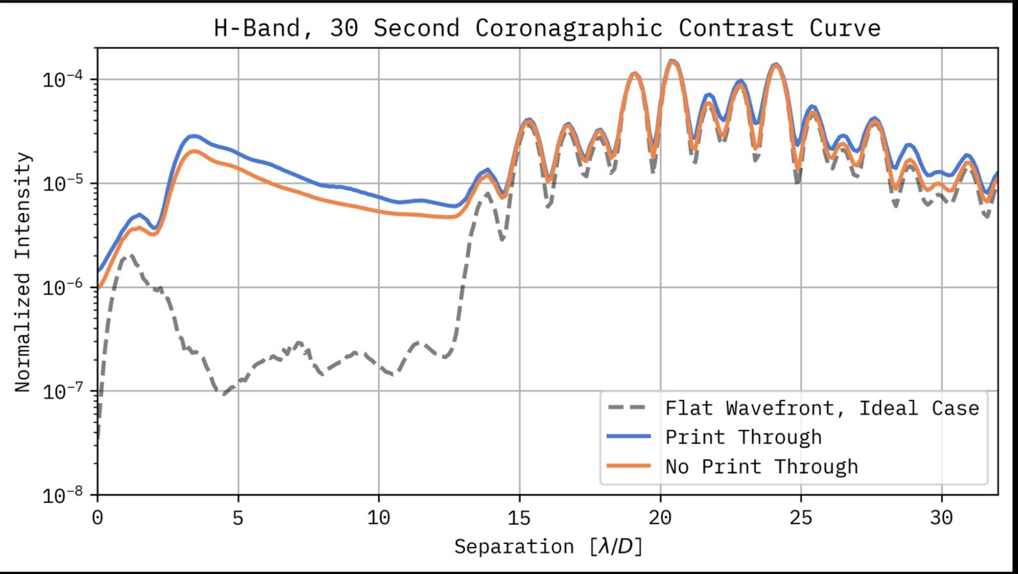
Some Challenges for GPI2.0 at Gemini North

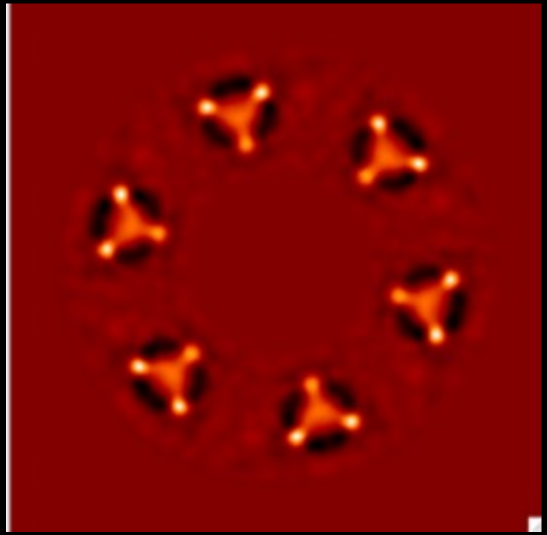
(Please reach out to the Presenter before using the content of this slide)

M2 Print-Through Simulation: Long-exposure, Multiwavelength

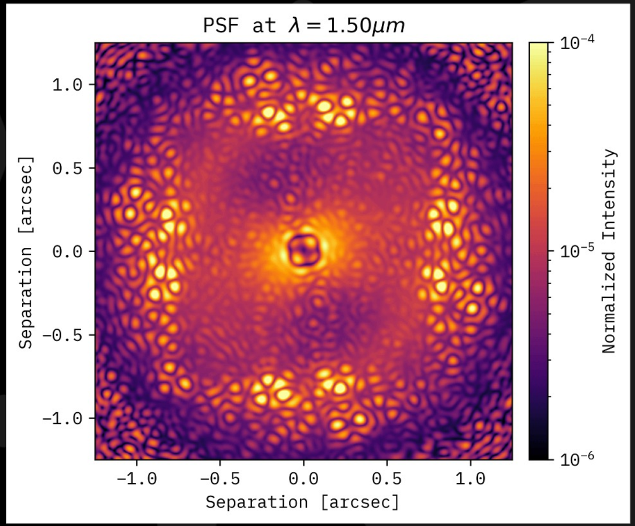
Credit - Jayke Nguyen, Vincent Chambouleyron







M2 print-through errors (achromatic and phase-only errors),
$\sigma = 175\ nm\ rms$,
PtV = 1.93 microns, Olivier Lai



30 second exposures at different wavelengths, can perform Spectral Differential Imaging (SDI) on this sequence

On-going Simulation work: different seeing and noise regimes, dark-hole digging, post-processing (SDI and ADI, etc.)

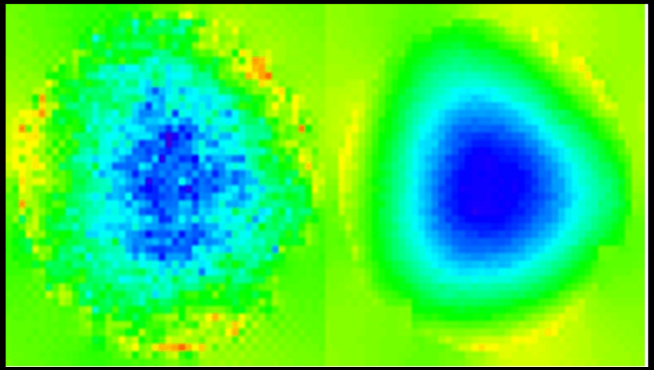
Flat wavefront, ideal case: No atmosphere, no M2 print-through, no other errors → coronagraph was designed with this case

Note: The plots are radial averages and not the radial standard deviations. The ratio of print-through to no print-through is roughly 40%.

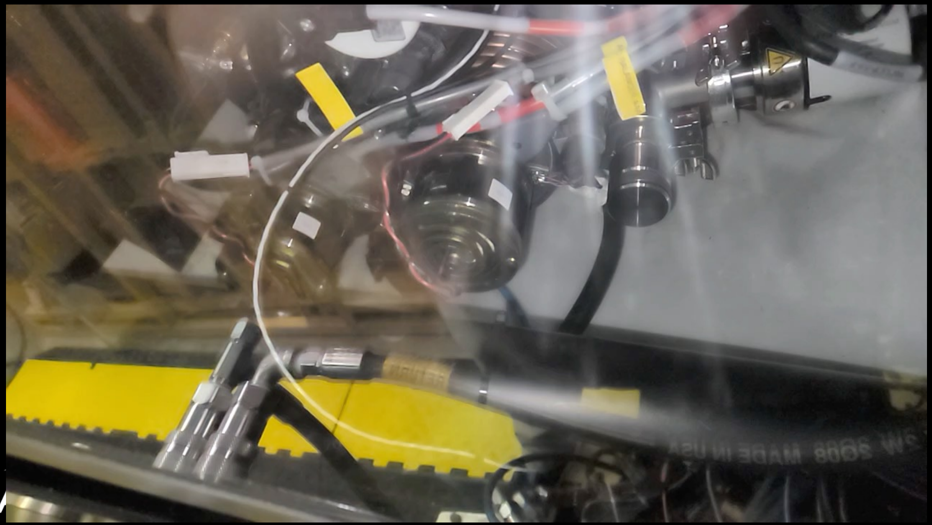
(Please reach out to the Presenter before using the content of this slide)

GPI1.0 instrument vibration history at GS - Hardware Mitigation

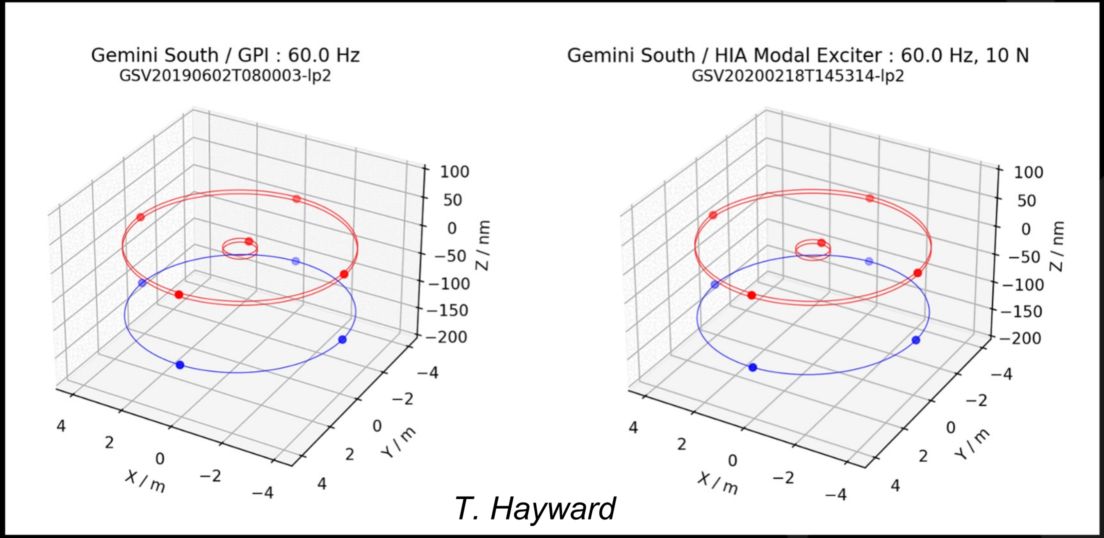
First light: On-sky image motion, vibration due to GPI 1.0 cryocoolers. The total rms wavefront error was 50 nm worse than expected.



GPI 1.0 Sunpower Cryotel Sterling-Cycle cryocoolers
Emitting vibration energy at 60 Hz and higher harmonics



GPI1.0 cryocoolers versus Modal Exciter test, 60 Hz excitation, 10N force amplitude



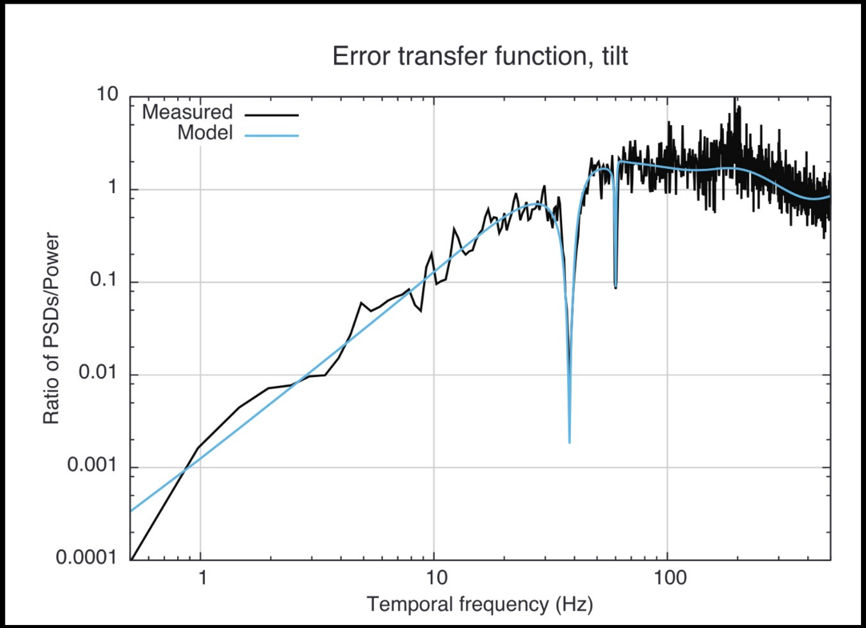
Red points: M1 Glass sensors including central hole and Z component
Blue points: M1 cell sensors

(The amplitude of center-to-edge flexure is ~ 42 nm, corresponding to ~ λ/13 rms wavefront error)

Sinusoidal force input to the ISS with an amplitude of ~ 10 N roughly reproduces the M1 wavefront error induced by the GPI cryocooler (after active vibration cancelation with open-loop AO) at 60 Hz at both GN and GS.

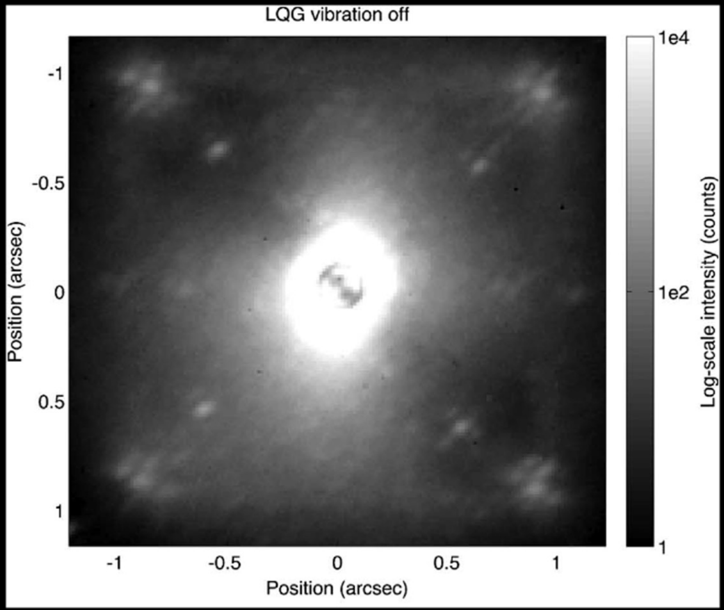
(Slide and data taken from P. Byrnes (HAA-NRC), B. Chinn, T. Hayward (Gemini South), Bruce Macintosh, and Jeff Chilcote)

GPI2, just like GPI1, will incorporate a flexible AO controller with Kalman/LQG vibration canceling options.

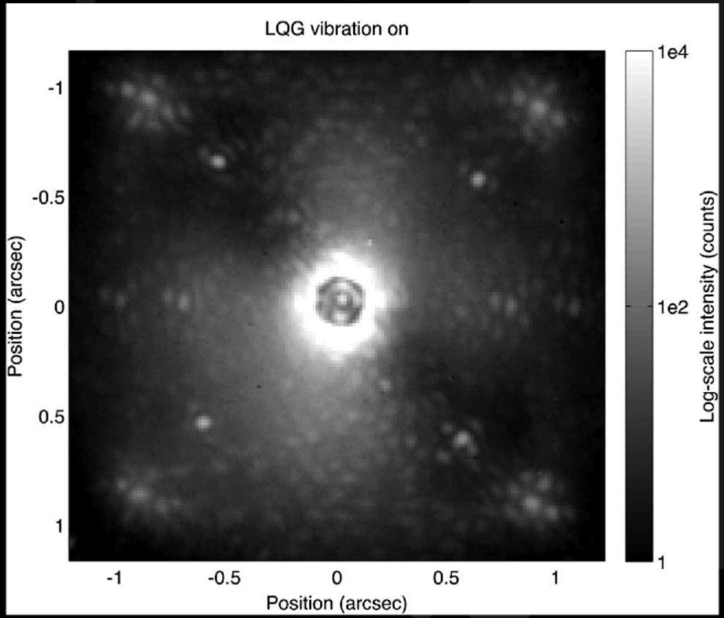


A bad telescope fan created strong (20 mas+) vibration of Gemini M2 at 37 Hz. GPI telemetry identified this immediately LQG controller adapted the next day (See Poyneer et al 2016)

Coronagraphic leaks (on-sky)
No LQG



LQG on



GPI1.0 with active cancellation and Kalman filtering reached < 5mas vibration image motion on a routine basis.

Poyneer et al 2016

Future - GPI2.0/Gemini and SCExAO/Subaru

Collaboration and Knowledge Exchange Opportunities

- On-sky AO experience exchange between SCExAO and GPI2.0 using common techniques-

  Pyramid Wavefront Sensor

  Focal-plane wavefront Sensing with algorithms such as Electric Field Conjugation and Self-Coherent Camera.

  Coronagraphic low-order wavefront sensing using Lyot-stop low-order wavefront sensor

- Cross-instrument testing of novel techniques for PSF reconstruction using AO telemetry.

- Commissioning of SPIDERS on SCExAO/Subaru, and CAL2.0 on GPI2.0/Gemini by the same external team (NRC-HAA in Canada) -

  Exchange of on-sky testing and verification guidelines and procedures for risk mitigation.

- Impact of Vibration on the science image quality -

  Feeding real-time accelerometer data to AO loops

- Cross-instrument observations of follow-up targets and false positives -

  Promoting Science Collaboration