GPI 2.0: Revealing Exoplanets through High-Contrast Imaging

Jeffrey Chilcote

Gemini North 2023

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

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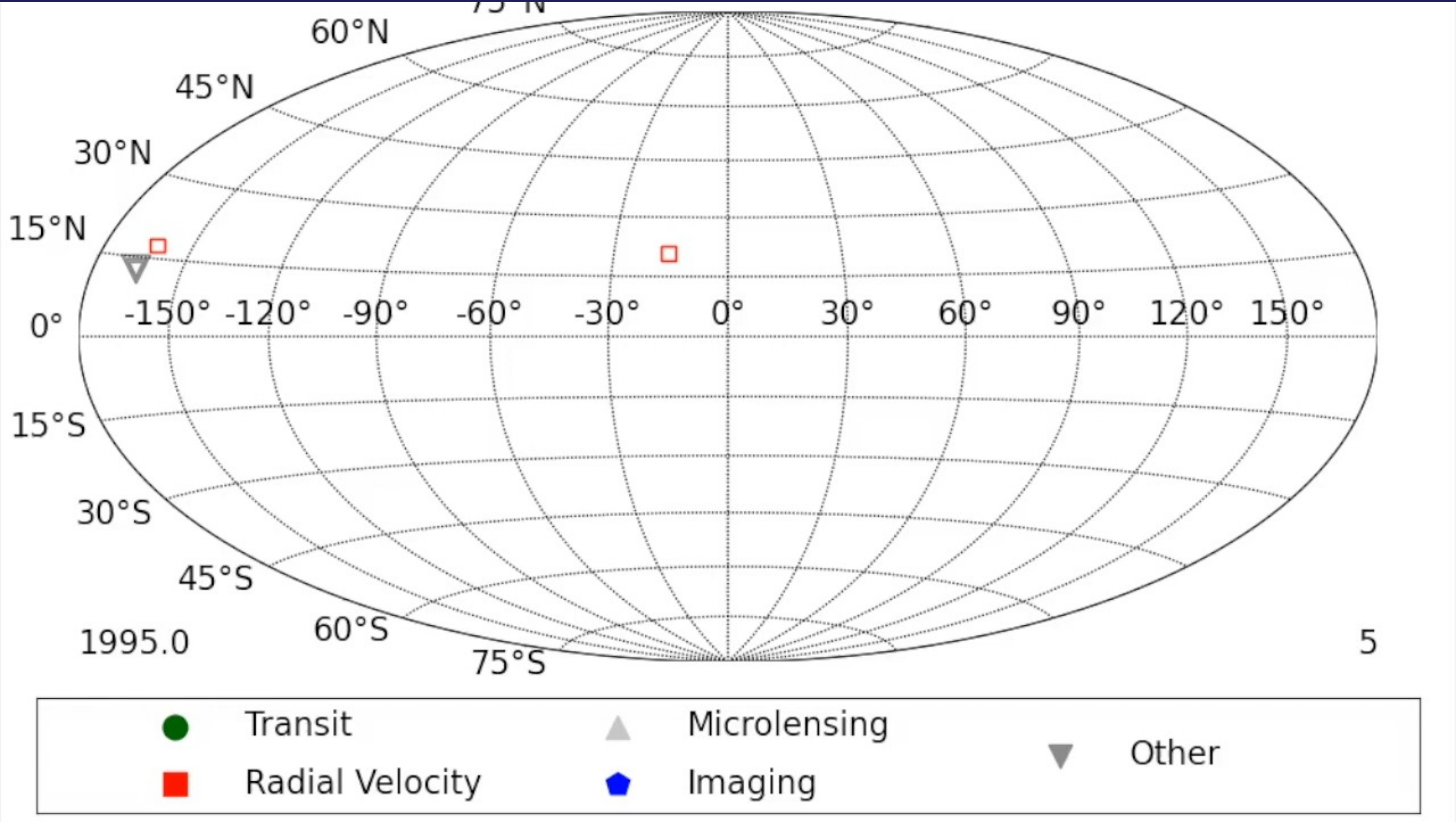
GPI 2.0

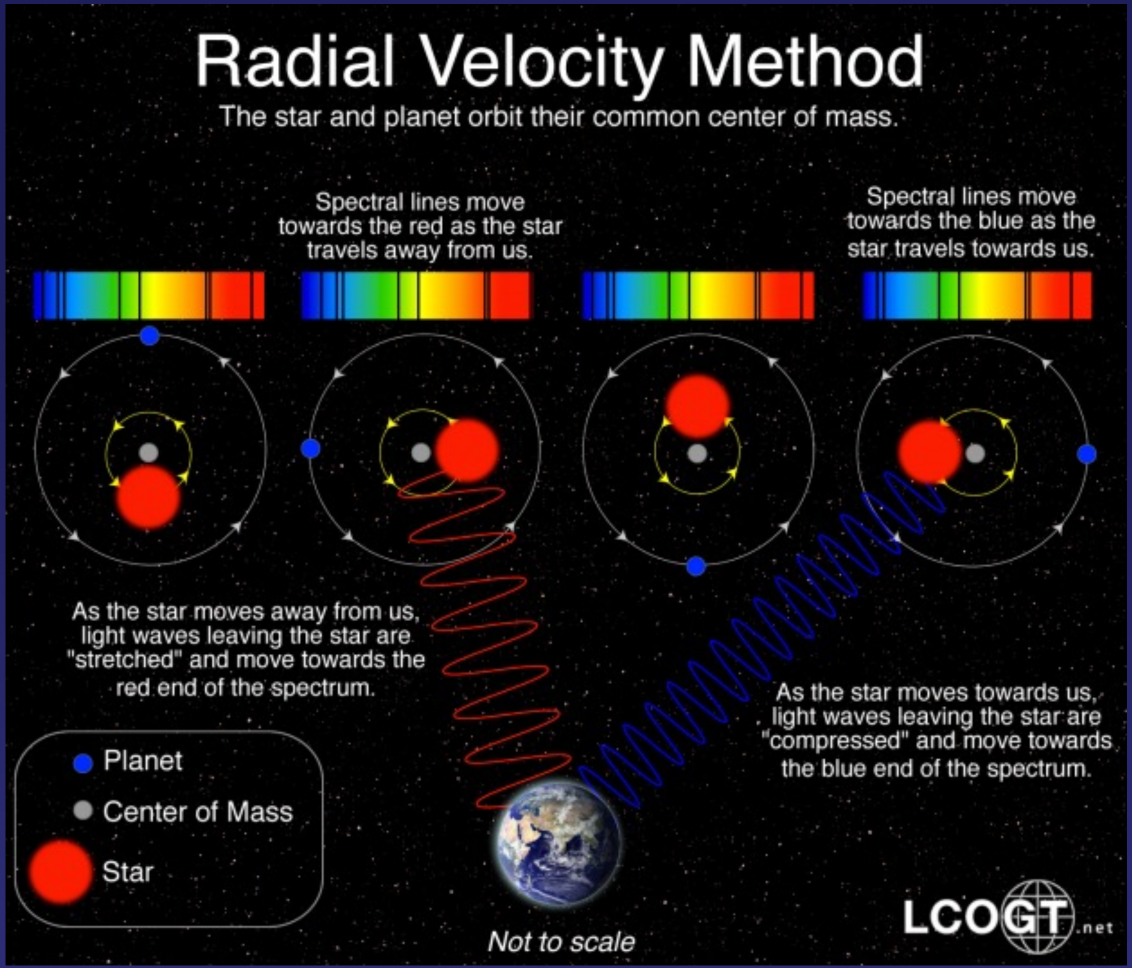
Jeffrey Chilcote, Quinn Konopacky, Robert J. De Rosa, Joeleff Fitzsimmons, Randall Hamper, Bruce Macintosh, Christian Marois, Marshall D. Perrin, Dmitry Savransky, Remi Soummer, Jean-Pierre Veran, Guido Agapito, Arlene Aleman, S. Mark Ammons, Sheila Balu, Marco Bonaglia, Marc-Andre Boucher, Maeve Curliss, 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

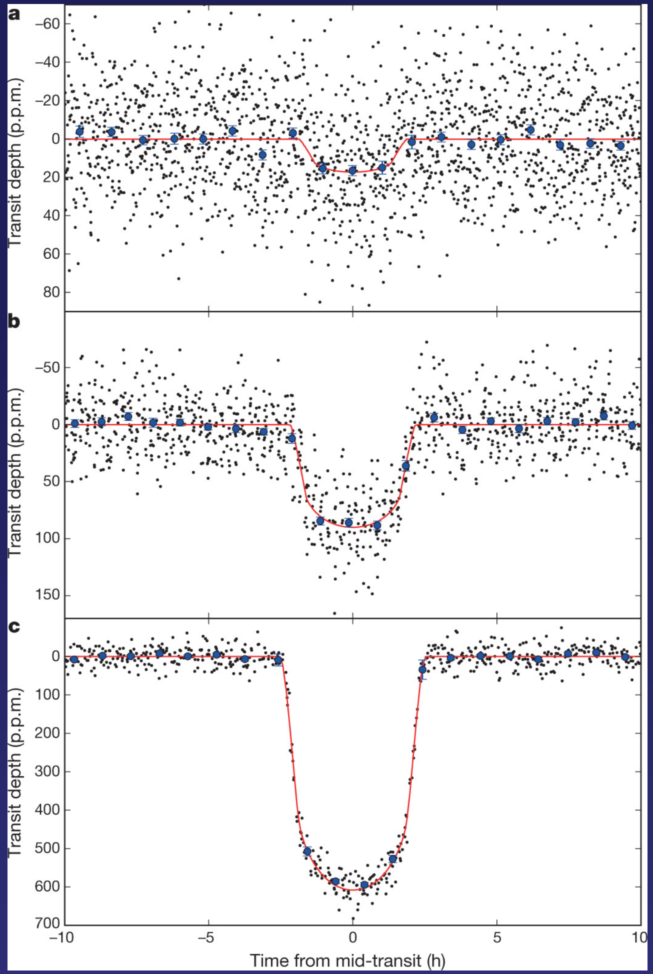
Exoplanet Discoveries



Credit: D. Savransky

Radial Velocity & Transit Methods

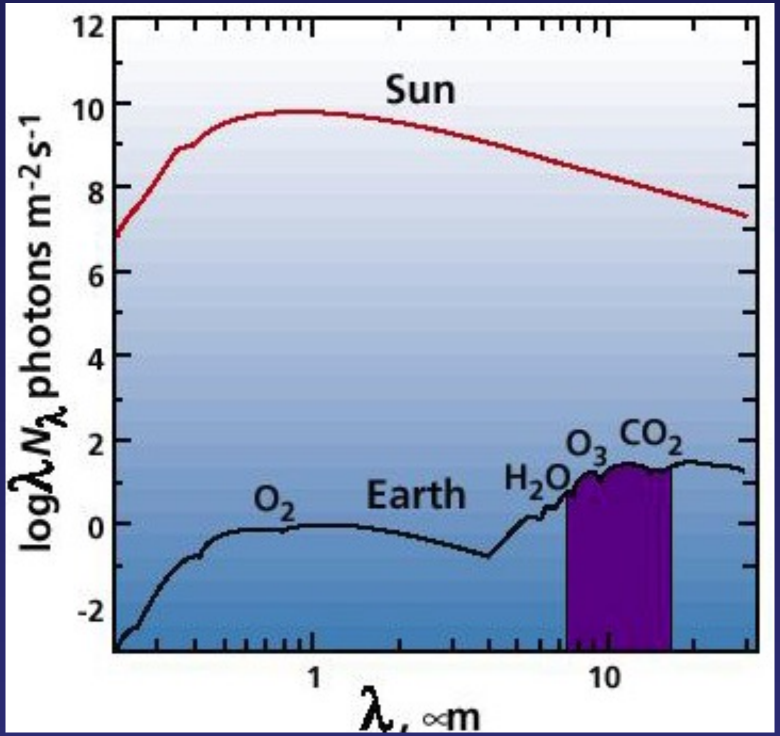




T Barclay *et al. Nature*

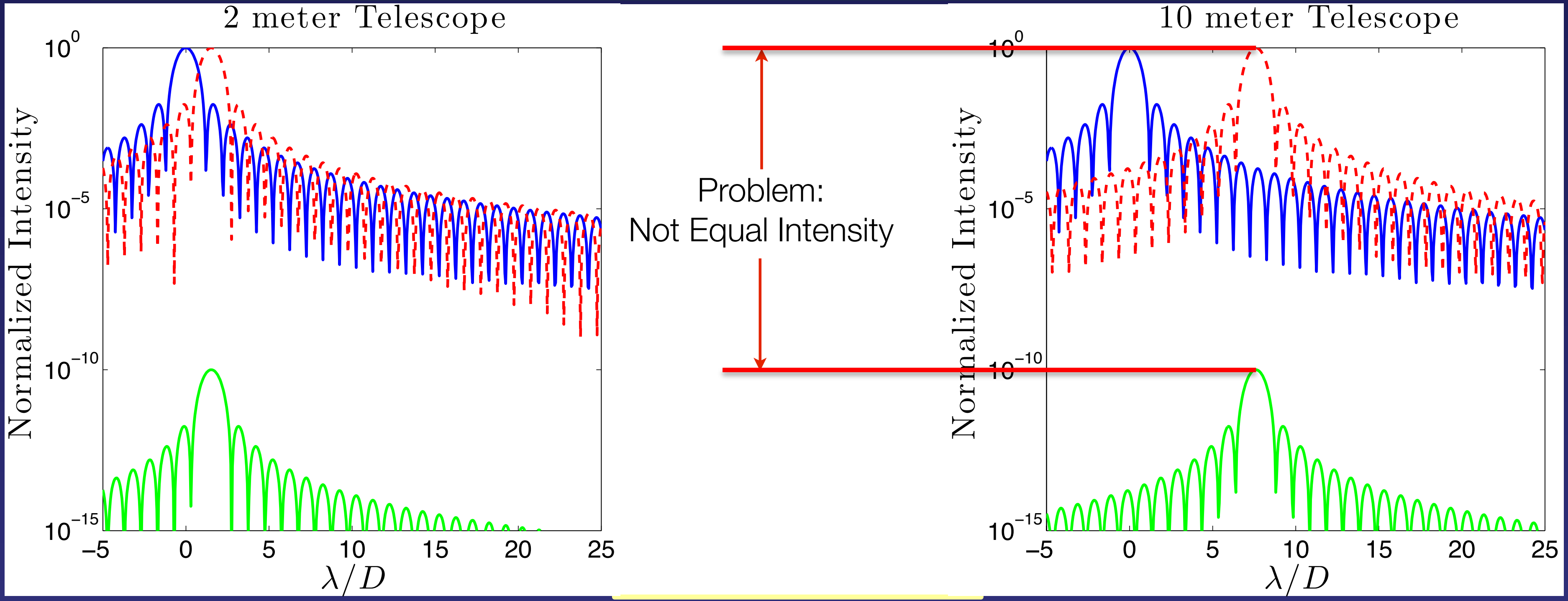
Extrasolar Planets via Direct Imaging

- Contrast Ratio:
  - Reflected Light (Optical): $>10^9$ in our solar system
  - Thermal emission from young Jovians can be $\sim 10^4$ times brighter at early times.



What Makes Imaging Exoplanets Hard

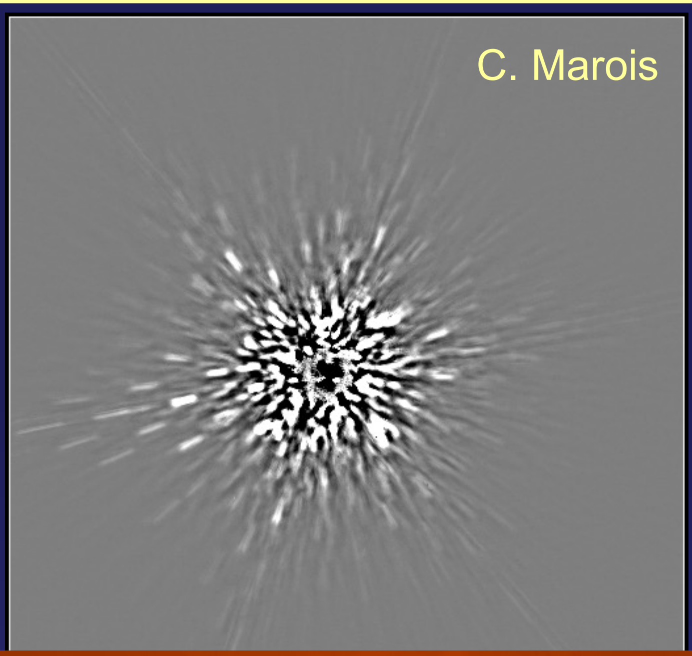
- Separation & Photons are not the fundamental limit
- The contrast ratio of Earth is 1×10^{-10}
- Detection at 1×10^{-5} contrast levels is already challenging at low inner working angle

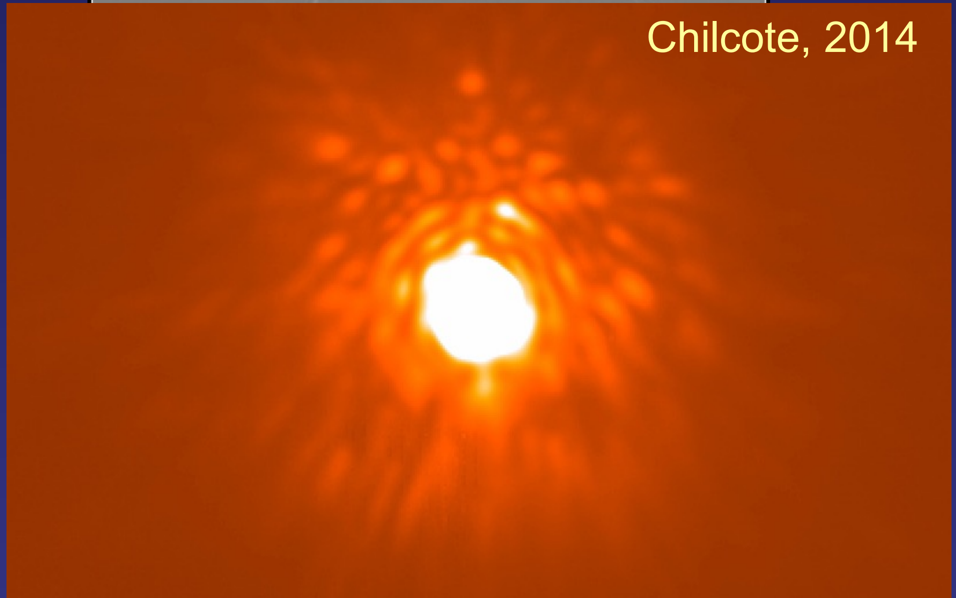


Detecting an Earth-analog, at 1 AU, Orbiting a star 10pc away requires a 2km circular aperture

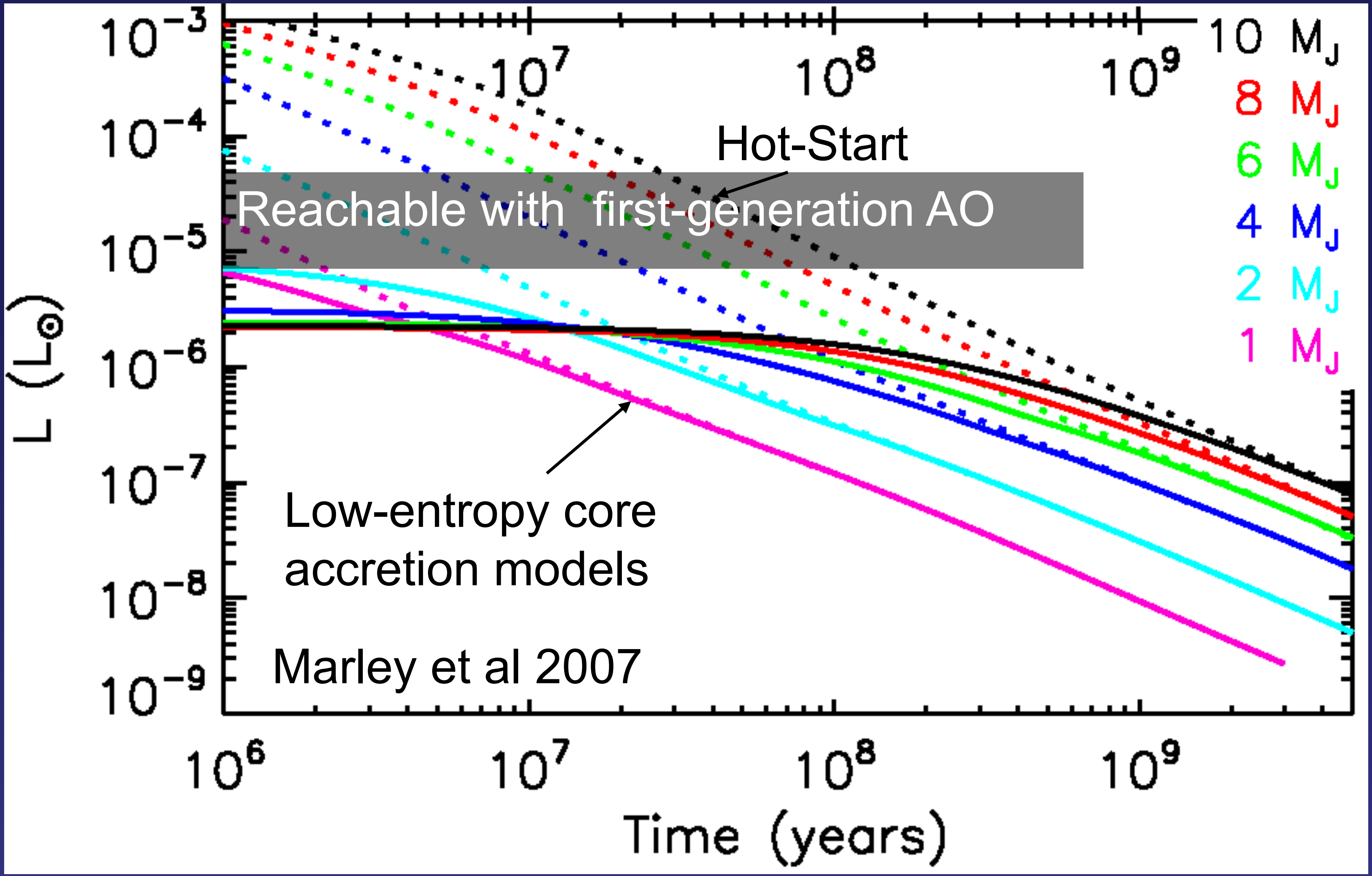
Development of techniques: recognition of quasi-static speckle aberrations

- Rapidly recognized that sensitivity did not reach atmospheric limits
- Speckle artifacts due to non-common-path, high-frequency, other errors
- Temporal variations on minute-long timescales





Luminosity depends on initial conditions



Bottom-up: Core Accretion

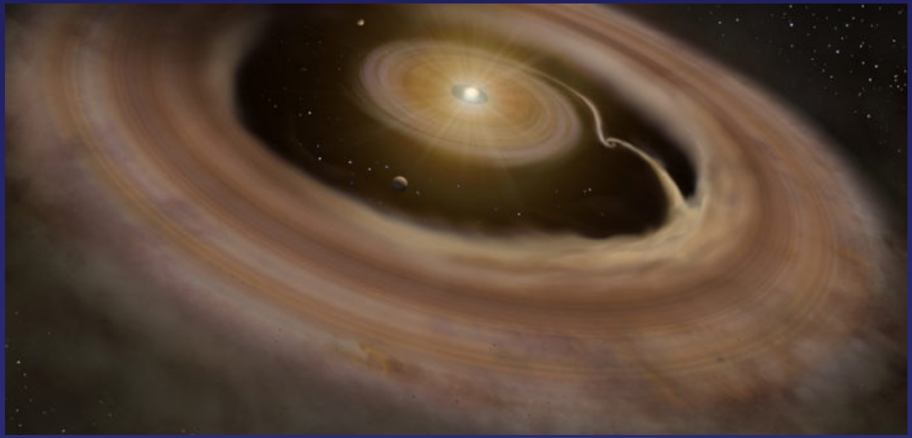
Alan Brandon/Nature

Bottom-up: Core Accretion (Cold Start)

Step 1: Accrete 10 Earth masses of solids

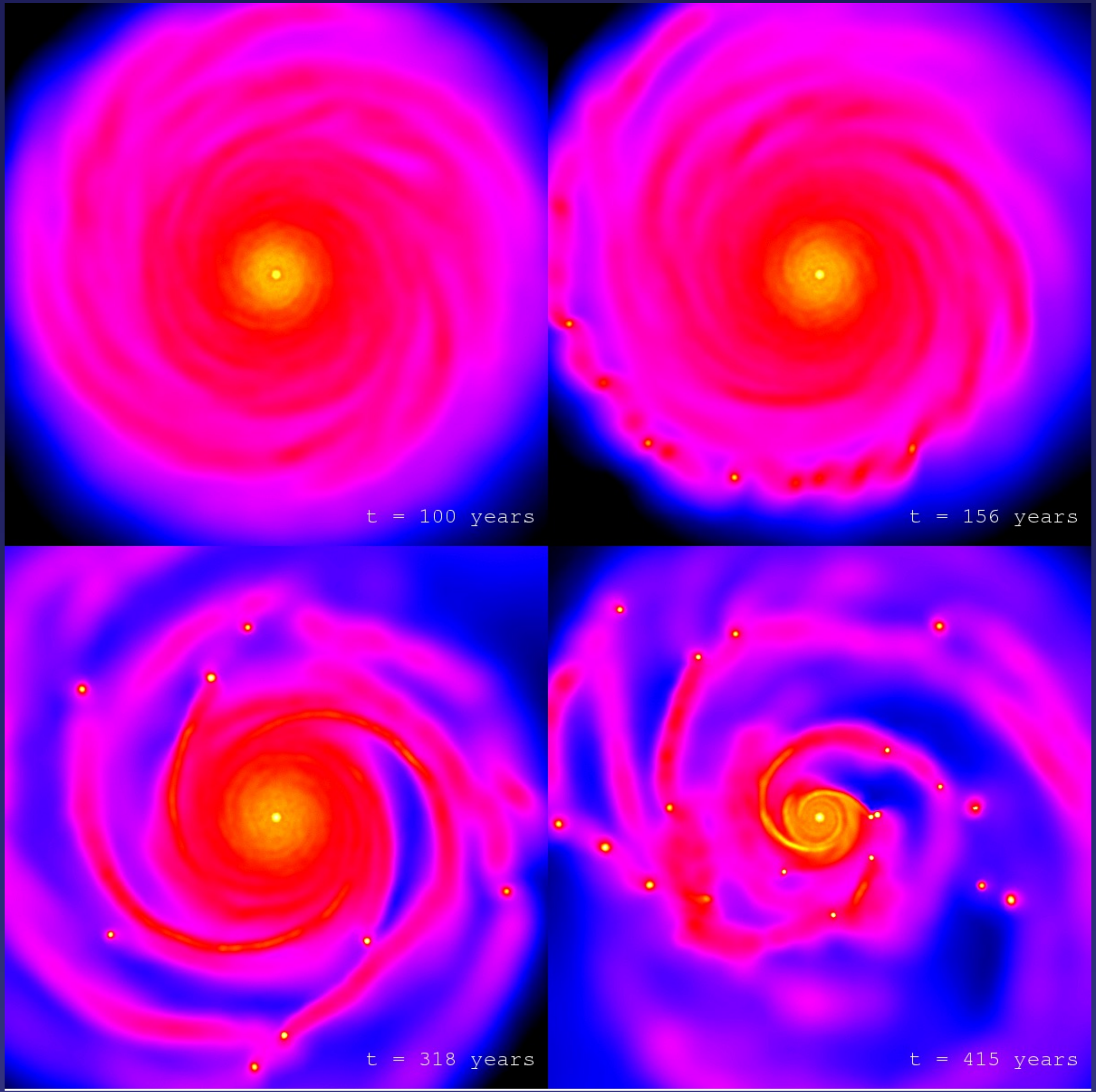
Alan Brandon/Nature

Step 2: Pull 300 Earth masses of gas from disk



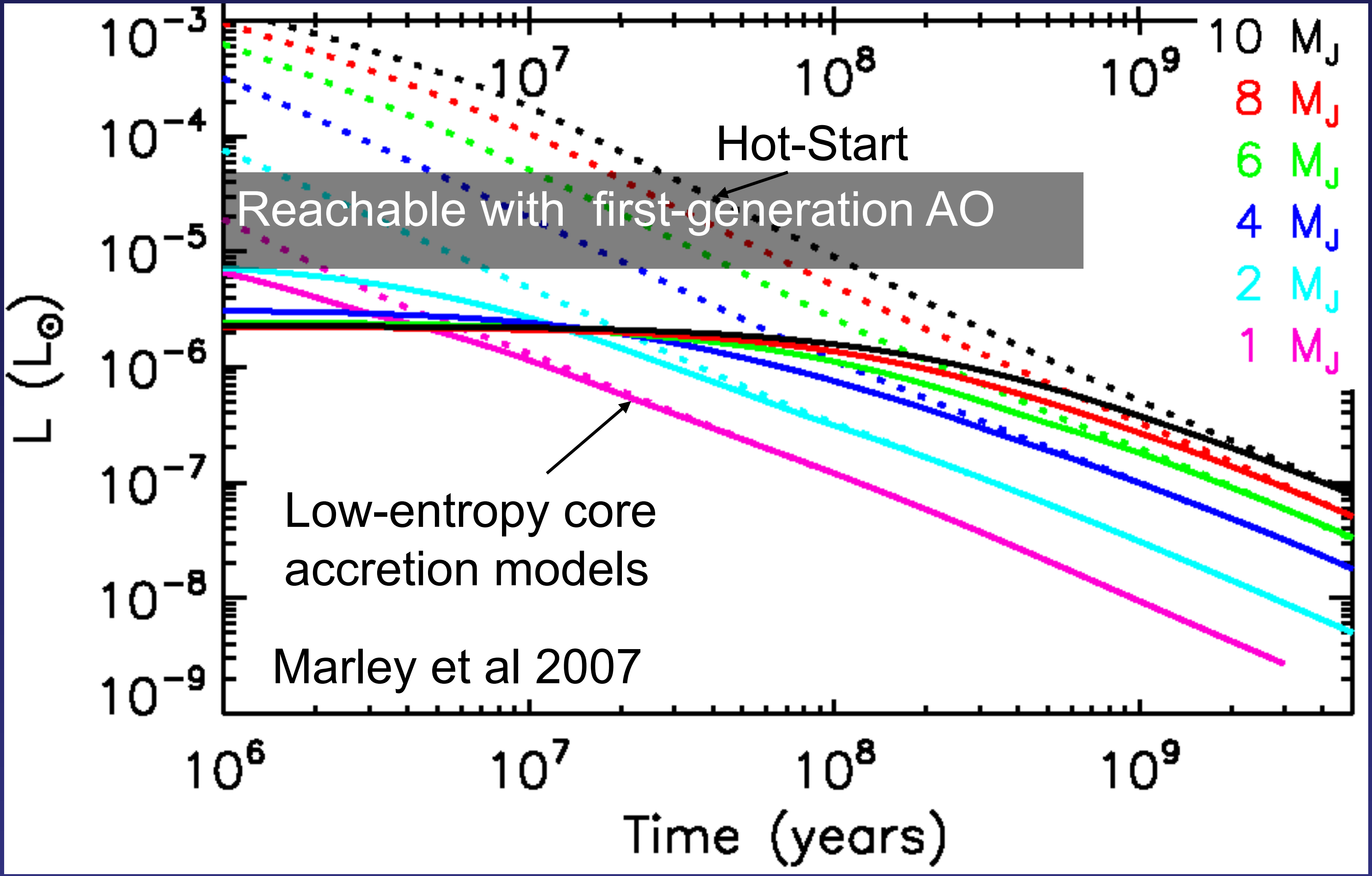
The Graduate Institute for
Advanced Studies/NOAJ

Top-down: Gravitational Instability (Hot Start)

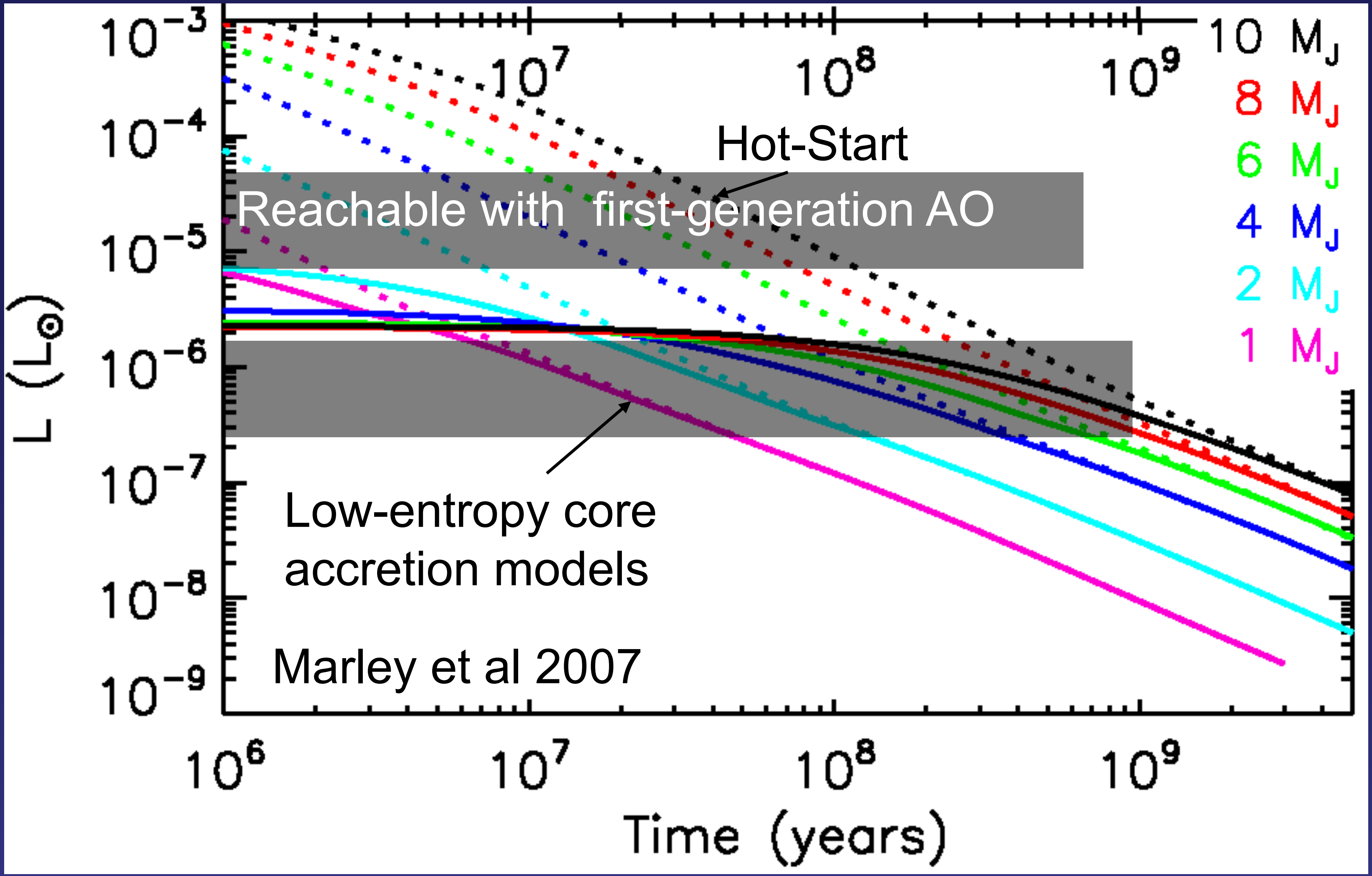


G. Lufkin et al.

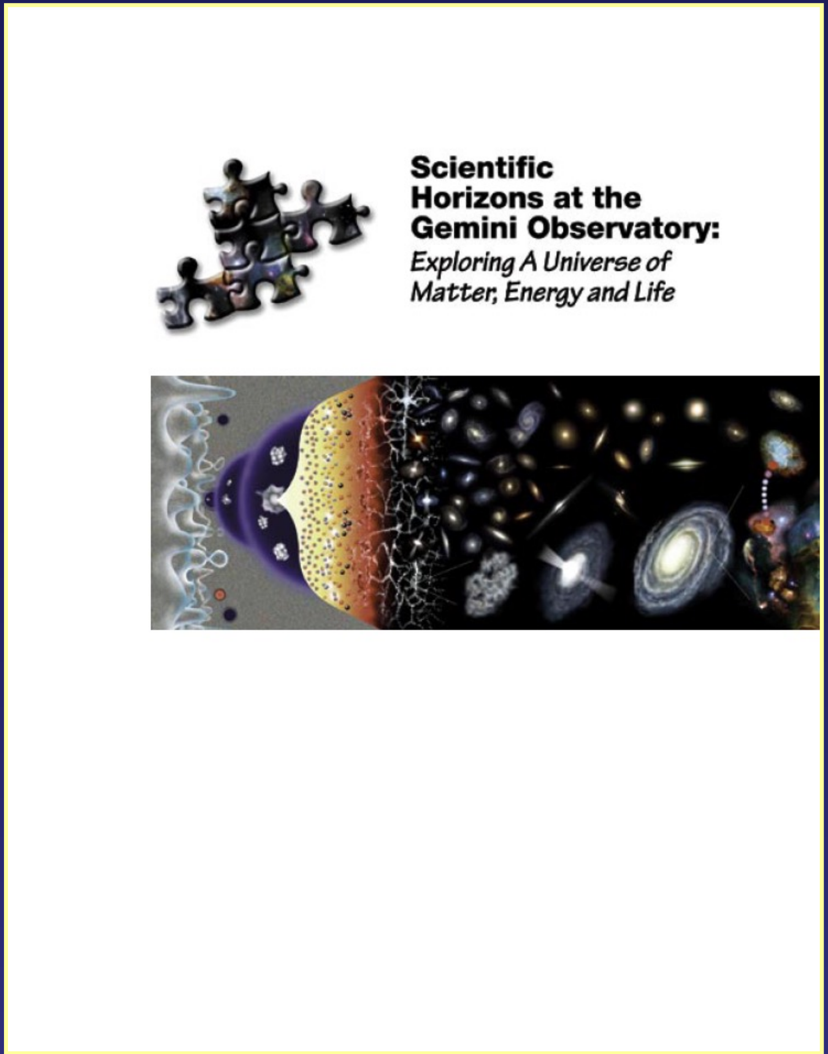
Luminosity depends on initial conditions



Luminosity depends on initial conditions



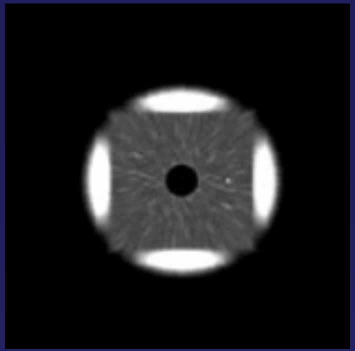
Gemini Planet Imager



<u>Aspen Process (2003)</u>

Key Question:

How common are extrasolar planets, including earth-like planets?



The Universe of Life

- **The Generation of Planets**
- **Gas Giant Planets**

New Capabilities Required:

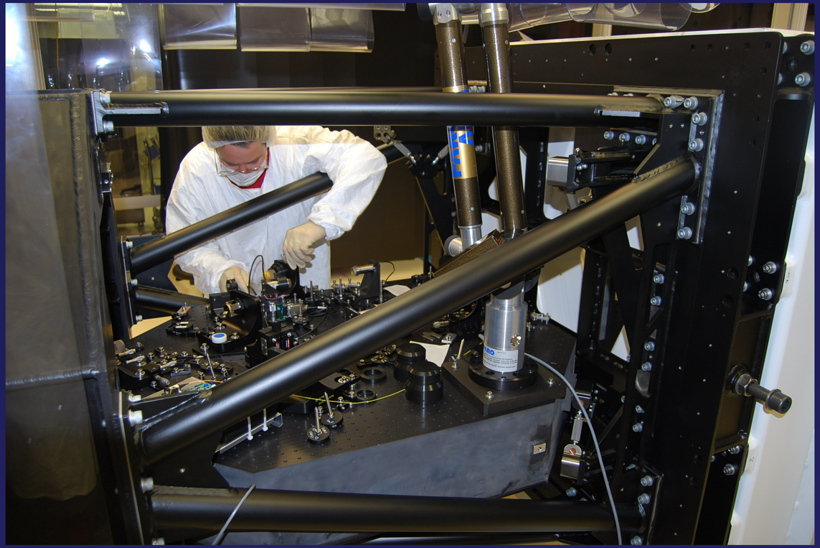
Extreme Adaptive Optics Coronagraph

- *Wavelength range: 0.9 - 2.5 μm*
- *Spatial resolution: 0.02 arcseconds*
- *Spectral resolution: 30 - 300 (IFU mode) or J, H, K (imaging mode)*
- *Field of view: 3 arcseconds*
- *Multiplex: 1 object*
- *Other: 10^7 contrast ratio in 0.1 - 1.5 arcsecond radius; includes polarimetry*

Slide courtesy of
Stephen Goodsell

The Gemini Planet Imager (GPI)

- GPI is an advanced high contrast imager with a high-order adaptive optics system, coronagraph and interferometric calibration unit, all feeding a 1-2.4 μm integral field spectrograph
- Components built by 7 institutions in the US and Canada
- GPI achieved first light on Gemini South November 11, 2013
  - Routine operations 2014B



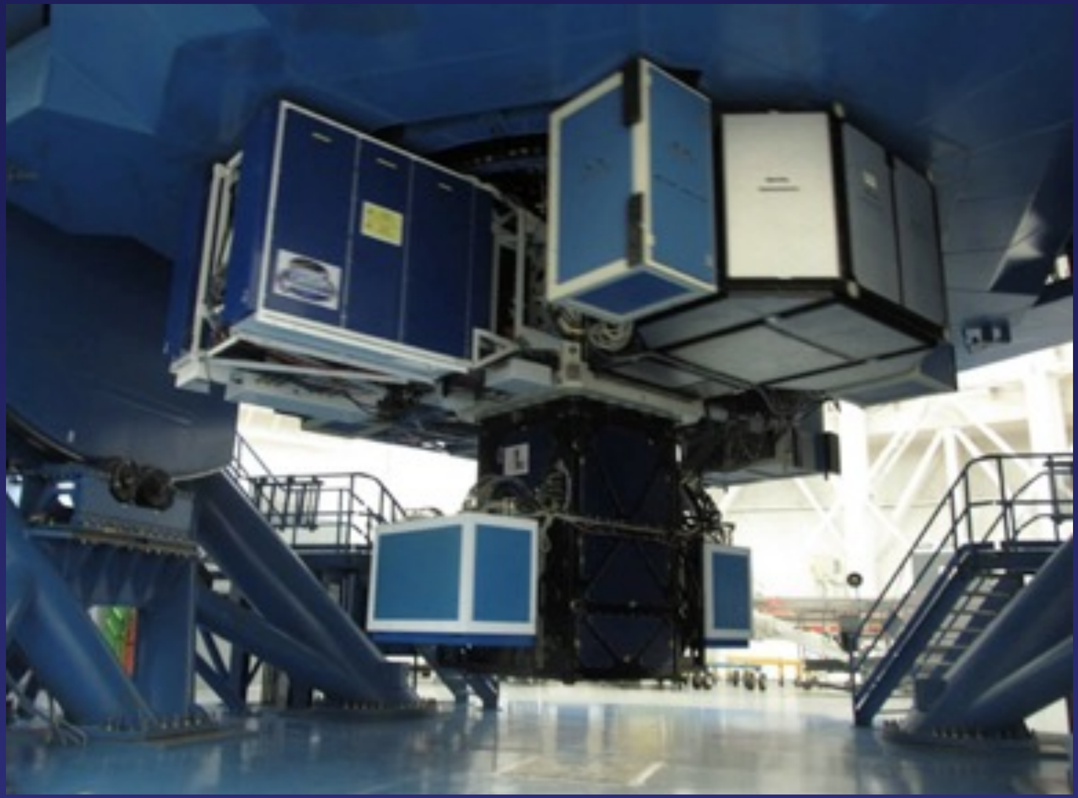
Assembly at HAA, Victoria, BC

Mounting on Gemini South

GPI 1st Light

GPI 1st Light

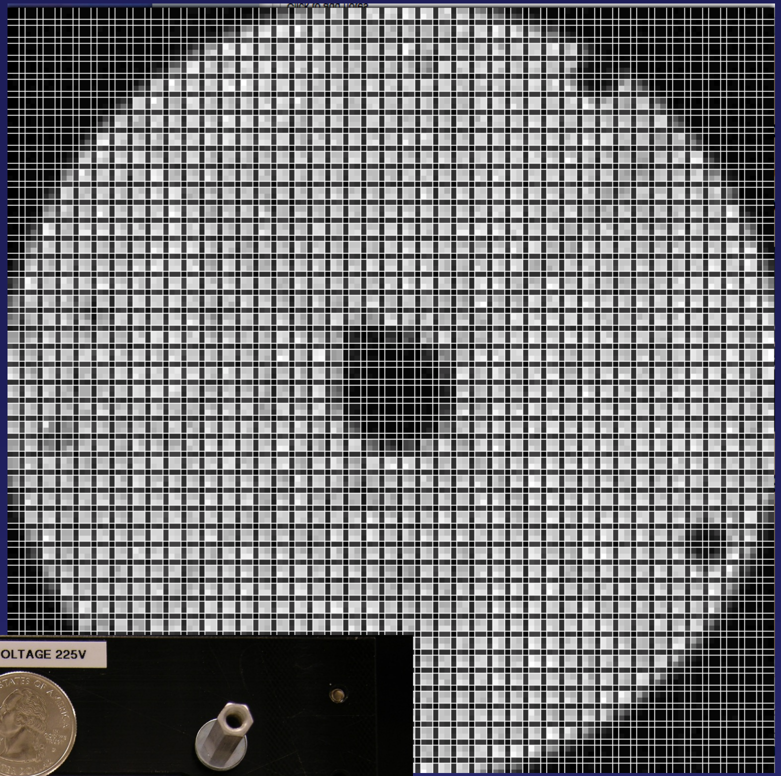
GPI 1.0

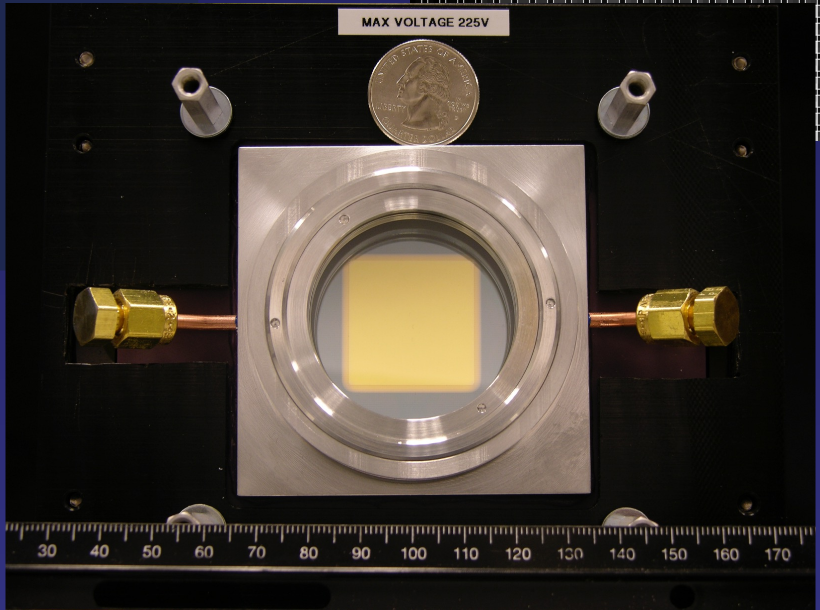


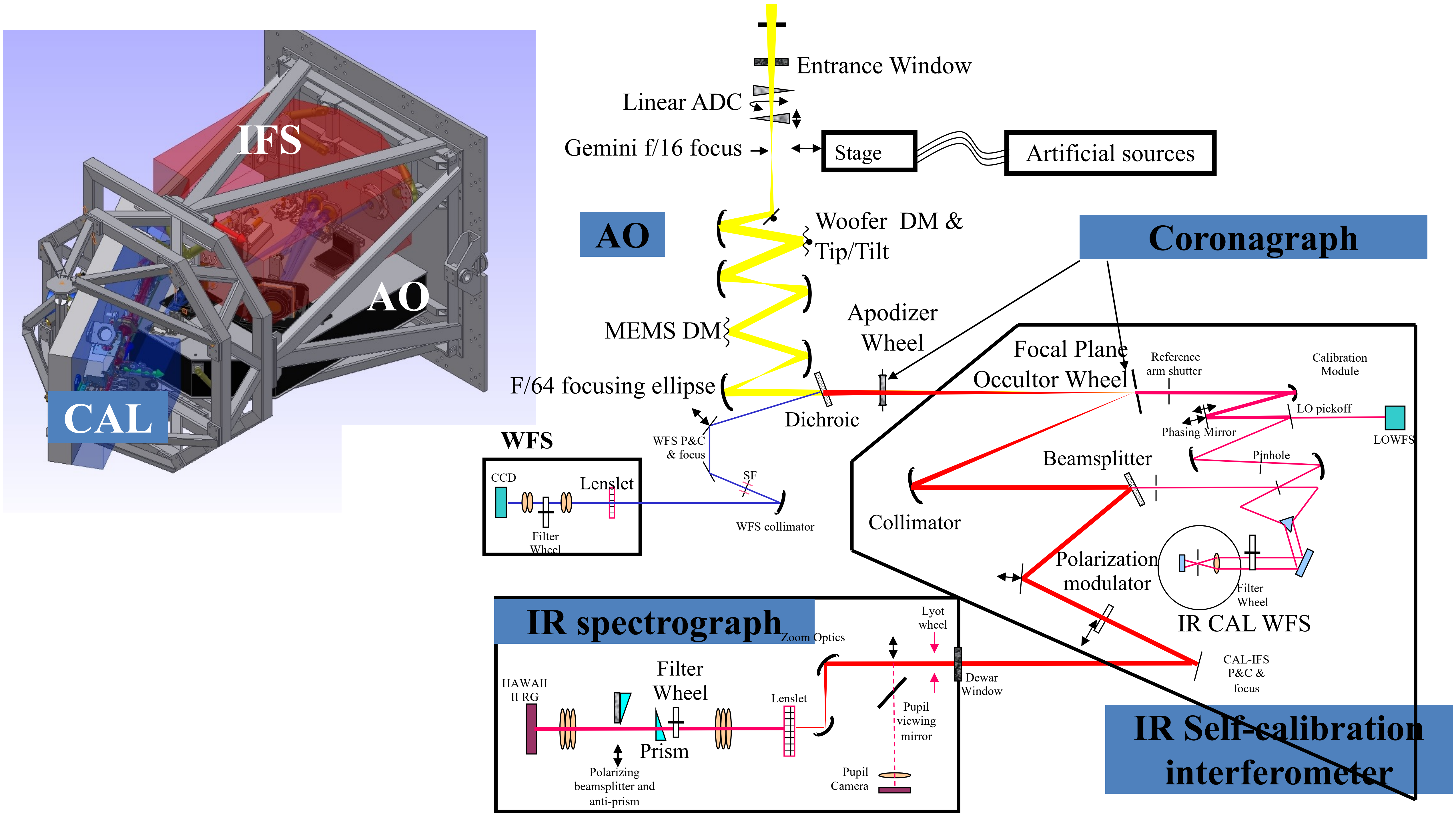
- Operations from 2014B – 2020A
- 58 unique principal investigators
- ~1700 hours of queued time
- 83 Refereed Publications
- Cited 4001 times (~48 citations per paper published)
- Instrument h-index 34 (37 including instrument papers)
- 14 PhDs (from science data)
- Delivered with robust IDL data reduction pipeline

GPI 1.0 Key features

- BMM 4096-actuator MEMS deformable mirror + piezo woofer (5 bad actuators)
- Spatially-filtered Shack-Hartmann WFS with 160x160 pixel Lincoln Labs CCD
- 1 kHz update rate with approximately 1.4 ms delay
- I<9-10 mag limit
- Superpolished (1nm RMS) optics
- 1 – 2.4 micron 2.7" x 2.7" FOV IFS

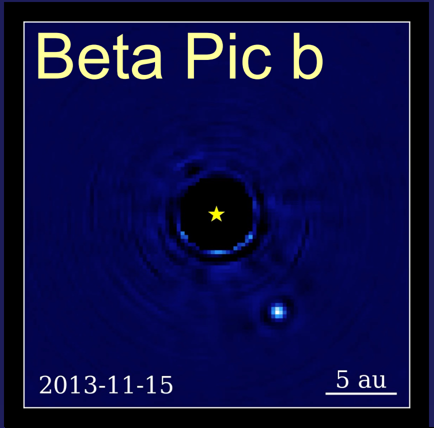


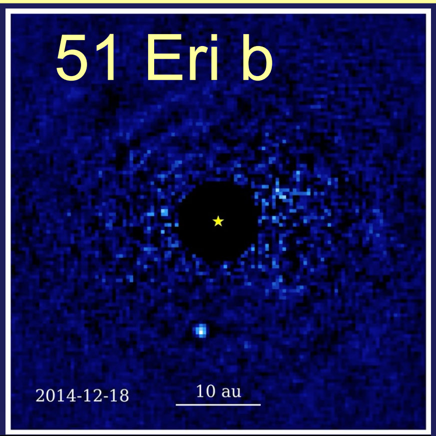


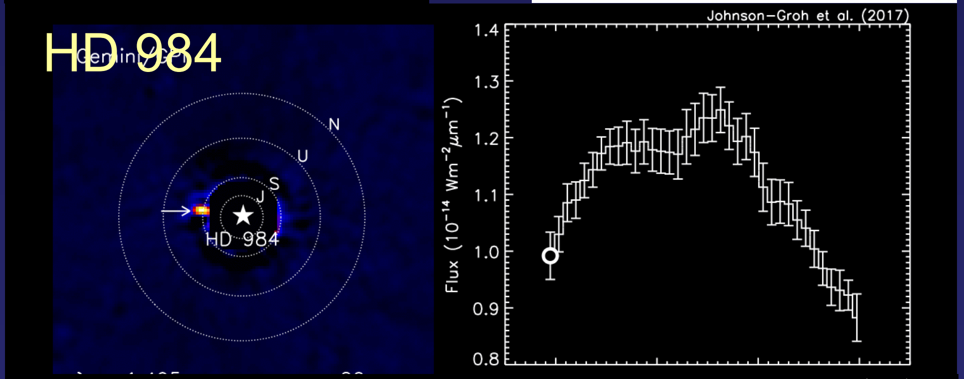


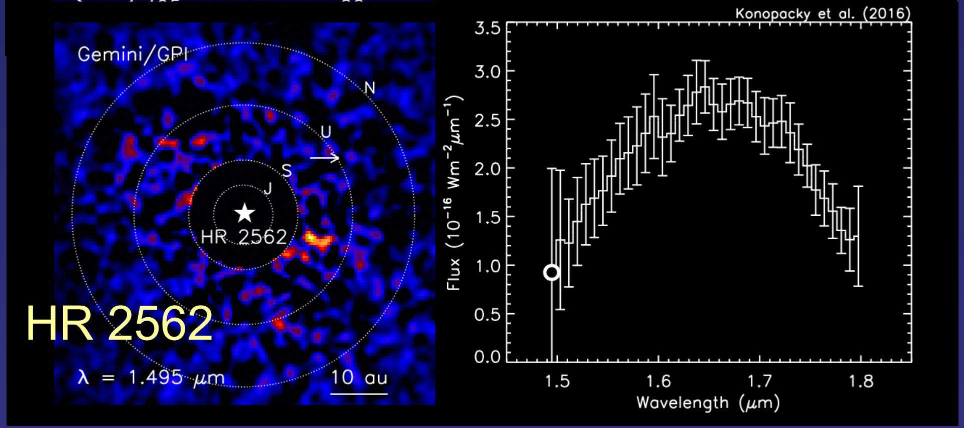
IFS
AO
CAL
Entrance Window
Linear ADC
Gemini f/16 focus
Stage
Artificial sources
AO
Woofer DM &
Tip/Tilt
Coronagraph
MEMS DM
Apodizer
Wheel
Focal Plane
Occultor Wheel
Reference
arm shutter
Calibration
Module
F/64 focusing ellipse
Dichroic
LO pickoff
LOWFS
Phasing Mirror
WFS
WFS P&C
& focus
CCD
Lenslet
SF
Filter
Wheel
WFS collimator
Beamsplitter
Pinhole
Collimator
Polarization
modulator
Filter
Wheel
IR CAL WFS
IR spectrograph
Zoom Optics
Lyot
wheel
HAWAII
II RG
Filter
Wheel
Lenslet
Dewar
Window
CAL-IFS
P&C &
focus
Pupil
viewing
mirror
Prism
Polarizing
beamsplitter and
anti-prism
Pupil
Camera
IR Self-calibration
interferometer

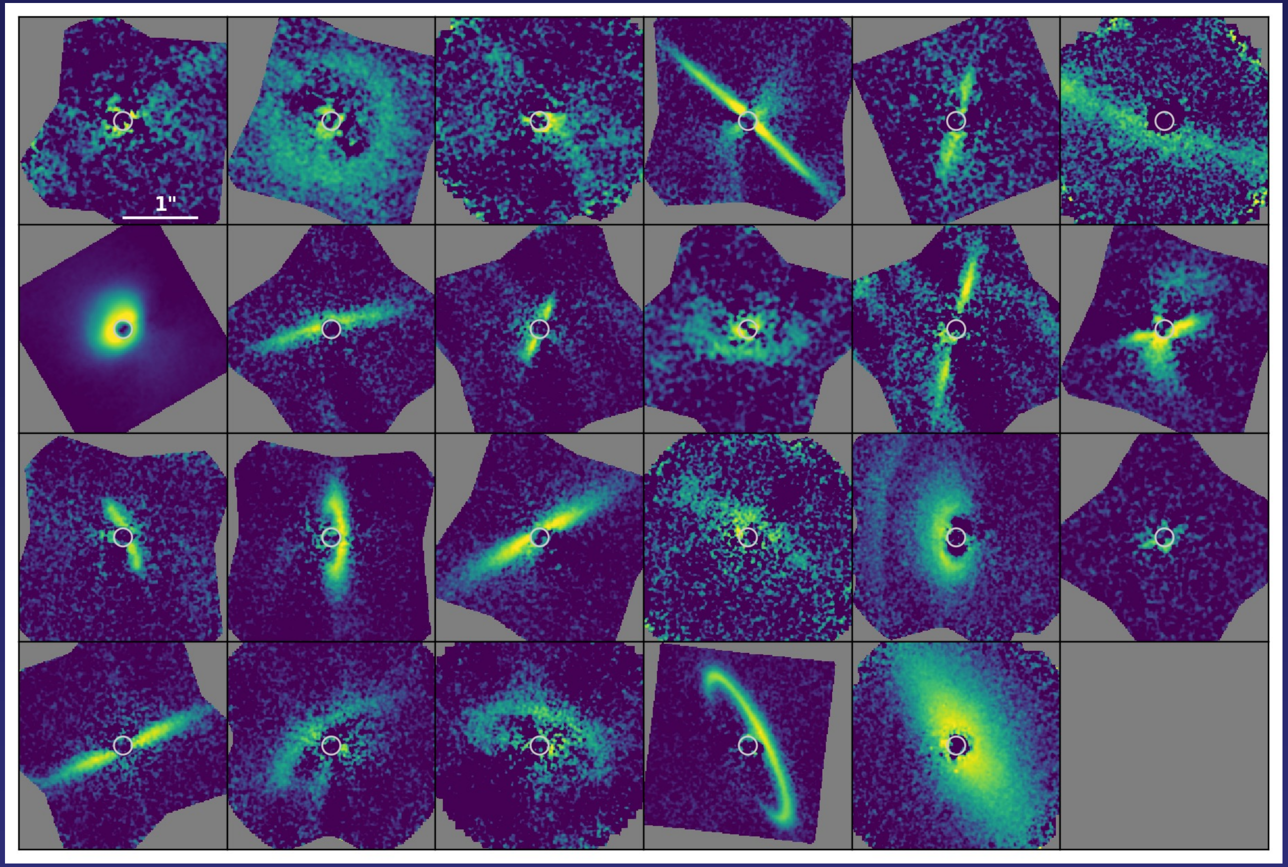
Important GPI Results



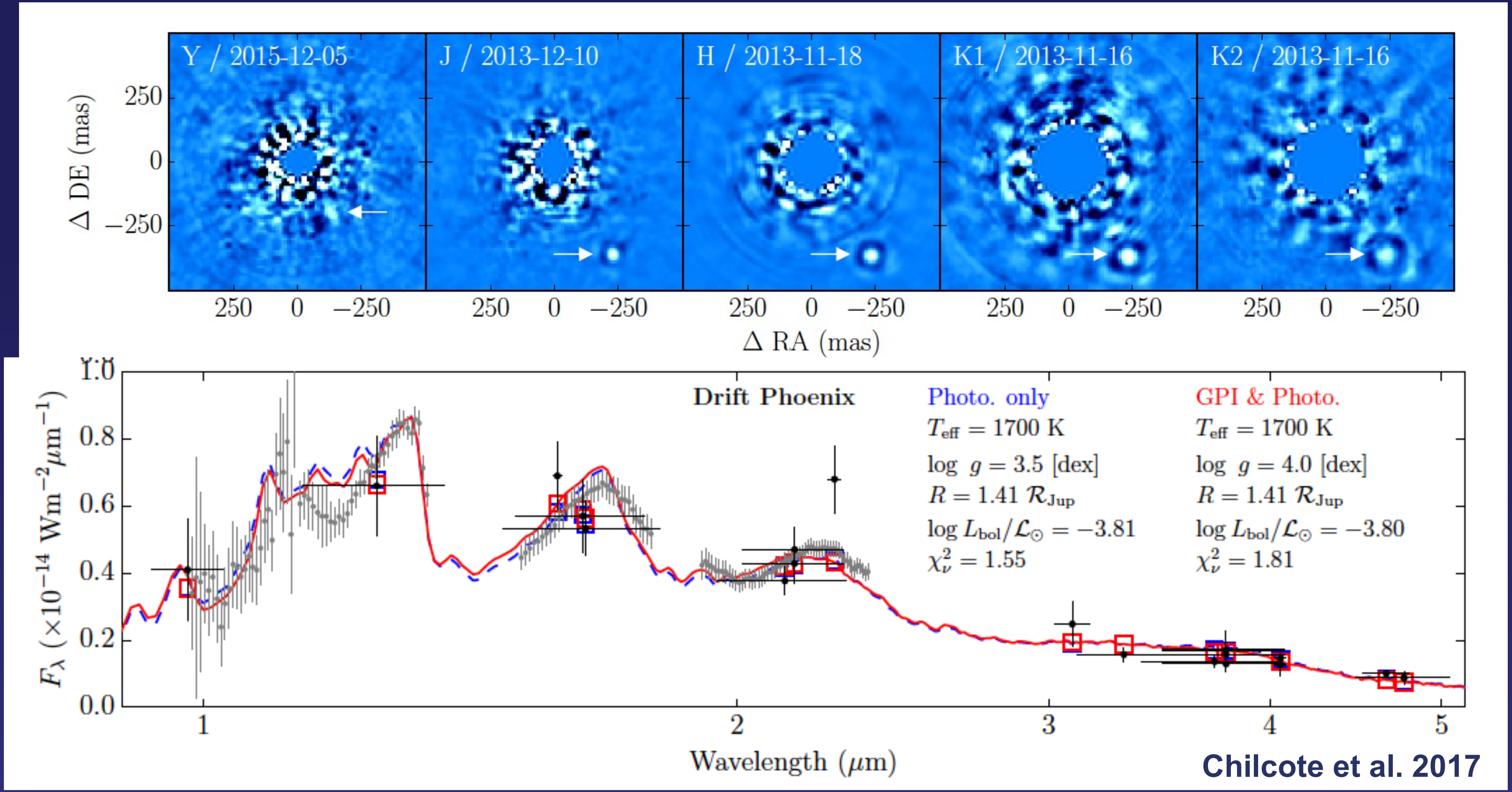






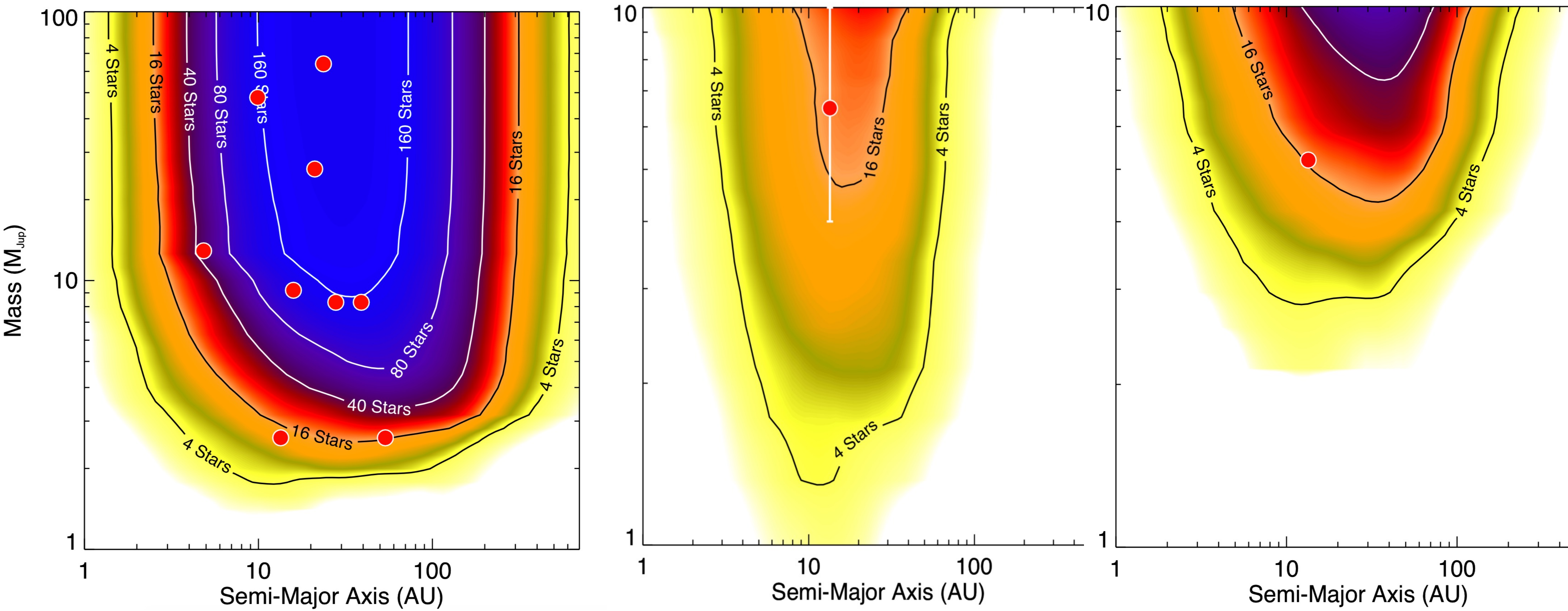


beta Pic b



Chilcote et al. 2017

Sensitivity to hot-start vs cold-start planets



Hot start (BTSET)

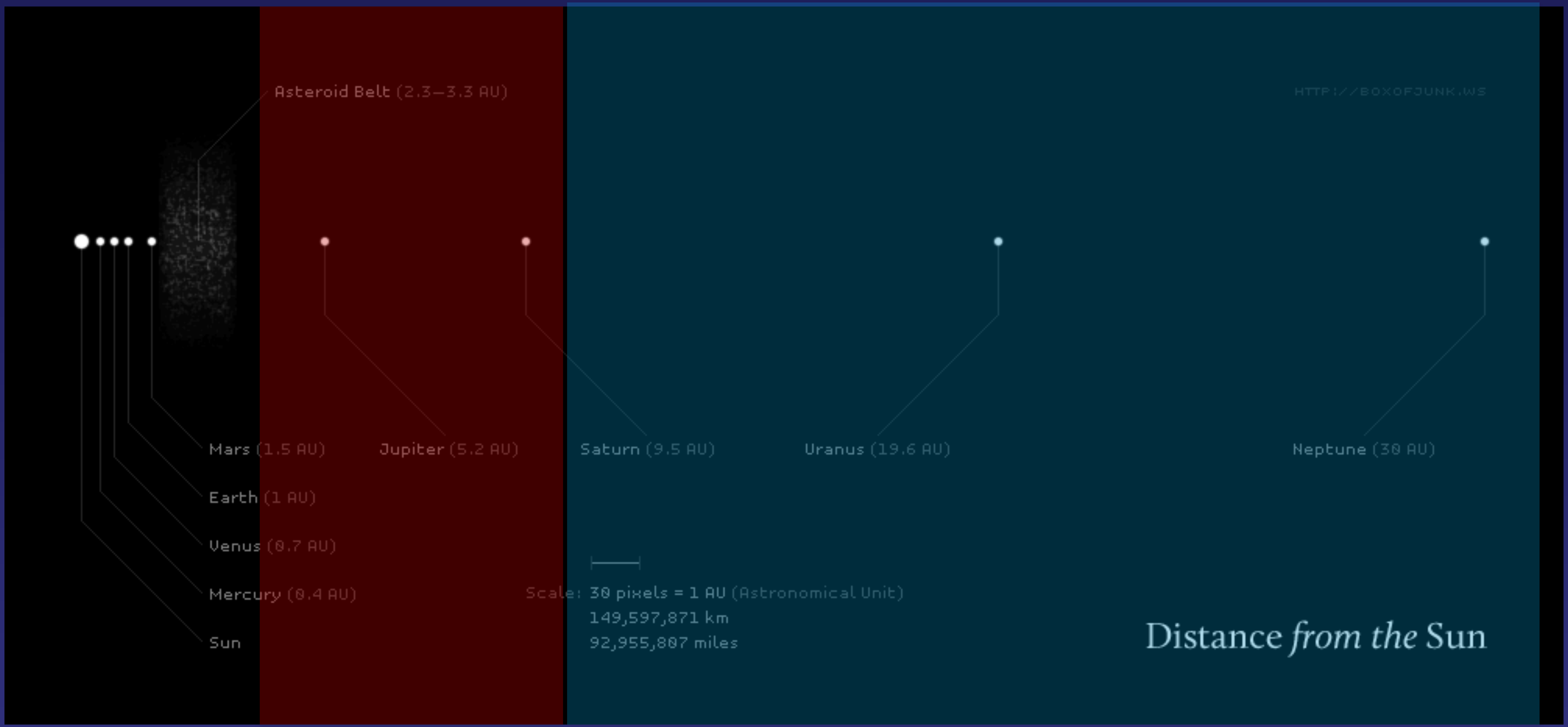
Cold start (Fortney 2008)

Cold start (Sonora models)

Lesson from GPI 1.0 and other surveys: get closer and fainter to see more planets.

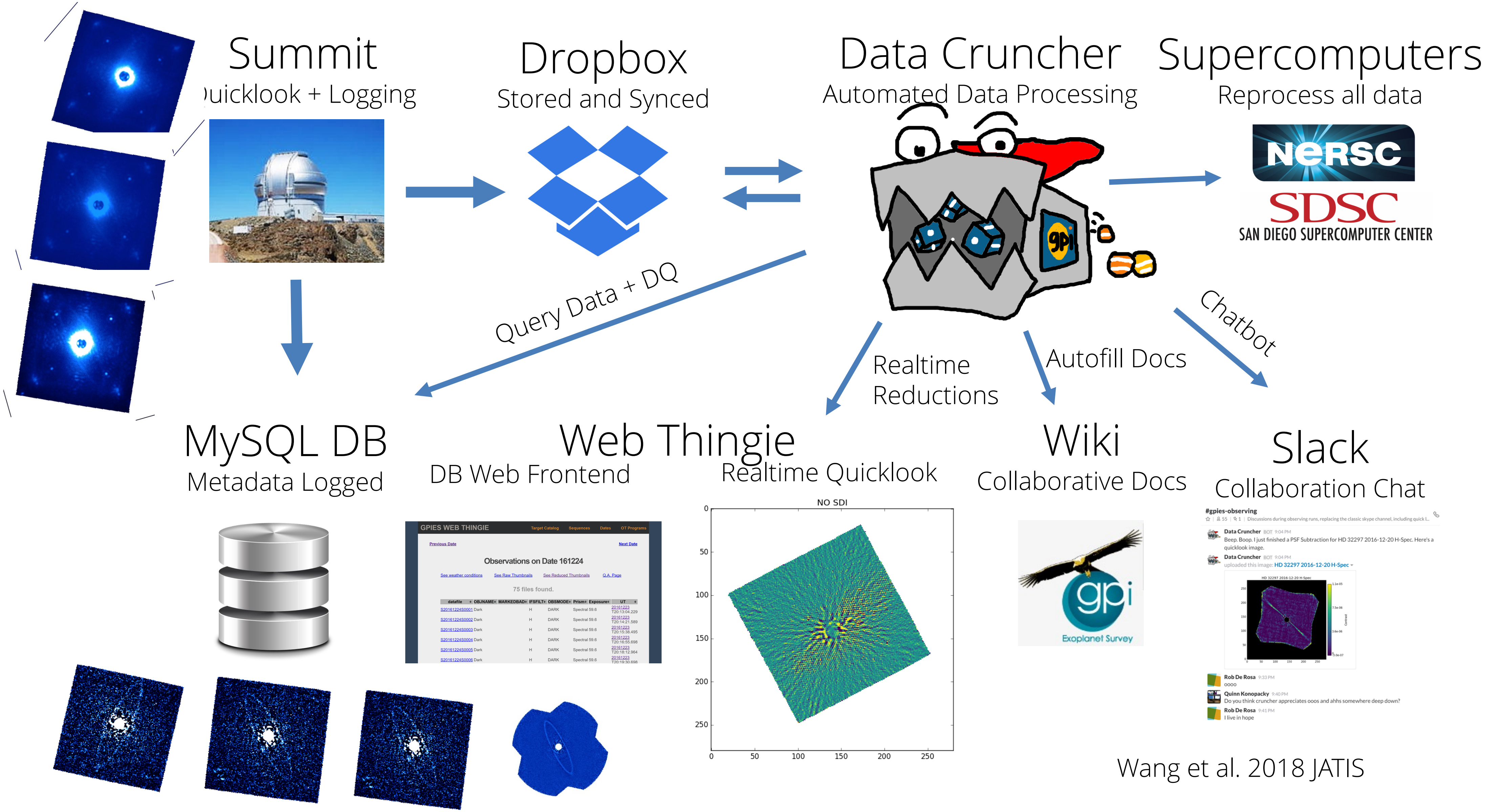
MOST JUPITERS HERE

VERY FEW JUPITERS HERE



Nielsen et al. 2019

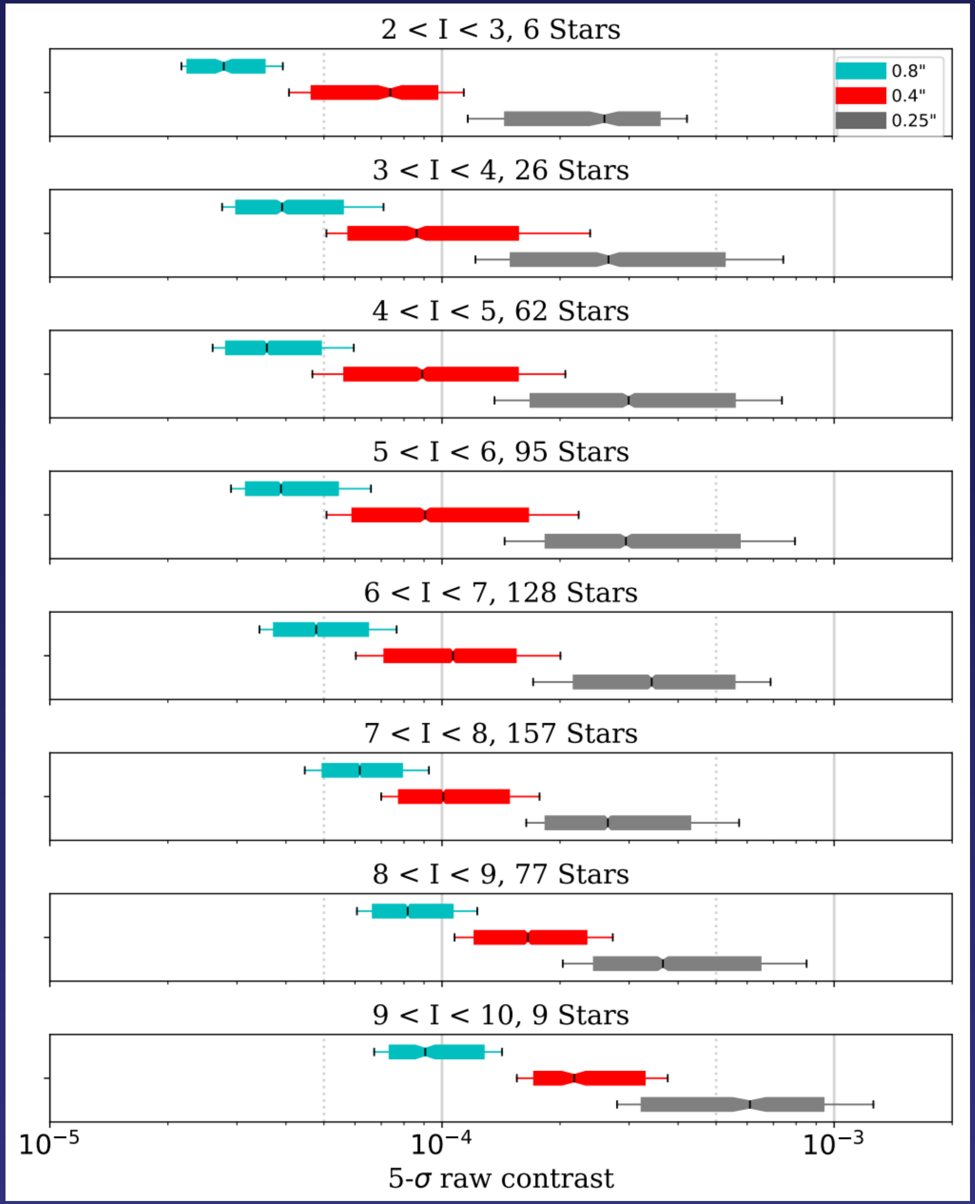
The GPIES Data Infrastructure



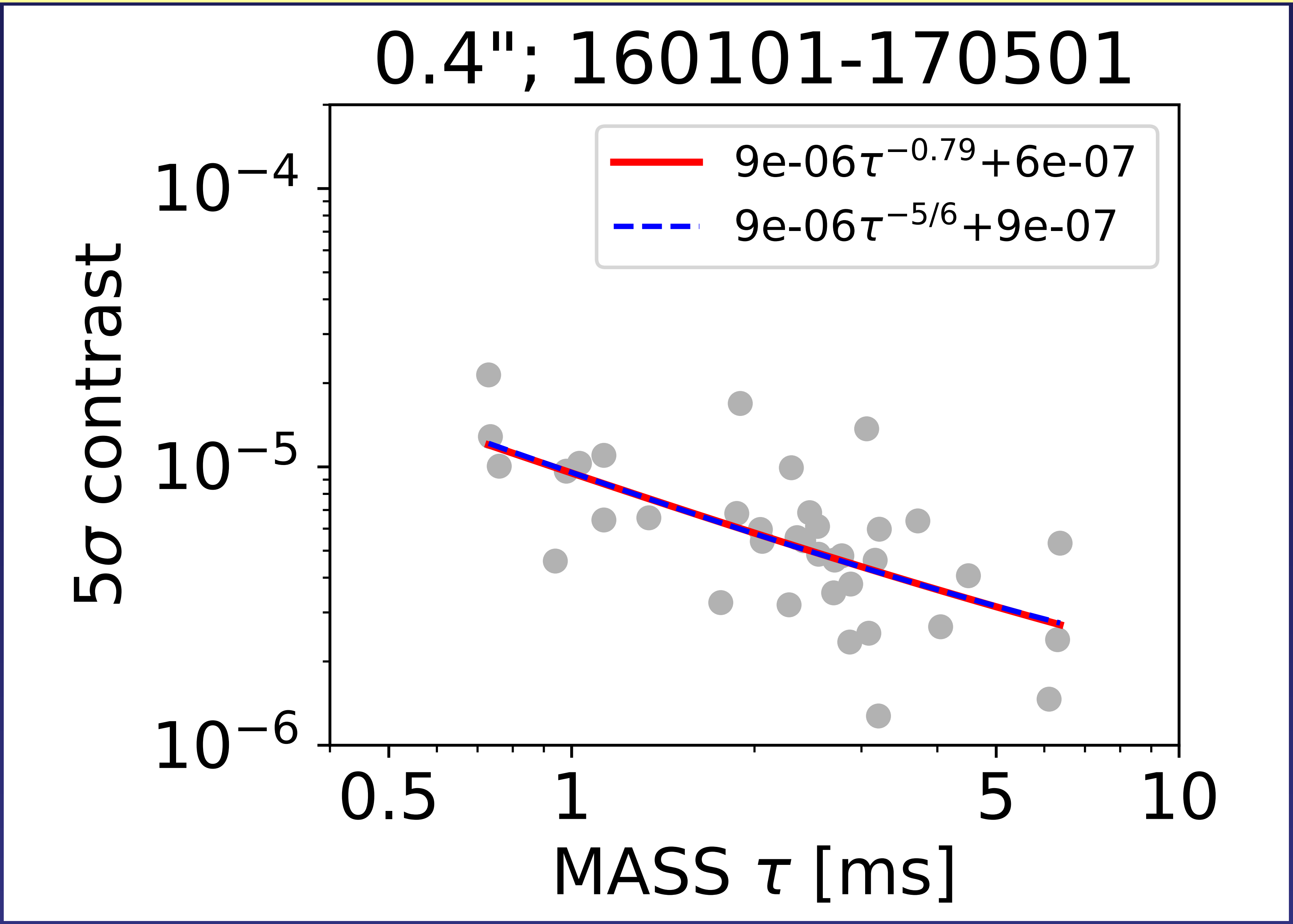
Wang et al. 2018 JATIS

Empirical Contrast Models (Vanessa Bailey)

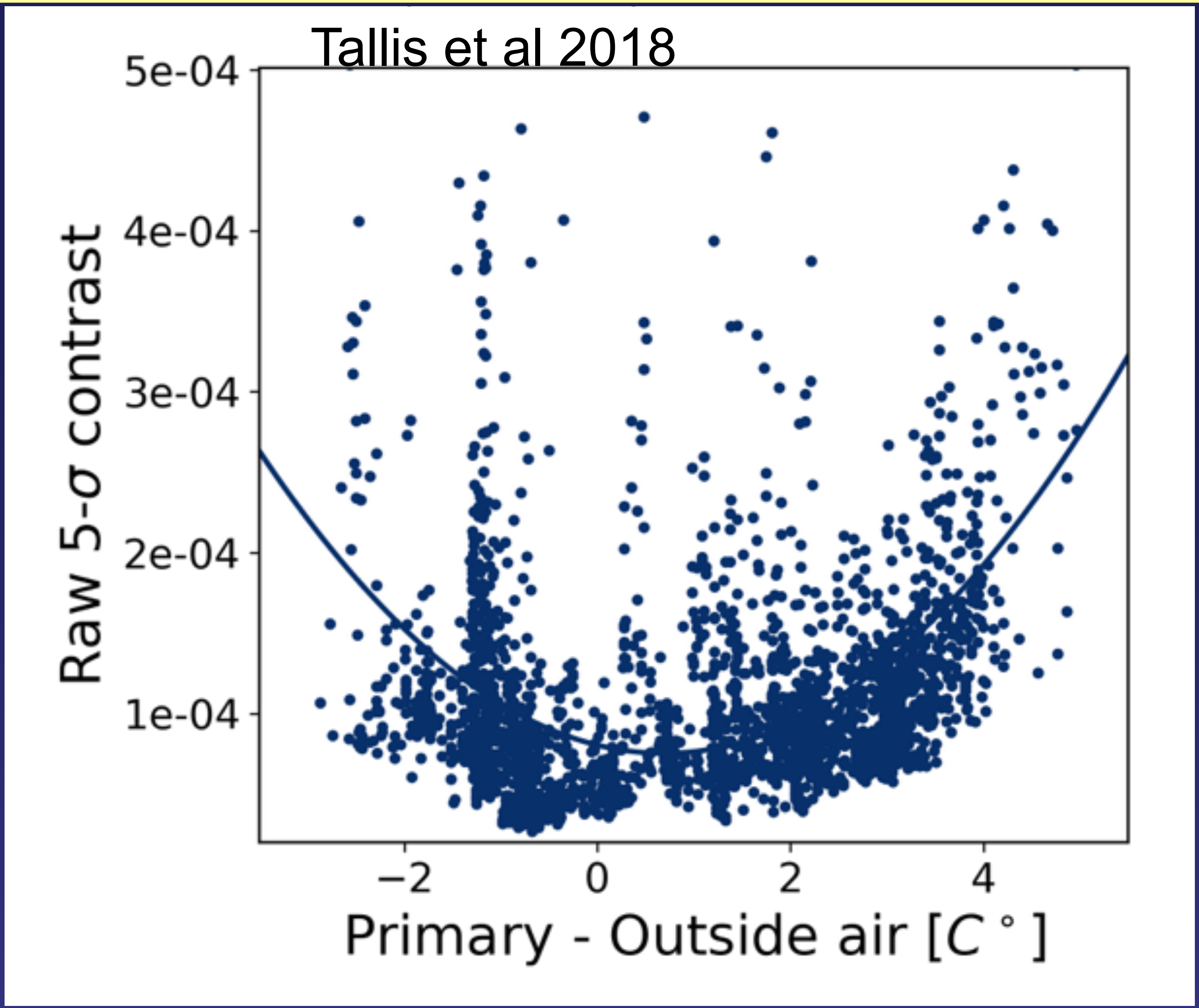
- Empirical multiparameter fit to contrast vs telemetry
- 25,000 raw images
- 500 combined datasets
- Extension of work in Bailey et al 2016



Strongest predictor of contrast: tau_0 from MASS



Dome seeing also degrades performance



GPI Migration

GPI 2.0 – Upgrade Science Driven

Developing science cases relevant to 2020-2030

1. Emphasize GPIs strengths: reliable, efficient operation
2. Quantify science requirements -> practical design
3. Don’t try to compete head-to-head with Keck or Subaru

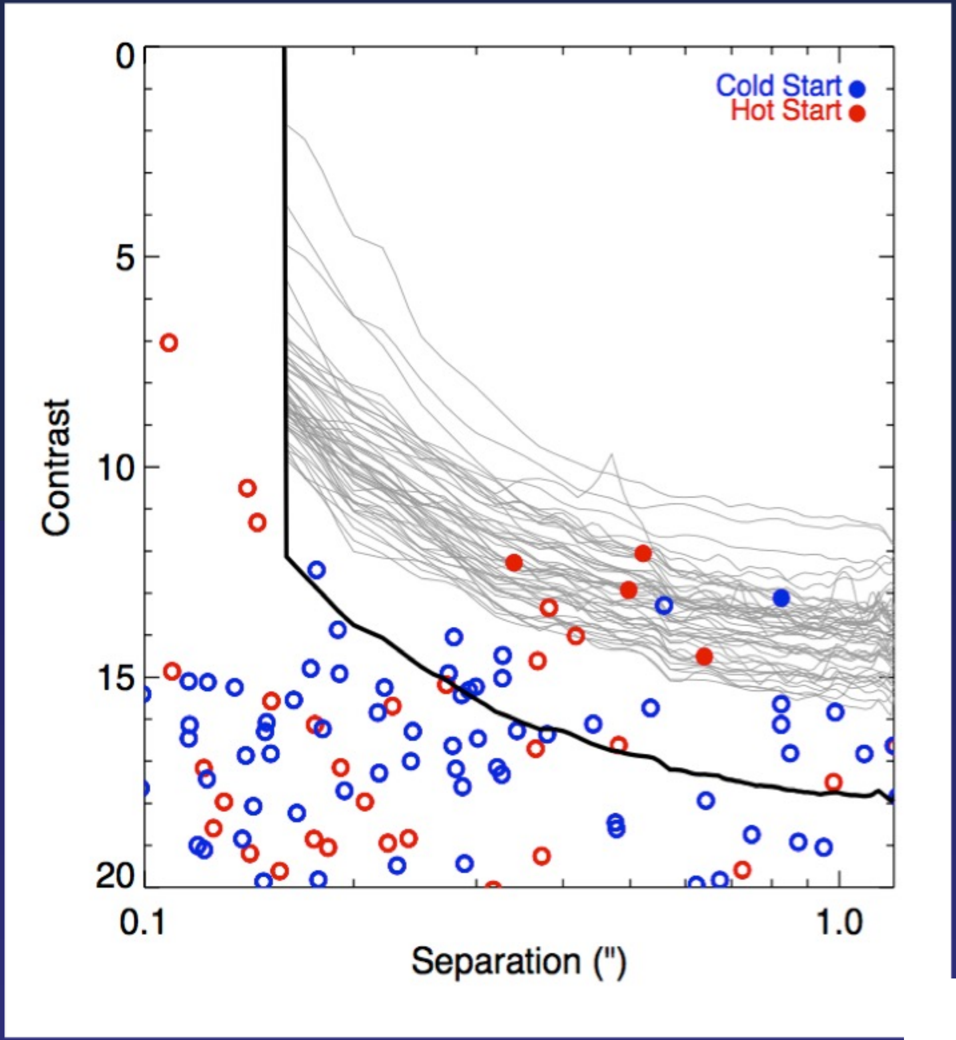
GPI 2.0 – Science Cases

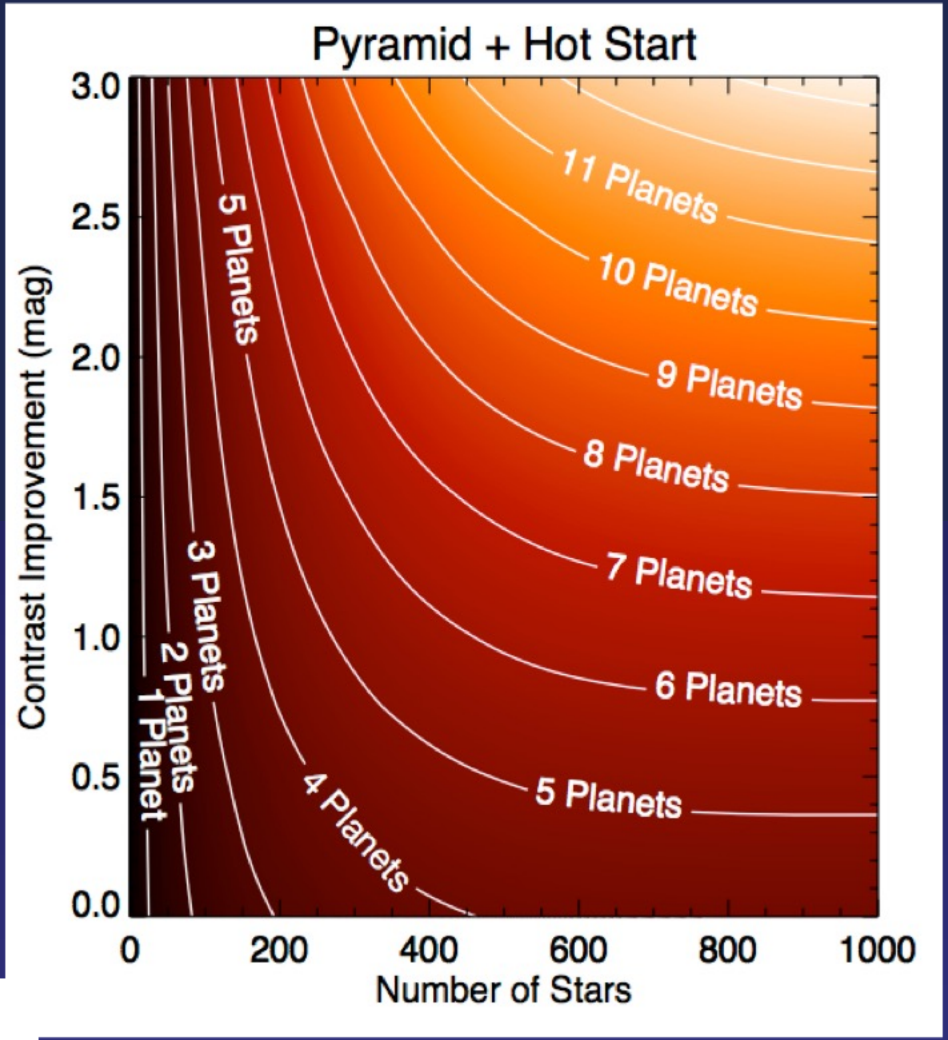
Science Cases	WFS I Mag Limit	Inner Working Angle	Contrast Improvement
Large scale survey / cold-start planets	10	0.15″	2+ mag
Very young stars + transitional disks	13 (or IR WFS)	0.1″	0
Asteriods & solar system objects	13-14	-	0
Debris Disks	9	0.2″	0
Planet Variability & abundance charcterisation	6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

GPI 2.0 – A Facility-Class High Contrast Imaging System in the North for the 2020s

- **~$8 Million upgrade project funded by NSF MRI, Heising-Simons Foundation, NRC**
  - PIs Jeff Chilcote (Notre Dame) and Quinn Konopacky (UCSD, also Project Scientist)
  - Co-Is Bruce Macintosh (Stanford) and Dmitry Savransky (Cornell)
  - CAL 2.0 upgrade on a different schedule, led by Christian Marois (NRC-HAA)

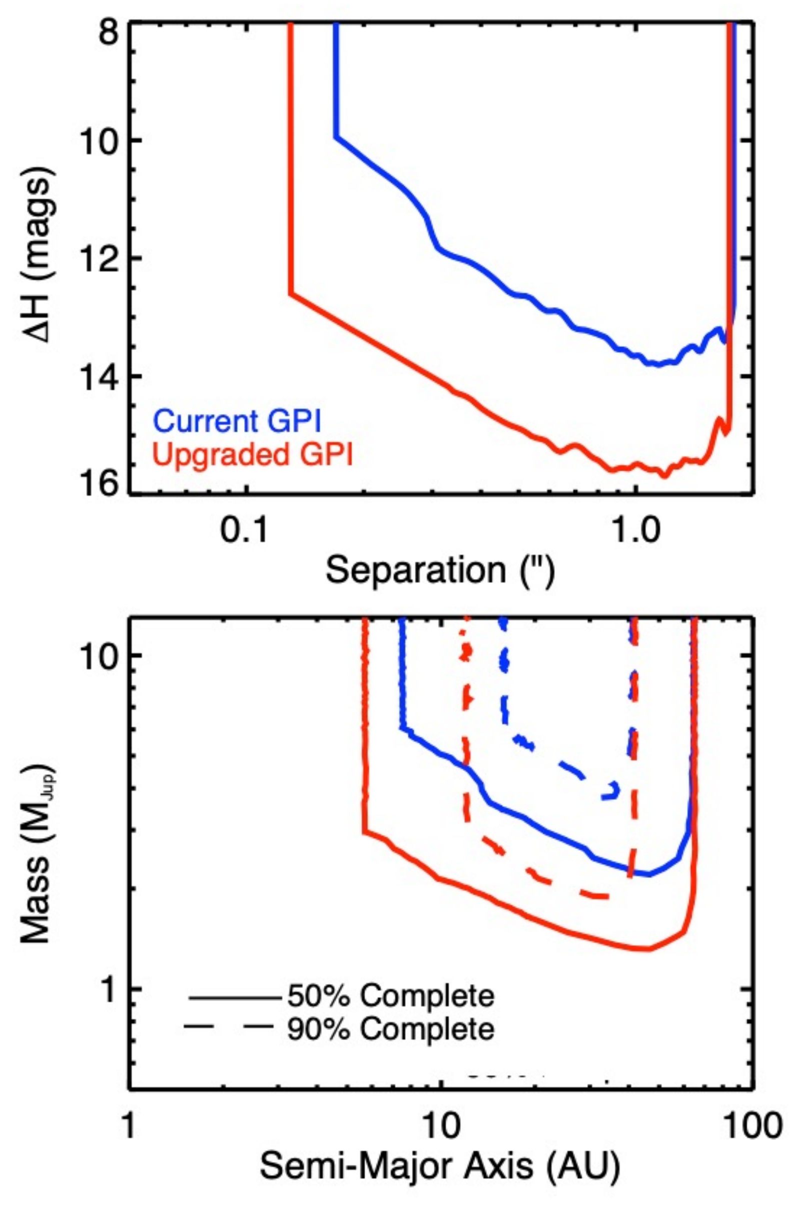
Hot-Start Planets

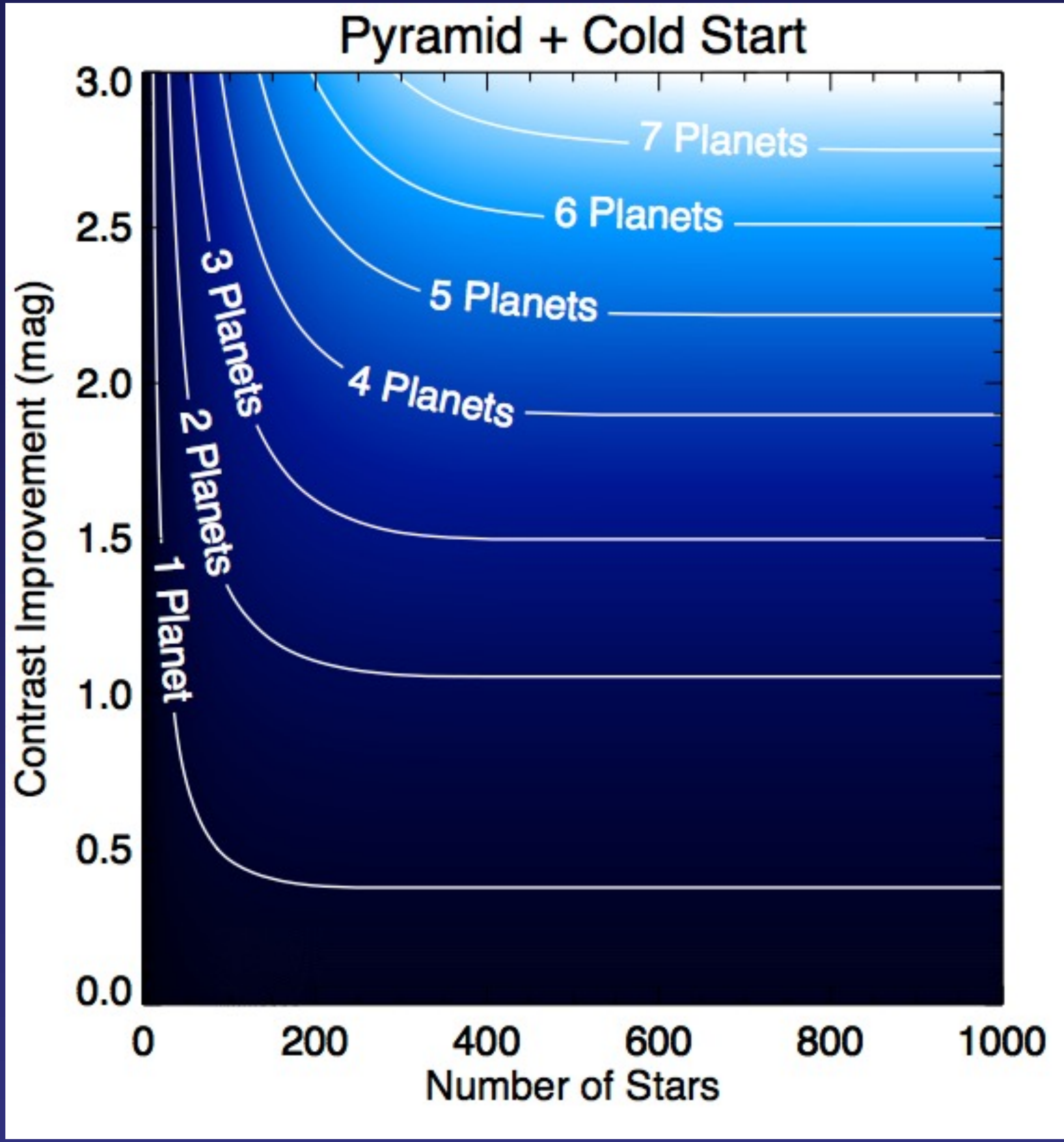




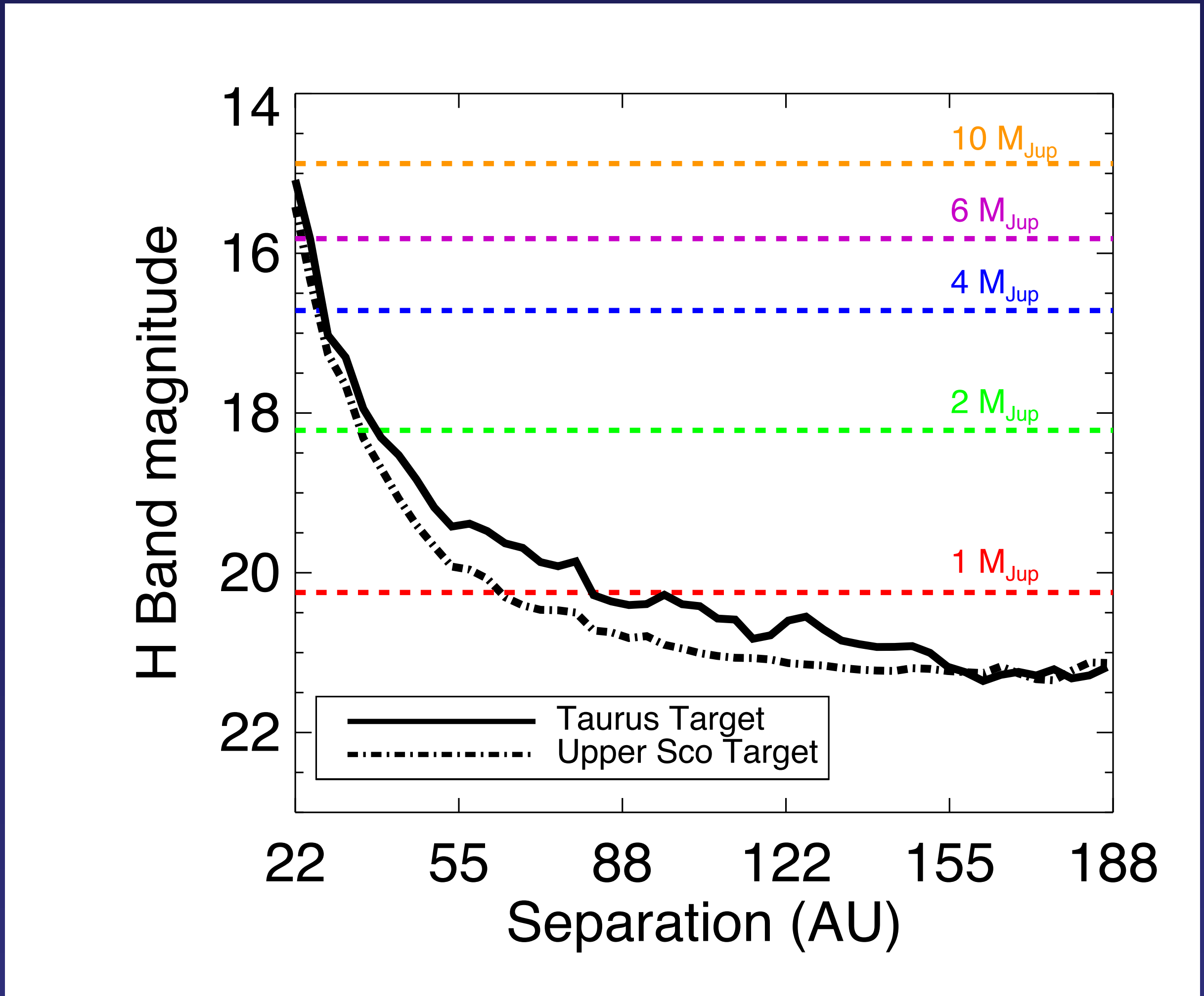
Monte Carlo
Simulations

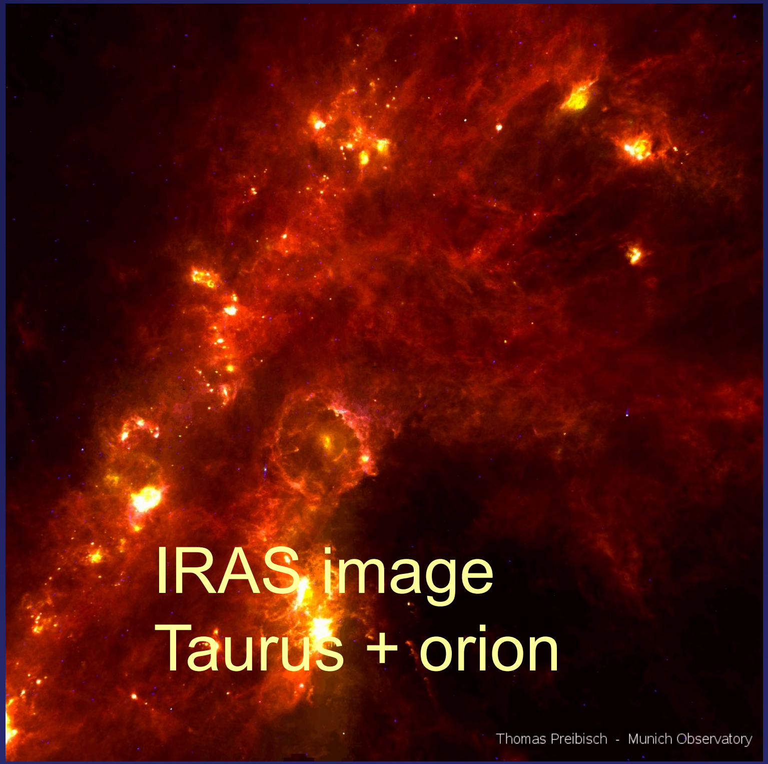
Cold-start planets require +2 mag contrast





Very young planets in Taurus + others

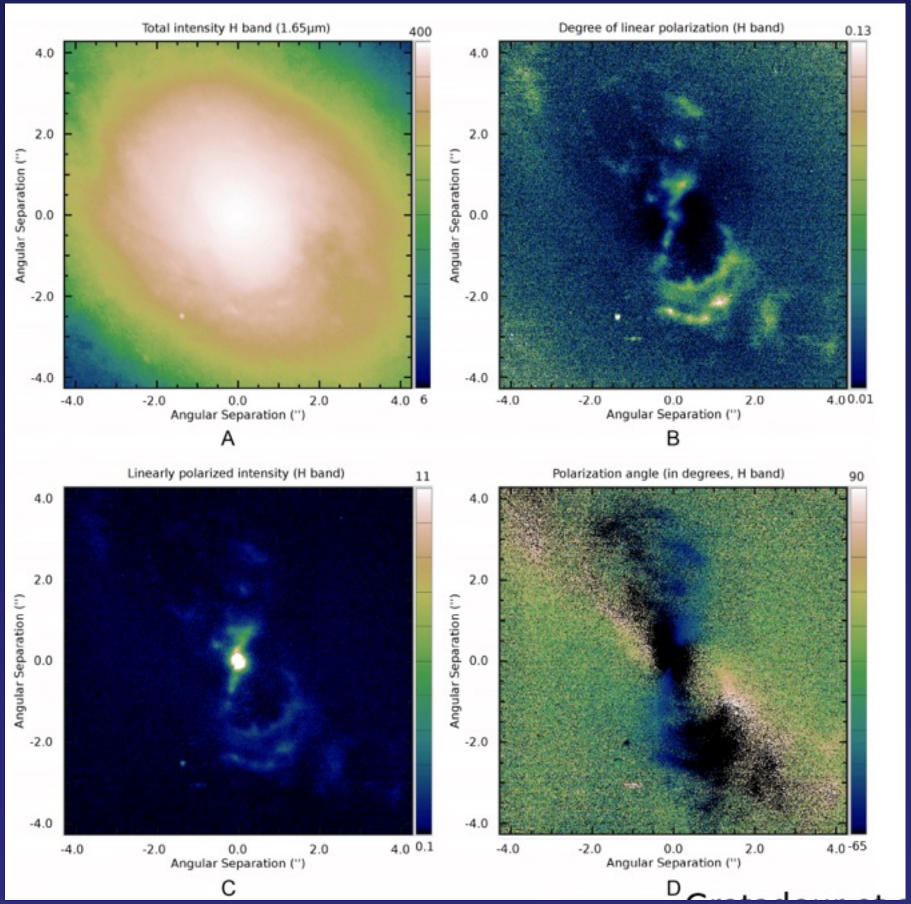




Closest active planet formation?
140 pc, 1-2 Myr
Requires: I~13 mag
close inner working angle

Additional sensitivity will provide access to new sources, such as nearby AGN

NGC 1068

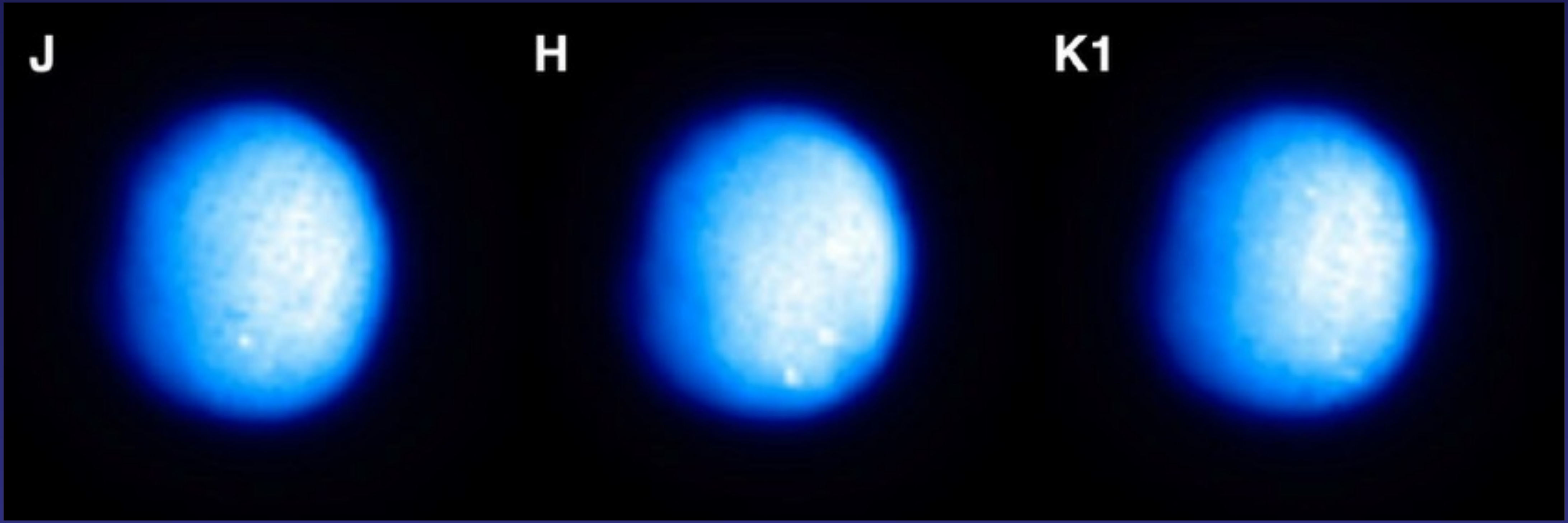


Gratadour et al. 2015 (SPHERE Polarimetry)

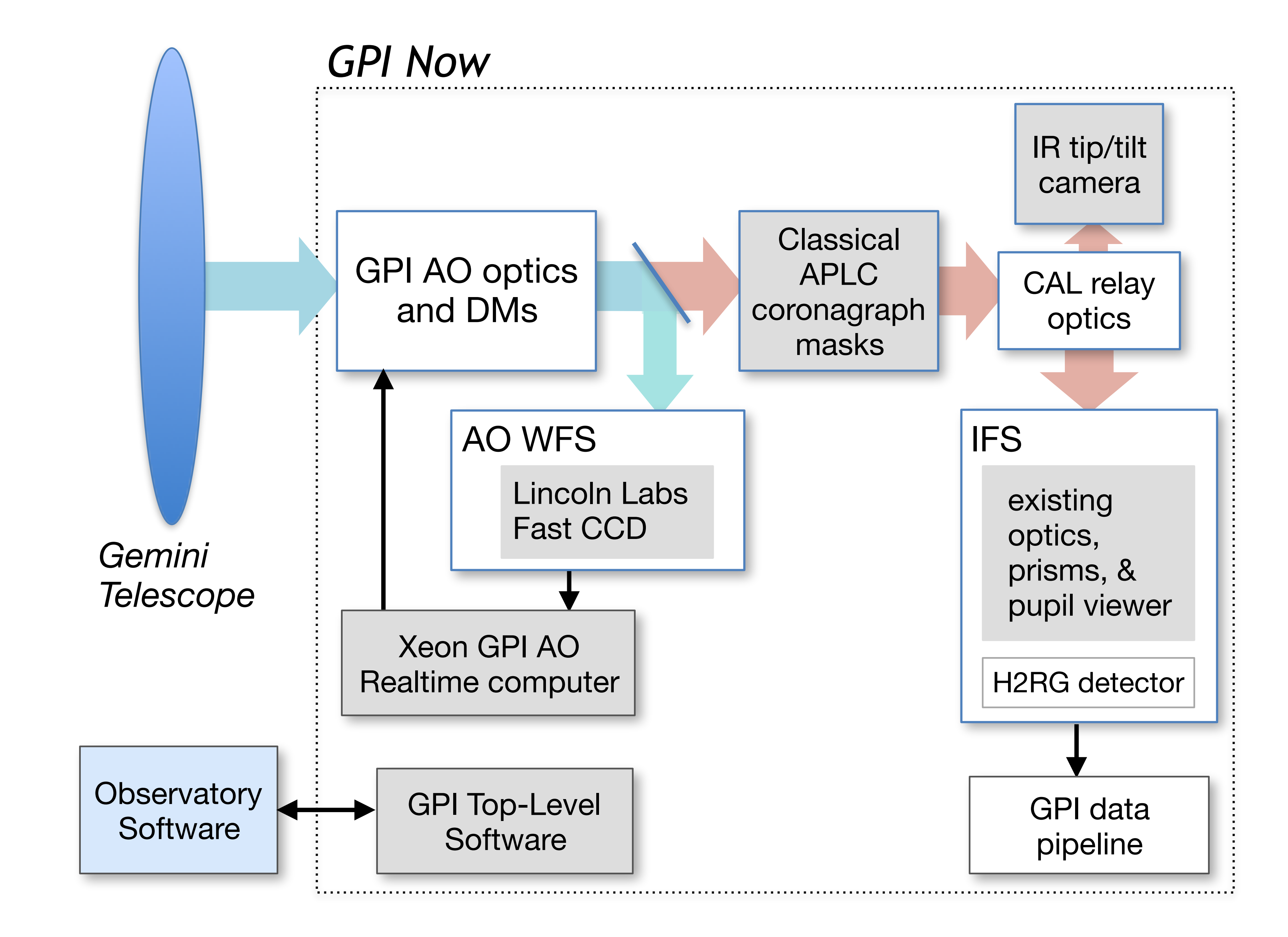
- AO-assisted near-IR polarimetry is a potentially powerful tool for resolving dusty torus, outflow structures
- Ability to perform this measurement on an R-mag 14 (or H-mag 12) source will open up 10s of potential candidates

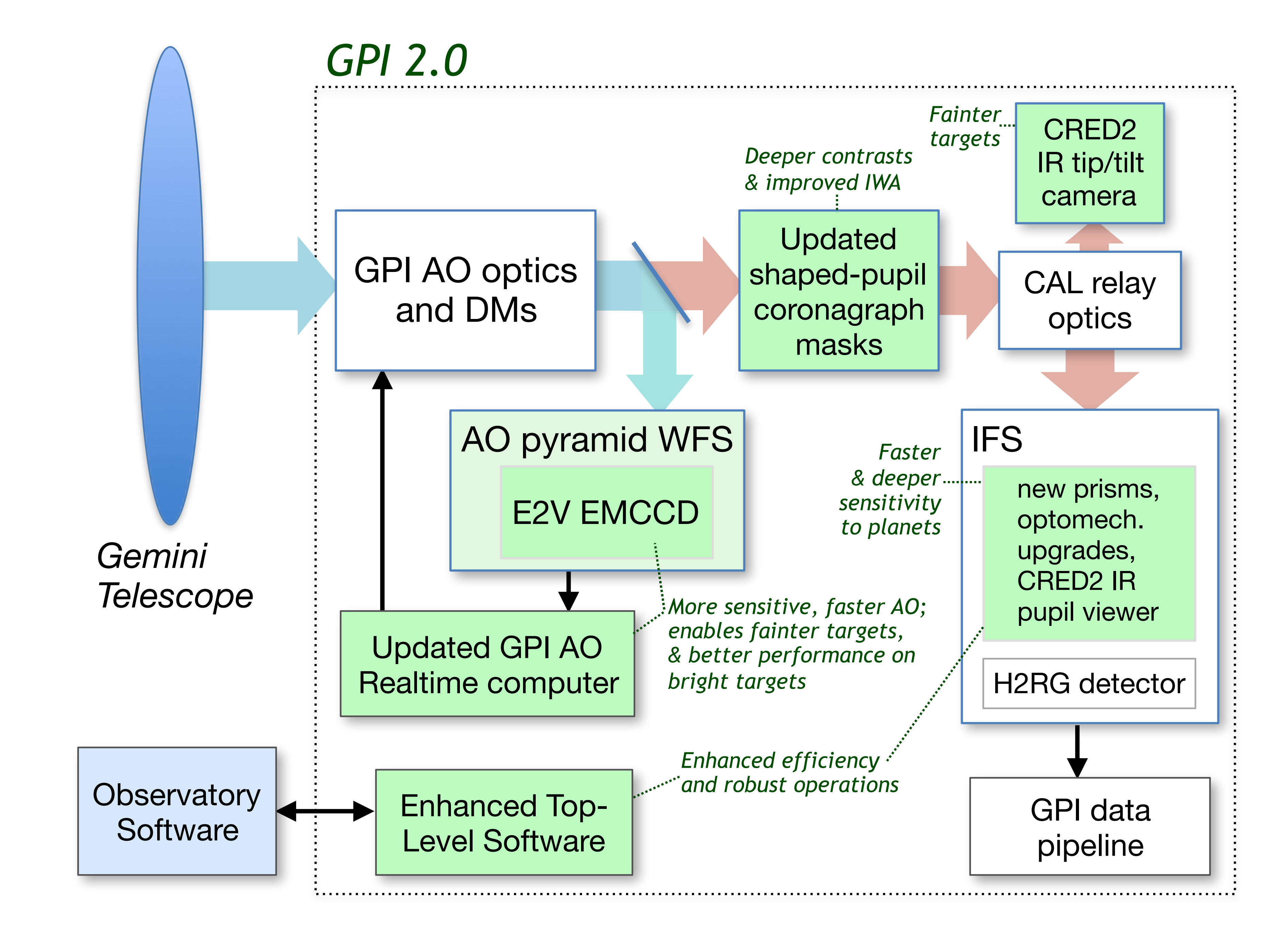
Additional Science Cases

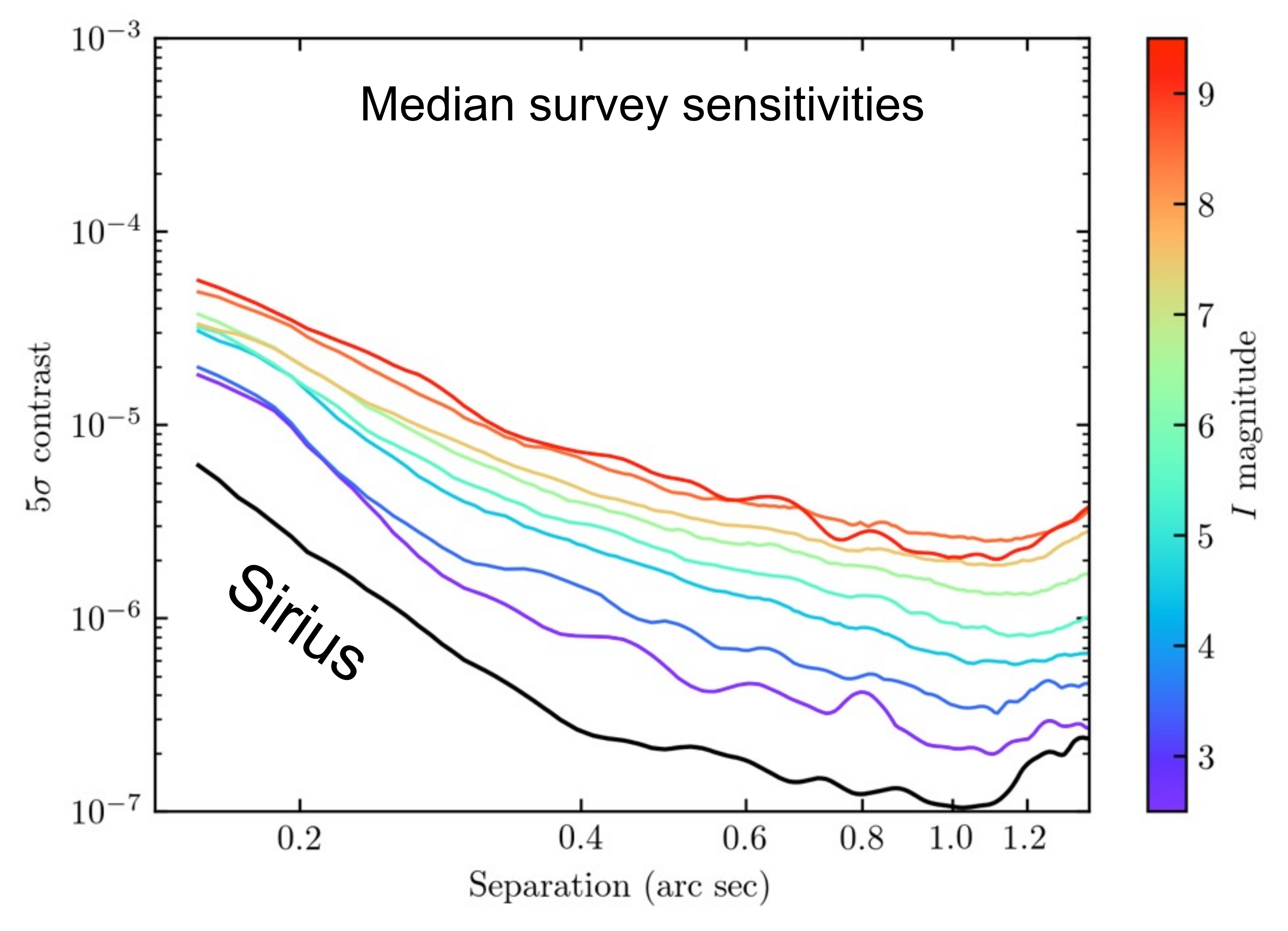
- **Asteroids & Solar System Objects**
  - limiting magnitude of V=14 ~1300 objects available for study



Perrin et. al, 2014

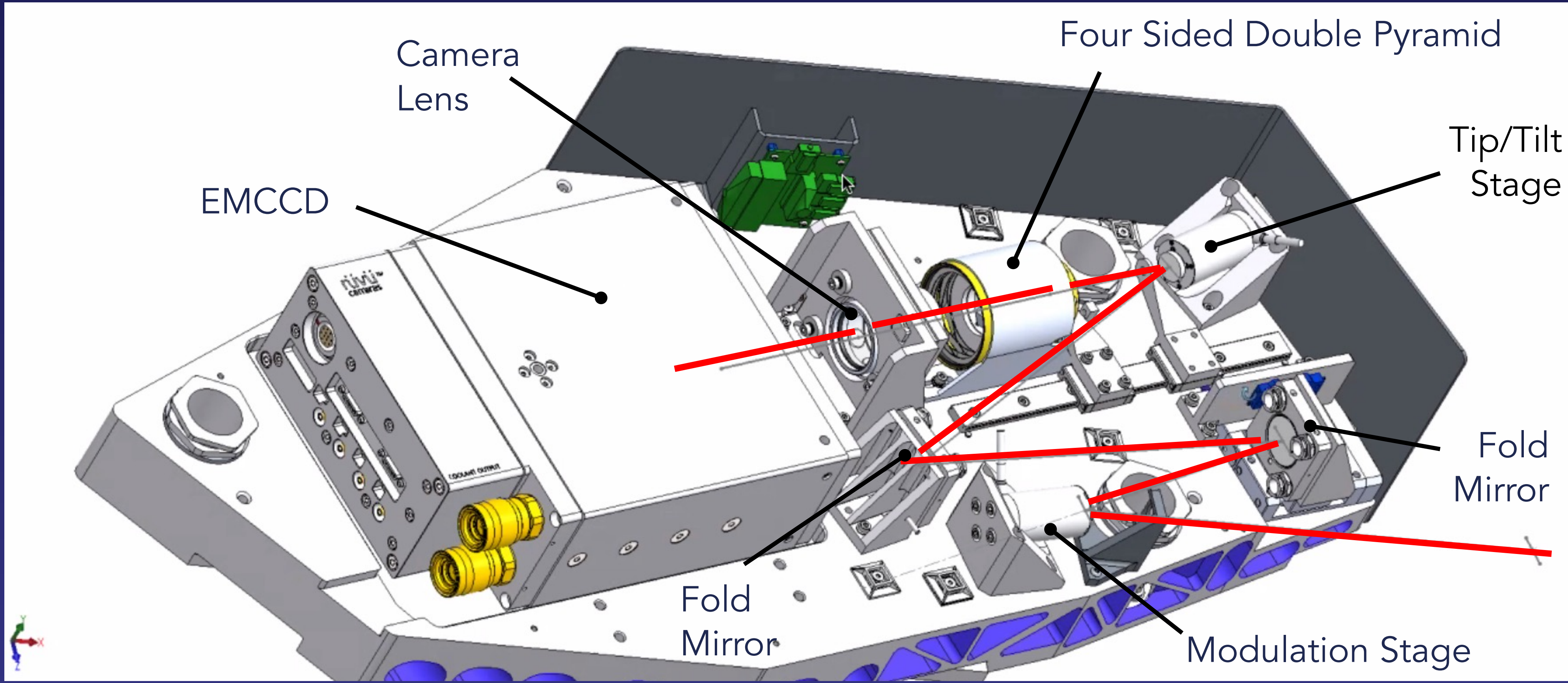

GPI Now
Gemini Telescope
GPI AO optics and DMs
Classical APLC coronagraph masks
IR tip/tilt camera
CAL relay optics
AO WFS
Lincoln Labs Fast CCD
IFS
existing optics, prisms, & pupil viewer
H2RG detector
Xeon GPI AO Realtime computer
Observatory Software
GPI Top-Level Software
GPI data pipeline


GPI 2.0
Gemini Telescope
GPI AO optics and DMs
Updated shaped-pupil coronagraph masks
Deeper contrasts & improved IWA
Fainter targets
CRED2 IR tip/tilt camera
CAL relay optics
AO pyramid WFS
E2V EMCCD
IFS
new prisms, optomech. upgrades, CRED2 IR pupil viewer
H2RG detector
Faster & deeper sensitivity to planets
Updated GPI AO Realtime computer
More sensitive, faster AO; enables fainter targets, & better performance on bright targets
Observatory Software
Enhanced Top-Level Software
Enhanced efficiency and robust operations
GPI data pipeline


Median survey sensitivities
Sirius
5σ contrast
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0.2
0.4
0.6
0.8
1.0
1.2
Separation (arc sec)
I magnitude
9
8
7
6
5
4
3

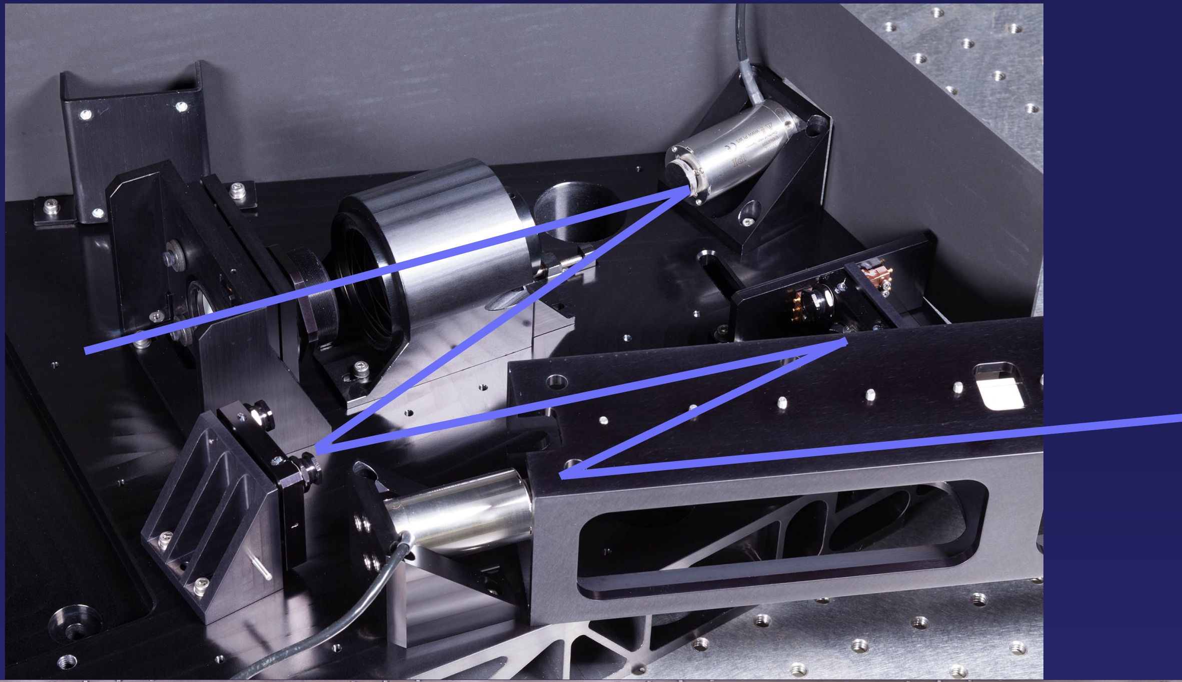
AO System - PYWFS

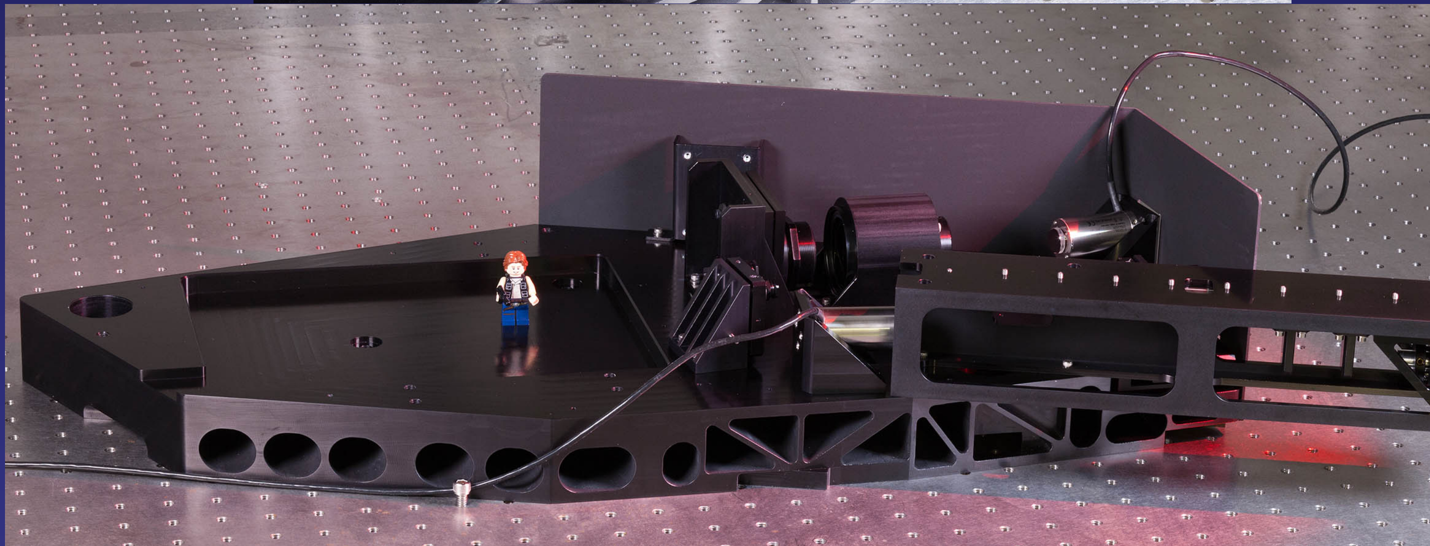
- Institutes: HAA (design), Stanford University (simulations) & UCSD (build)
- Replacing the current Shack-Hartmann WFS with a pyramid WFS
- Based on TMT NIFRAOS
- Narrow space envelope
- Operate at 2 kHz



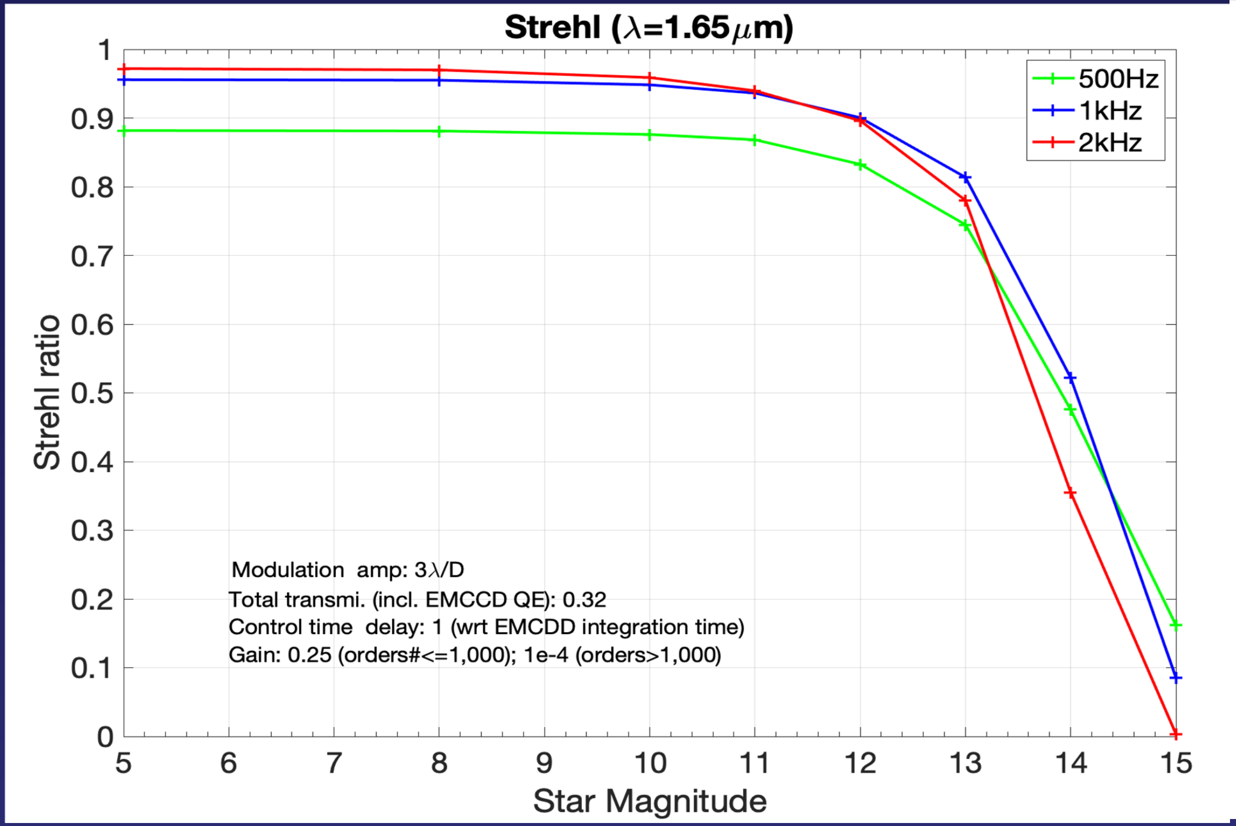
AO Status

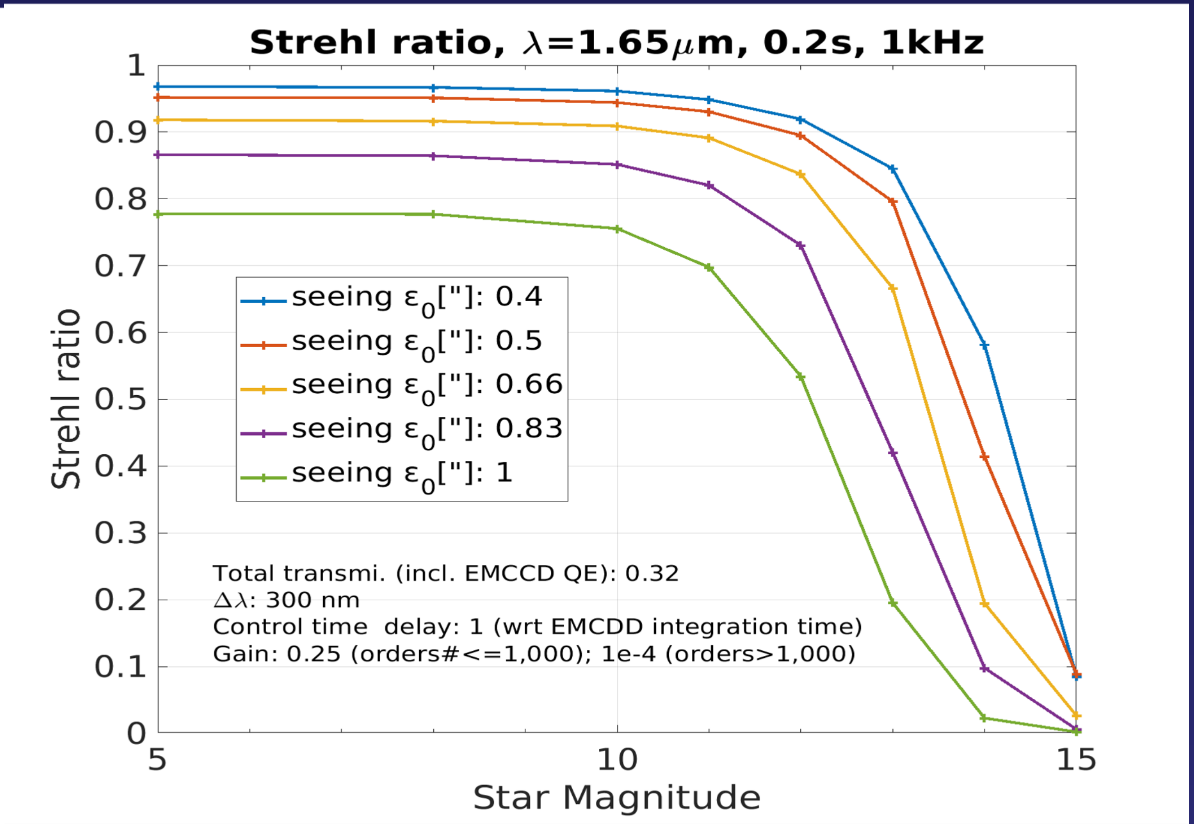
- PWFS:
  - Double four sided pyramid
  - Mirrors: Coastline Optics
  - Machined parts: Opto-Mécanique de Précision (OMP)
  - Stages: Physik Instrumente (PI)
- EMCCD:
  - Nüvü Cameras
  - Near-zero-noise, high QE
  - Fast readout (less lag-better performance)
  - Operate at 2 kHz
- Integration with GPI by early 2024





End-to-End AO Performance





- Assumed PWFS throughput: 0.32
- GPI2 will be able to operate on stars between I=0 and I=14

HEART

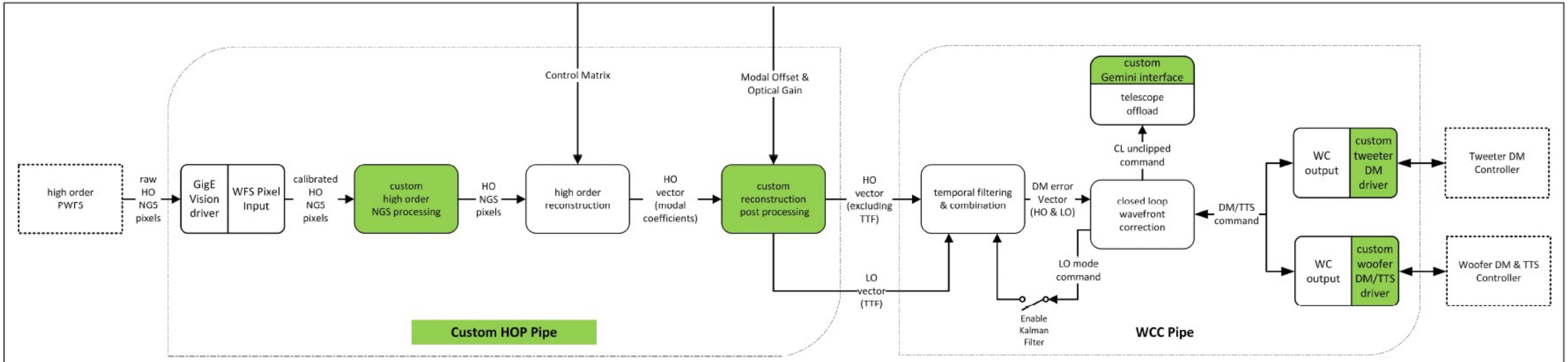
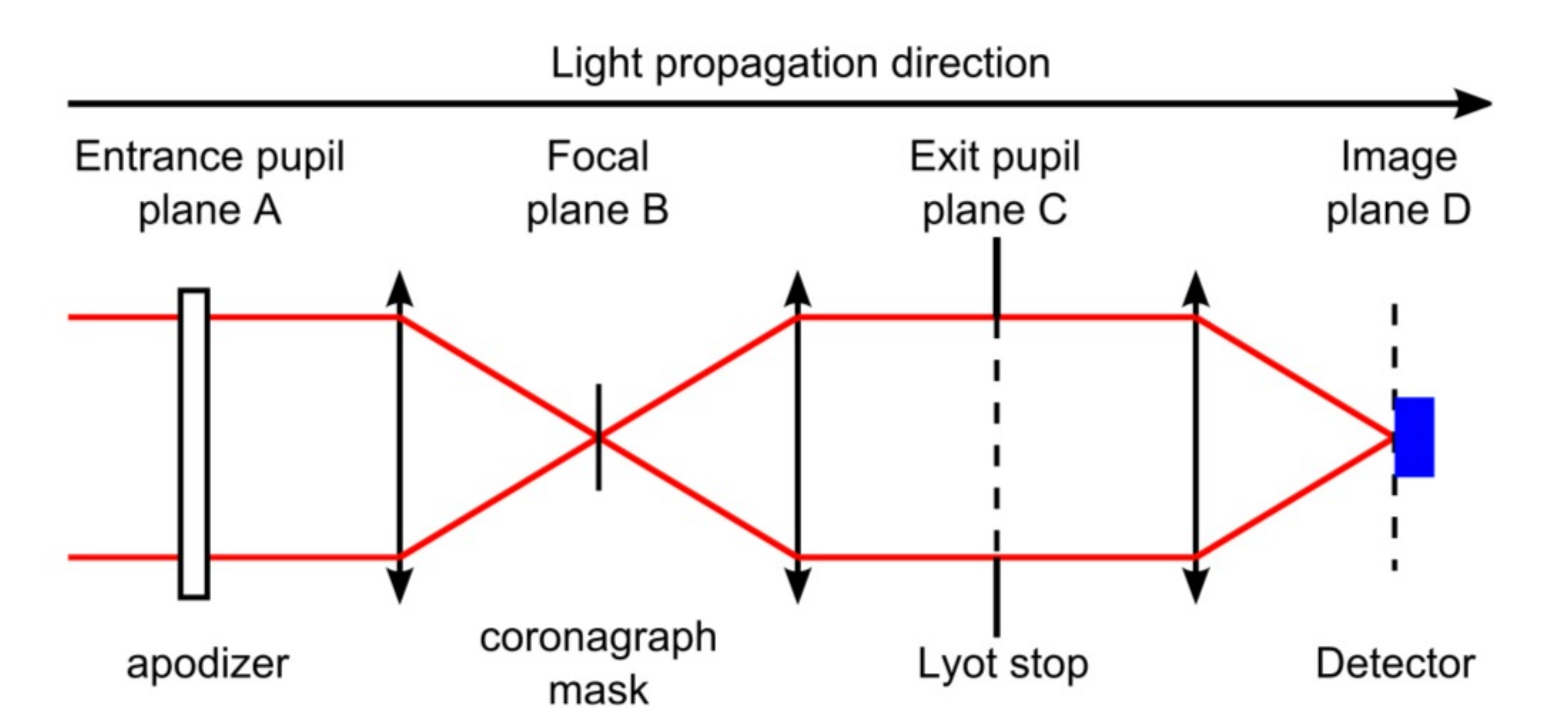


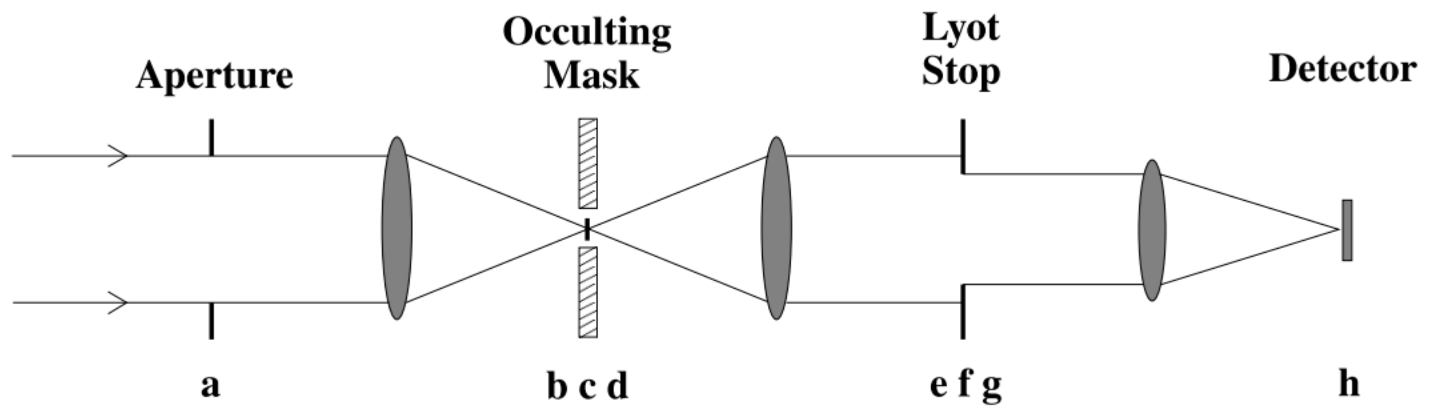
Figure 2. GPI2.0 RTC Block Diagram with HEART

New apodized pupil lyot coronagraphs based on design work done in the last 10 years for space-based platforms

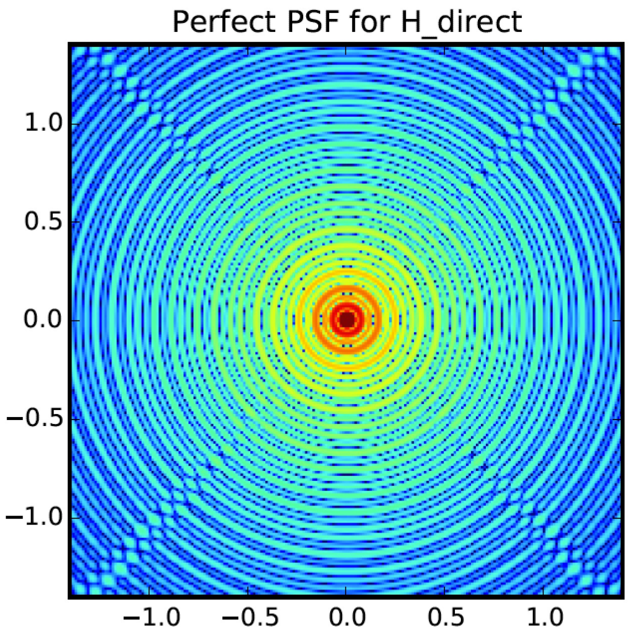


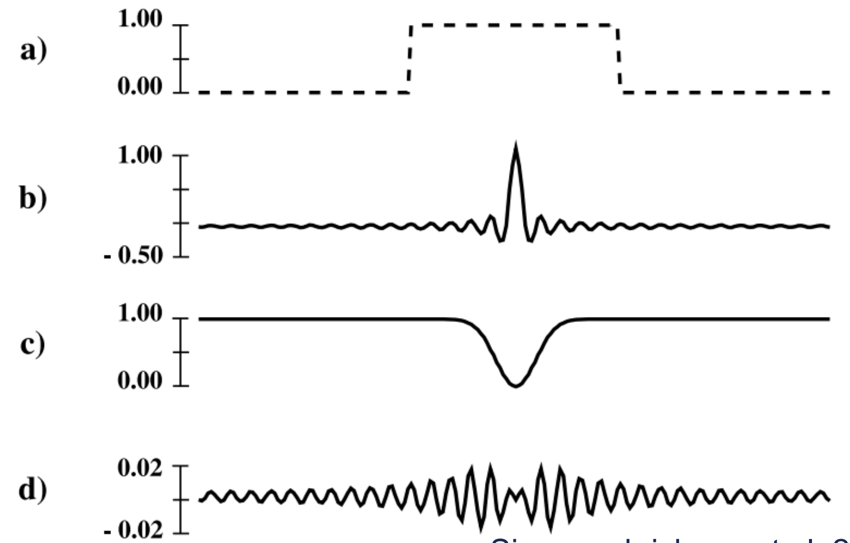
N'Diaye et al. 2015

Apodized-pupil Lyot coronagraph



Sivaramakrishnan et al. 2001

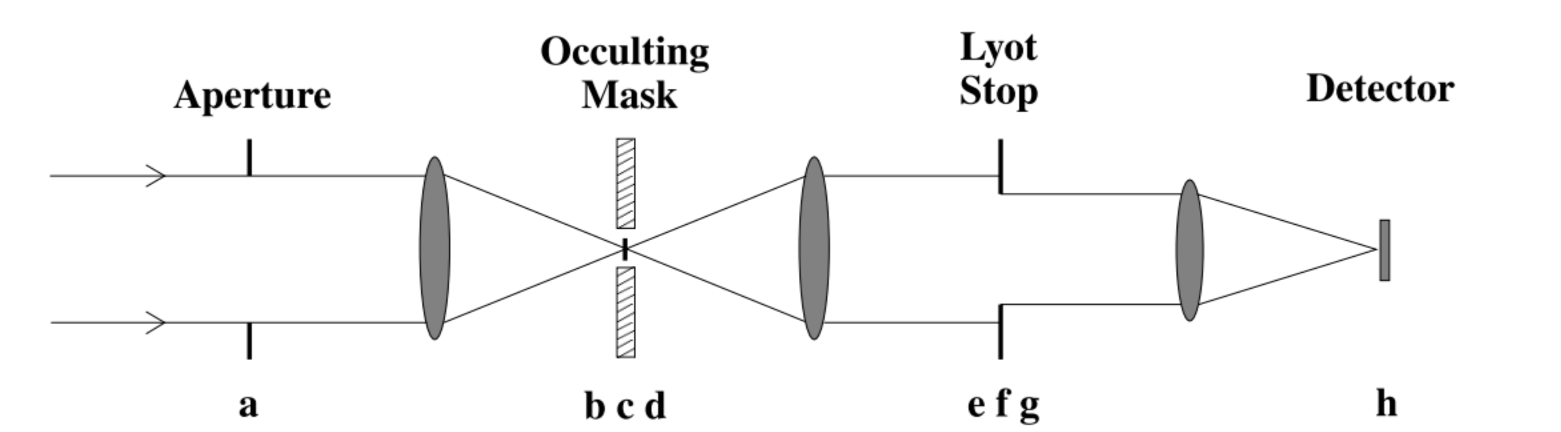




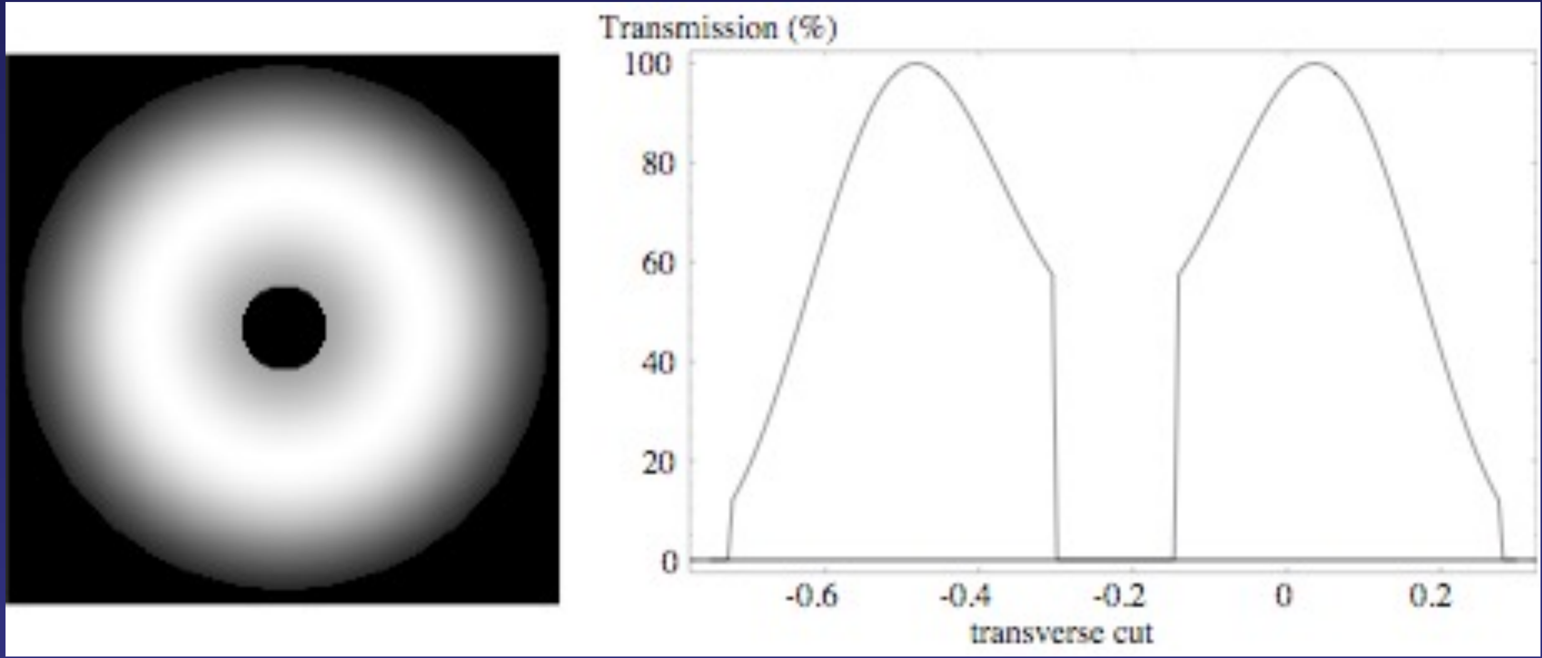
Sivaramakrishnan et al. 2001

Figure code credit M. Perrin

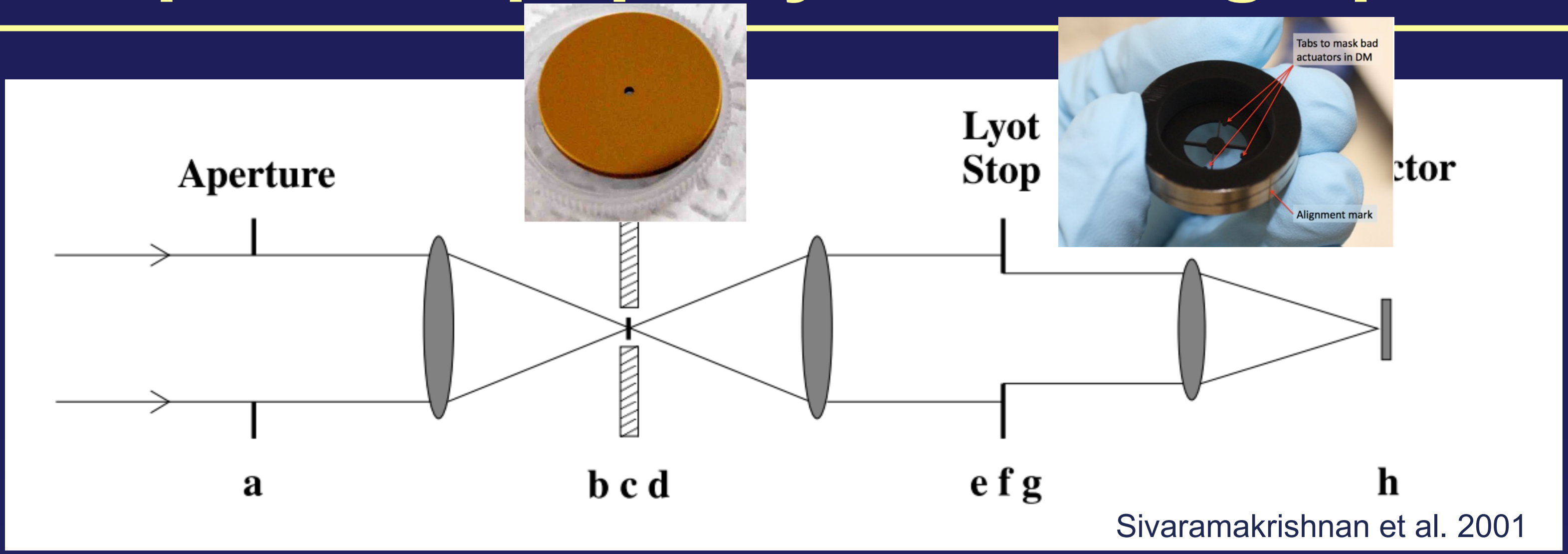
Apodized-pupil Lyot coronagraph



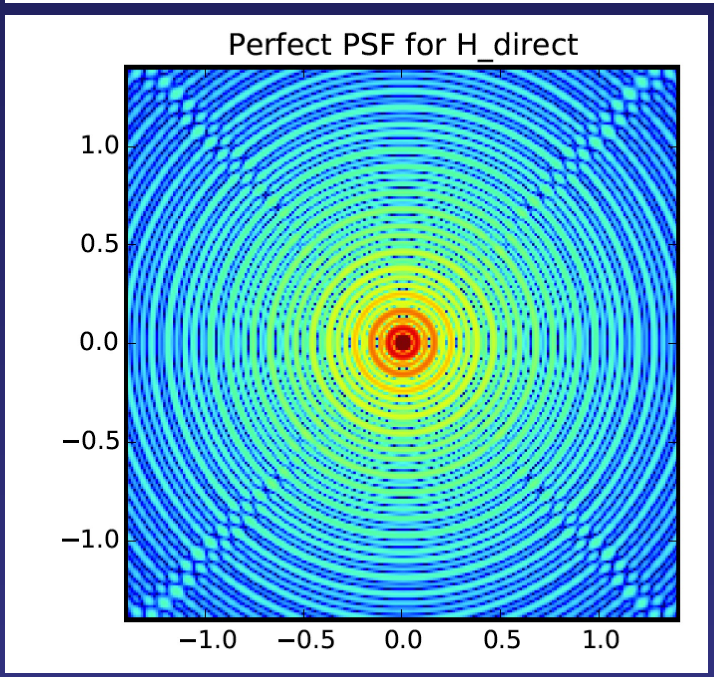
Sivaramakrishnan et al. 2001



Apodized-pupil Lyot coronagraph



Sivaramakrishnan et al. 2001



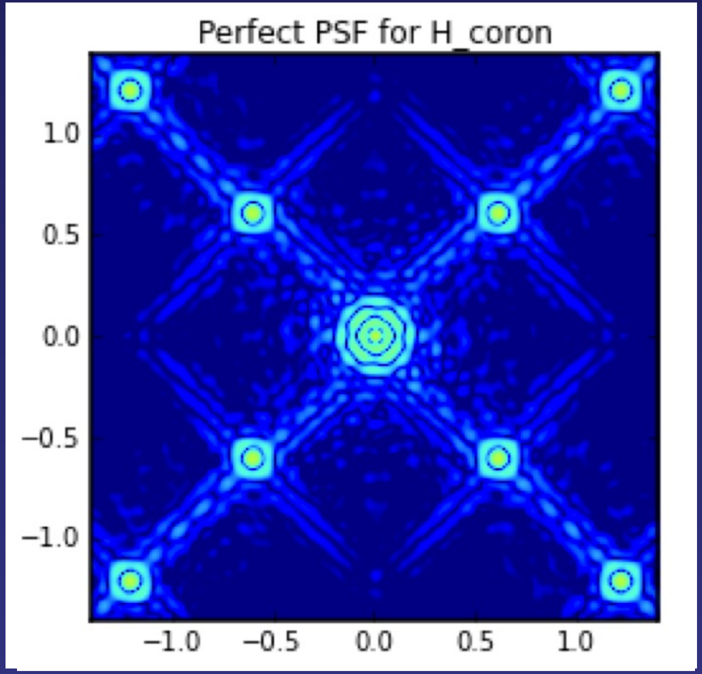
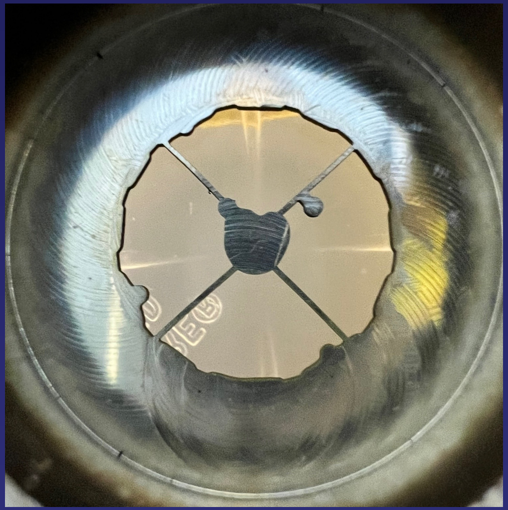
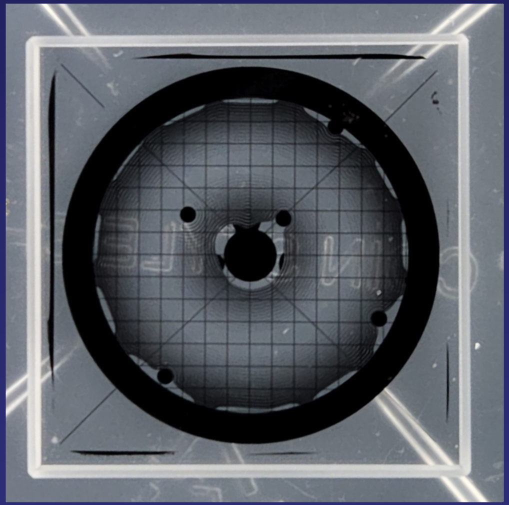


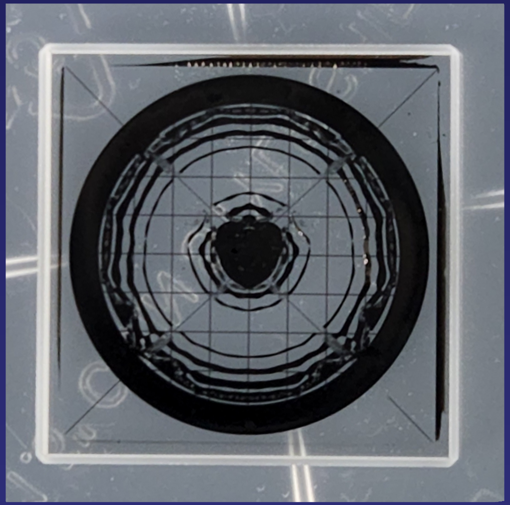
Figure code credit M. Perrin

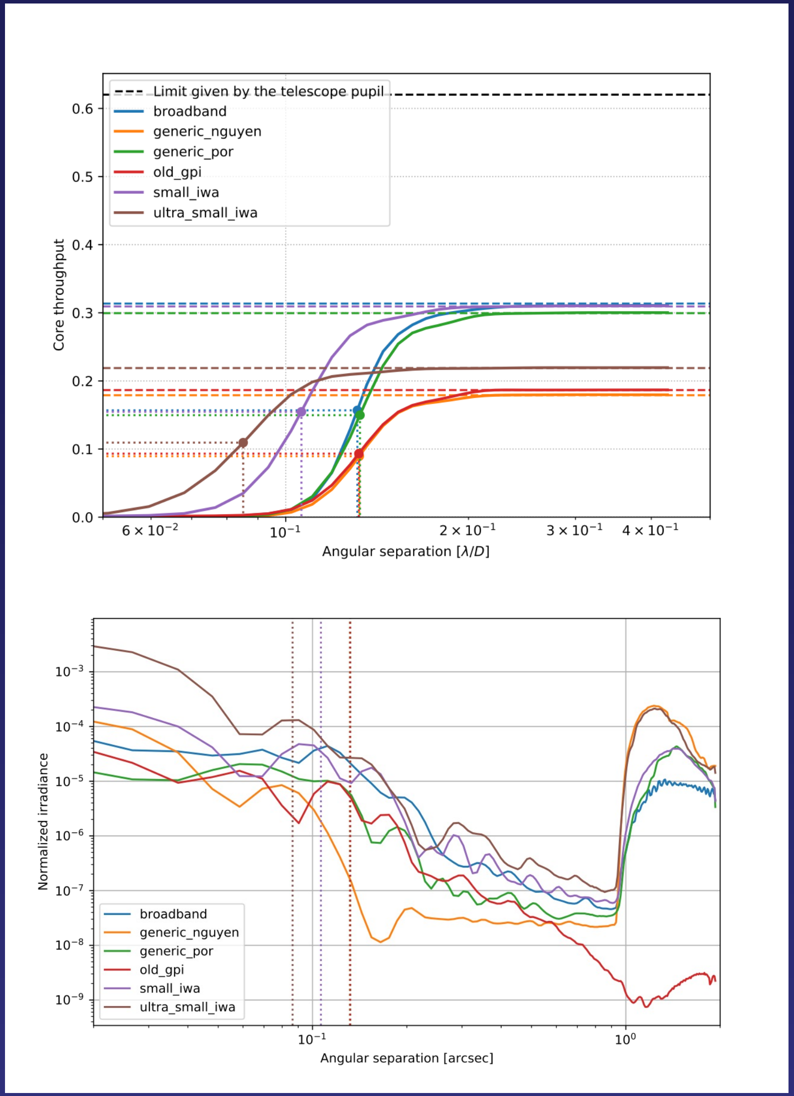
Coronagraph

- Retain focal plane masks but pair these with new pupil & Lyot plane masks
- Design based on work for space-based platforms from the last 10 years [e.g. N'Diaye et al. 2016]
- Reach deeper raw contrast at small separations
- Manufactured by λ Consulting



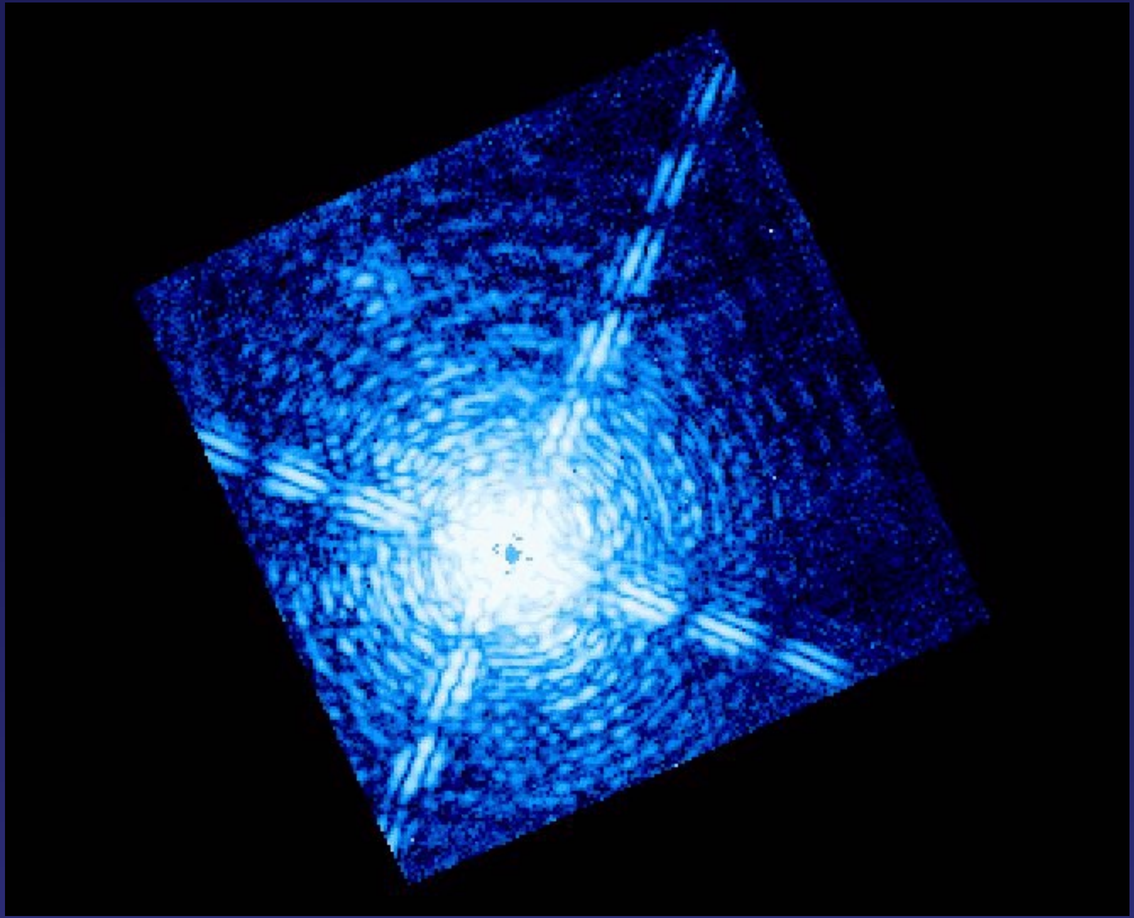






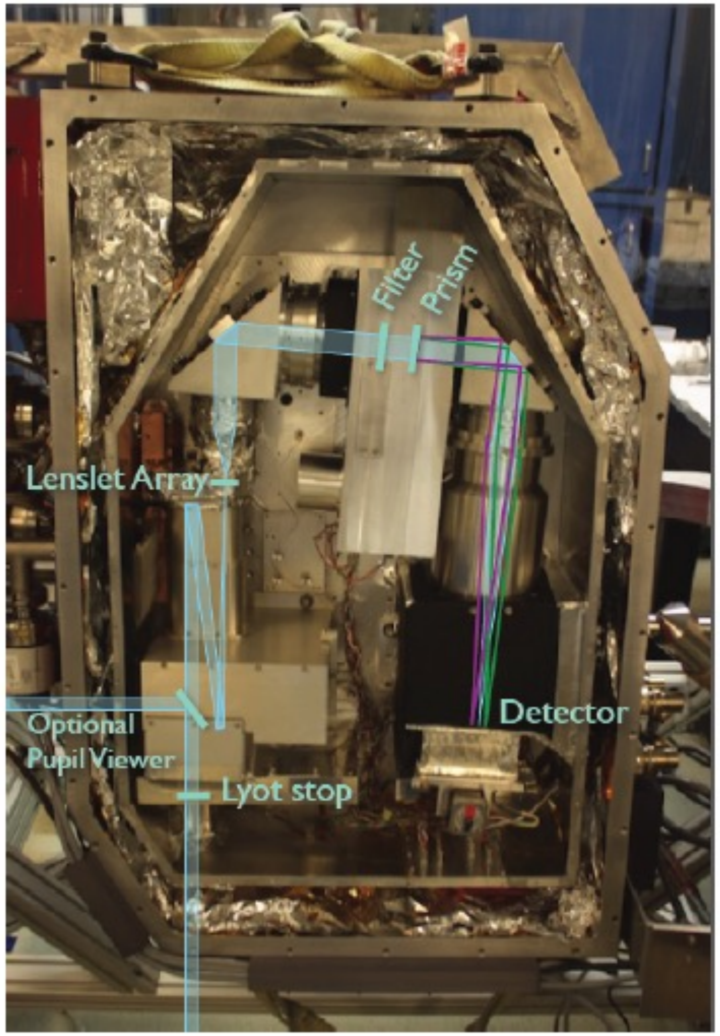
Integral Field Spectrograph

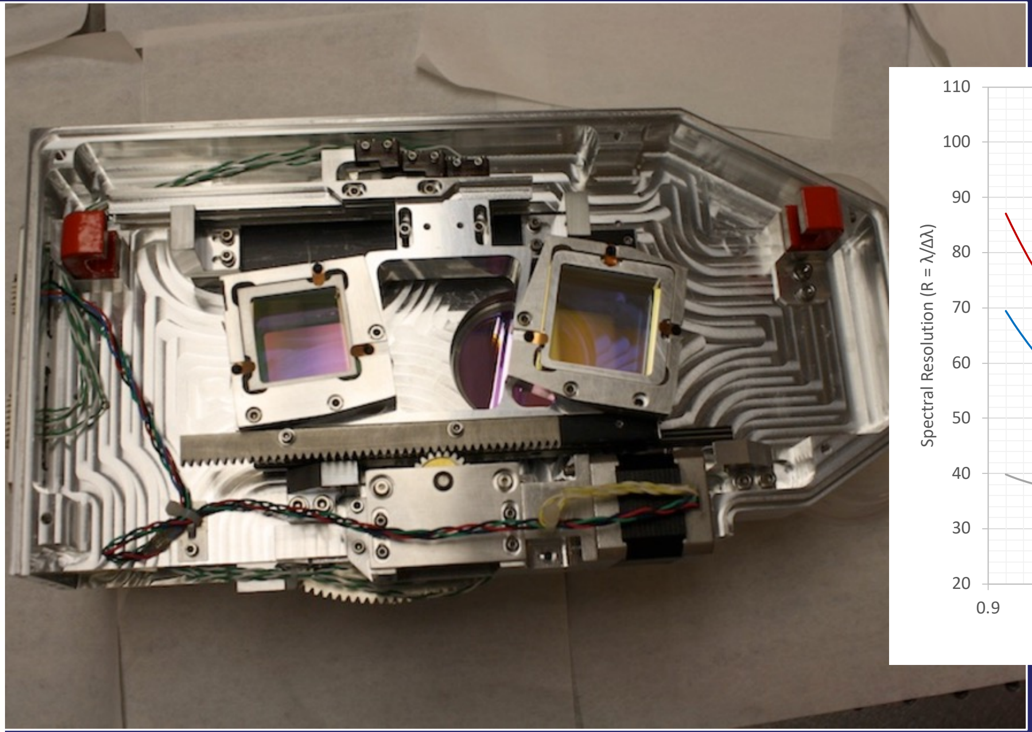
- After the advanced AO system, coronagraph and interferometer, a dominant background source arises from speckles
  - many from the instruments own optics.
- Speckles are a diffractive effect with predictable wavelength behavior.

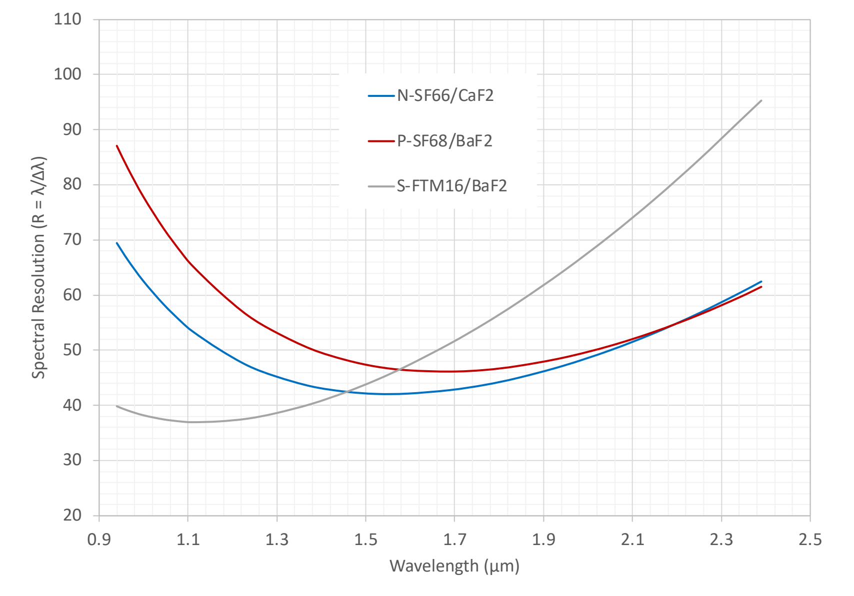


Stepping though wavelength channels

Adding Low-Res mode for Increased Sensitivity

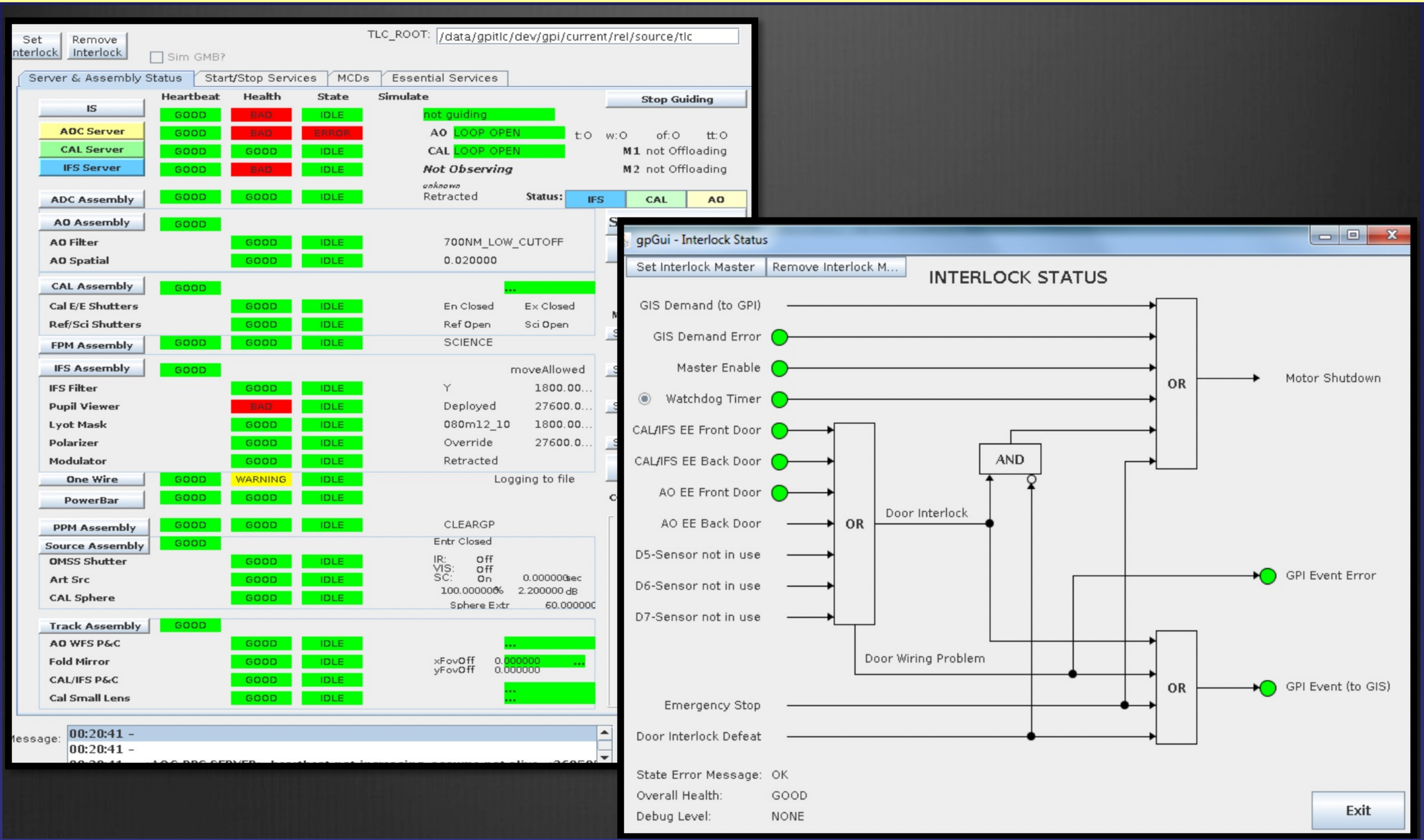






Band	Cut-on/-off (m)	R= $\lambda/\delta\lambda$
Y	0.95-1.07	62
J	1.12-1.35	48
H	1.5-1.8	43
K	2-2.4	55
Broadband	0.97-2.4	11.8

GPI Operations



Operations / Software Improvements

GPI Seqexec Checklist - Coronagraphic Spectral Mode

Target: ______________________ Acq Seq ID: _________ Sci Seq ID: _________

	Step	With	Task
☐	0		GPIES Only: check previous target has been flagged correctly in the database
☐	1	SOS	Ask SOS to slew to ID of **Science** seq., and tell you when done. Continue steps 2-5 during slew.
☐	2	Seqexec	**Load Sequence from OCS** and select **Acquisition** sequence ID. (#______)
☐	3	Seqexec	Expand Step 2 in the sequence (Acq), then **middle click on Observe** to add a pause. (hand)
☐	4	Seqexec	Press **Configure from current TCS setup**.
☐	5	Seqexec	In System Configuration section, press **ALL** button.
☐	6		**Wait** for telescope in position from SOS ***and*** config complete ("paused after configure" at top).
☐	7	Seqexec	Press **green RUN button** to run arc.
☐	8		**Wait** for arc to complete. Watch countdown on GPI ISD. Align & Cal will start automatically.
☐	9	GPI Cal Tool	**Wait** for Align & Cal to perform **Artificial Source Deploy** (check box for that step turns green)
☐	10	SOS	Ask SOS to **center star on acquisition camera**
☐	11	GPI Cal Tool	**Wait** for Align & Cal to complete. If it fails, go to Troubleshooting on Gemini internal GPI page.
☐	12	Seqexec	**Load Sequence from OCS** and select **Science** sequence ID. (#______)
☐	13	Seqexec	**Middle click on step 2** observation to add a pause (hand).
☐	14	Seqexec	In System Configuration section, press **INST** button.
☐	15		**Wait** for configuration to complete. ("paused after configure" at top)
☐	16	GPI ISD	**With loops open,** click **Clear Health** in GPI ISD (or GPI Engineering Tool)
☐	17	GPI Cal Tool	Using GPI Cal Tool, **apply offset in +TIP direction.** See table:
☐	18	SOS	**Ask** SOS to acquire and close the loops. **Wait** for loops to be closed.
☐	19	Seqexec	Press **Configure from current TCS setup**
☐	20	GPI Cal Tool	**Wait for LOWFS to converge to T/T errors < 6 mas (< 8 mas if I>7).** This can take a few mins. *Note the GPI Cal Tool display lags behind by several seconds. Observers may wish to look at the Cal Show tool on vnc:17 if they're comfortable in using that display.*
☐	21	cpogpi IDL	Optional but recommended: close down spatial filter to 3.5: `TLC_COMMAND_SF, 3.5`
☐	22	Seqexec	Press **green RUN button** to start science sequence
☐	23		Examine first image and coronagraph alignment in gpitv; if needed apply additional offsets.
☐	24	Seqexec	Press **CONTINUE** button to continue science sequence (or Run also works).
☐	25		**Monitor** sequence and data until the hour is up. *Apply additional offsets if needed (preferentially between rather than during exposures). Adjust spatial filter if appropriate. Add a pause if you desire to run less than the entire sequence. Be on the lookout for AO Loop loss or Seqexec errors. Monitor weather conditions (seeing, wind level, wind direction, clouds).*
☐	26	cpogpi IDL	Every ~10 minutes, save a set of AO telemetry and RMS WFE: `IDL> ult_telem` and `IDL> ult_ao_status`
☐	27	SOS	When complete, tell SOS to open loops. Move on to the next target.

Band	+TIP offset
Y	
J	
H	+7
K1	+15
K2	+20

9	GPI Cal Tool	**Wait** for Align & Cal to perform **Artificial Source Deploy** (check box for that step turns green)
10	SOS	Ask SOS to **center star on acquisition camera**

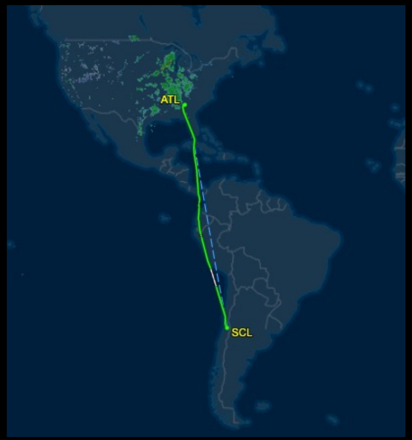
- Reduce the number of steps required to operate instrument
- GPI's high-level control library – translate to Python
- Improve Queue operations
- Improve time-domain science

Current Status

Preparing shipping Gemini South →

Going down the mountain →

In transit →



Arriving at Notre Dame →

Unloaded

↓

Safe and sound in the lab

- GPI Arrived at Notre Dame in June 2022 (24 month ship delay)
- Pre-shipping tests last year
- Procurement of major components done
- Ship to Gemini North 2024

GPI 2.0 Goals & Conclusion

- Upgrades to the Gemini Planet Imager (GPI) will enable it to study fainter, closer exoplanet populations
- New adaptive optics system will be capable of locking onto stars four magnitudes fainter
- Upgrades will allow us to find lower-mass planets closer to their parent star than the current system.
- It will be able to obtain full spectra across the entire near-infrared (near-IR) simultaneously
- Goal to be at Gemini North in 2024, on sky early 2025

Funding Agencies: NSF, HEISING-SIMONS FOUNDATION

End