PRINCETON UNIVERSITY

The CHARIS High-Contrast Imaging Spectrograph

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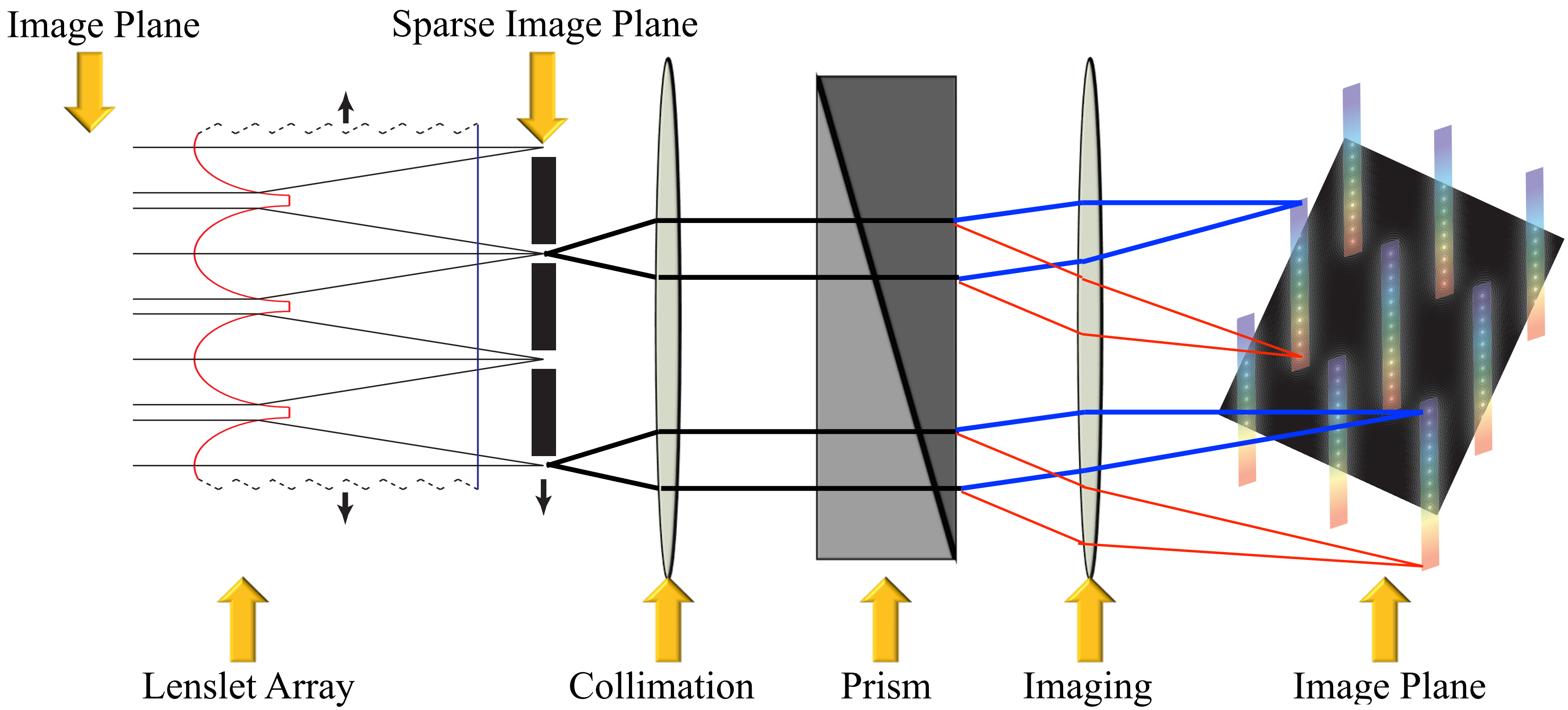
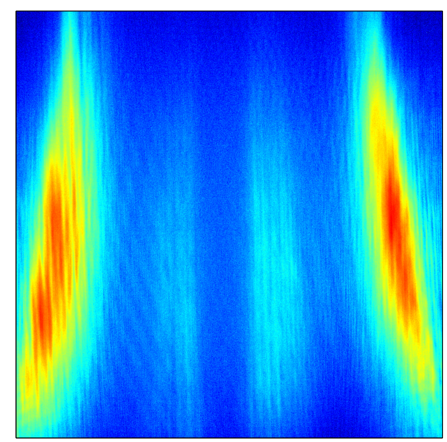
Integral Field Spectroscopy

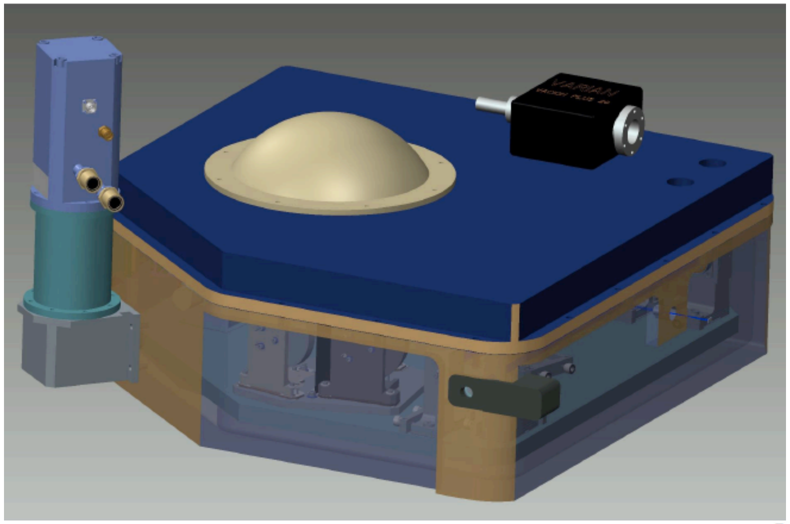


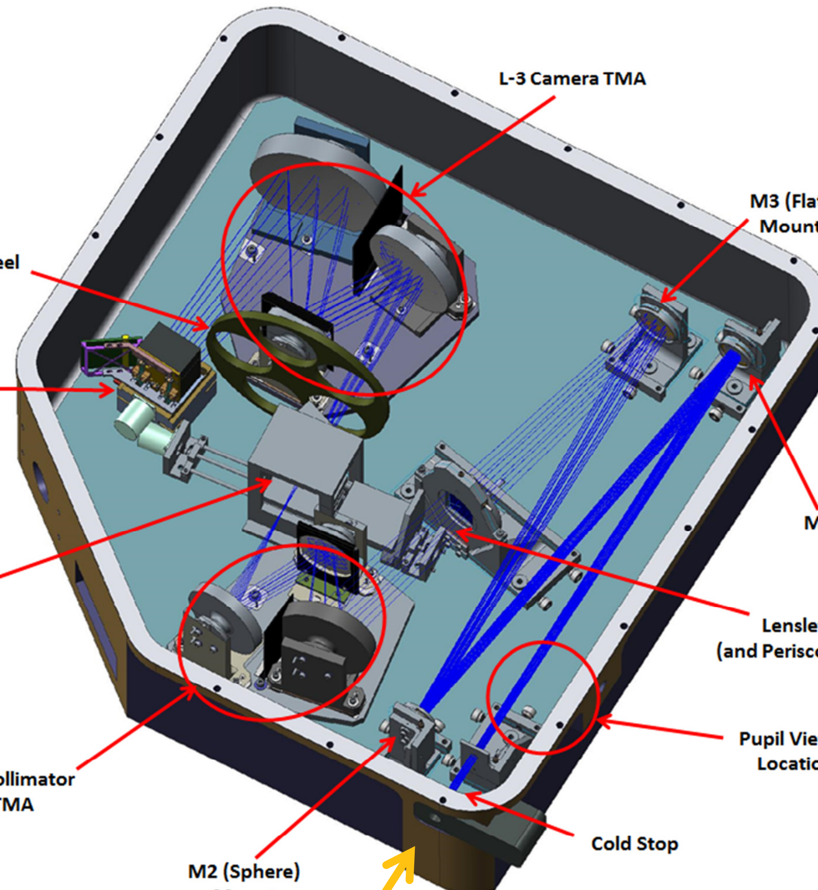
BIFS in HCIL, F/3 400–700nm



- Lenslet array creates a sparse image plane
- Prism disperses each each lenslet focus (PSFlet)
- Detector sees an array of separated spectra (spectralet)

The CHARIS Design





- Reflective Optics
- Lenslet-based design
- Pinhole Array at Lenslet
  Woodgate et al. 2006
  Bonfield et al. 2008
- F/420 Primary Image
- F/8 Lenslets and Collimator
- Teledyne H2RG detector

SCExAO Status:

- SCExAO was rebuilt in mid-2013:
  - New reflective relay optics (OAPs) for achromaticity
  - 2000 element deformable mirror running
  - Two interferometric imagers installed and tested on the visible bench (VAMPIRES and FIRST).
  - Now low order wavefront sensor installed.
  - Vibration dampers installed.

- Speckle nulling: upgraded to be robust to tip/tilt residuals. More powerful than ever.

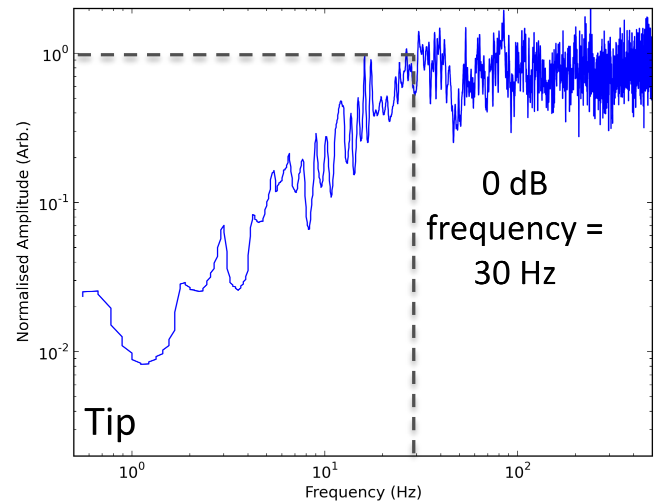
- Pyramid wavefront sensor is major ongoing effort:
  - Closed loop operation on 5 Zernike modes at 1.7 kHz in the laboratory!
  - Closed loop operation on 900 Fourier modes at 300 Hz in the laboratory!
  - Algorithims and speed of cameras and DM have been significantly upgraded. Will have GPU computing power soon.

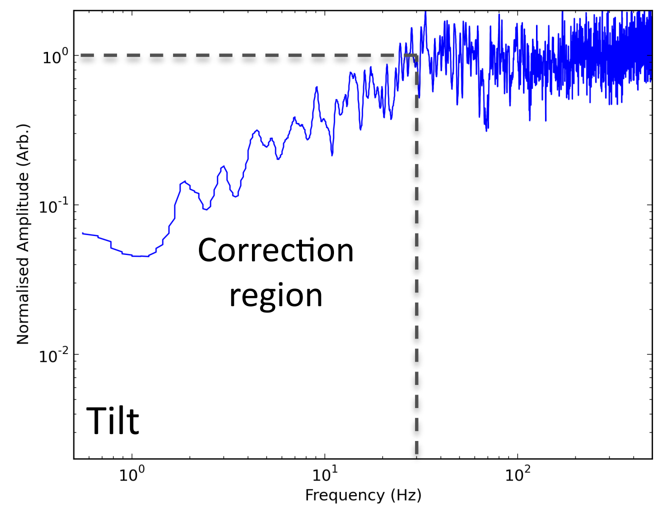
SCExAO ready for prime time:

- SCExAO will be offered in S14B to all users with phase I capabilities:
- Phase I capabilities:
  - Access to a host of coronagraphs: PIAA, vector vortex, 8OPM, 4 QPM
  - Low order tip/tilt correction.
  - Speckle nulling: Advanced methods to cancel quasi-static speckles

Pyramid Wavefront Sensor:

Closed loop laboratory performance on 5 Zernike's at 1.7 kHz.



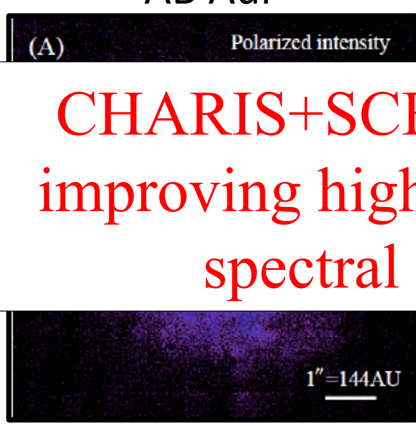


PLEASE APPLY IN S14B!

SEEDS Science Goals

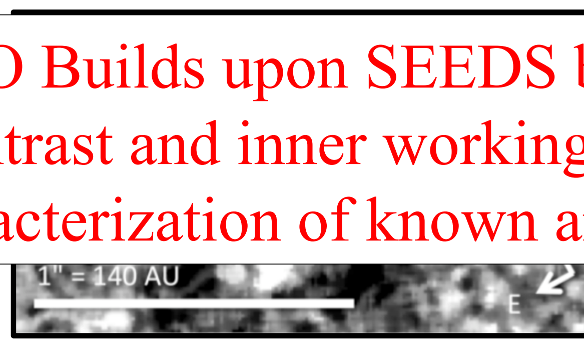
- Direct imaging census of giant planets in the outer systems of nearby solar-type stars (projected separations roughly 4-100 AU)
- Imaging of protoplanetary disks to explore structure and study in-situ giant planet formation
- Structure of debris disks
- Direct link between planets and planet formation

AB Aur



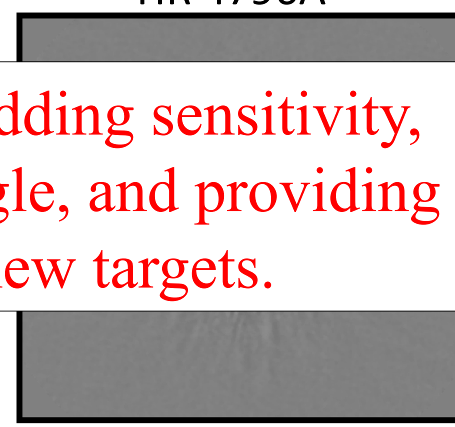
Hashimoto et al. 2011

LkCa 15



Thalmann et al. 2010

HR 4796A



Thalmann et al. 2011

CHARIS+SCExAO Builds upon SEEDS by adding sensitivity, improving high-contrast and inner working angle, and providing spectral characterization of known and new targets.

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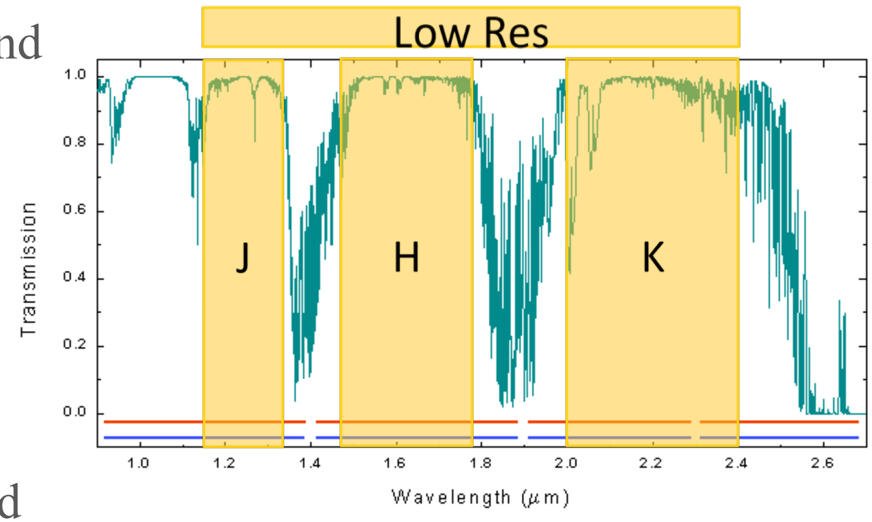
CHARIS Science

- CHARIS science goals
  - Discover new exoplanets
  - Characterize exoplanetary atmospheres
  - Astrometric orbits, complements IRD
  - Discover brown dwarf companions around stars
  - Study the inner regions of circumstellar disks

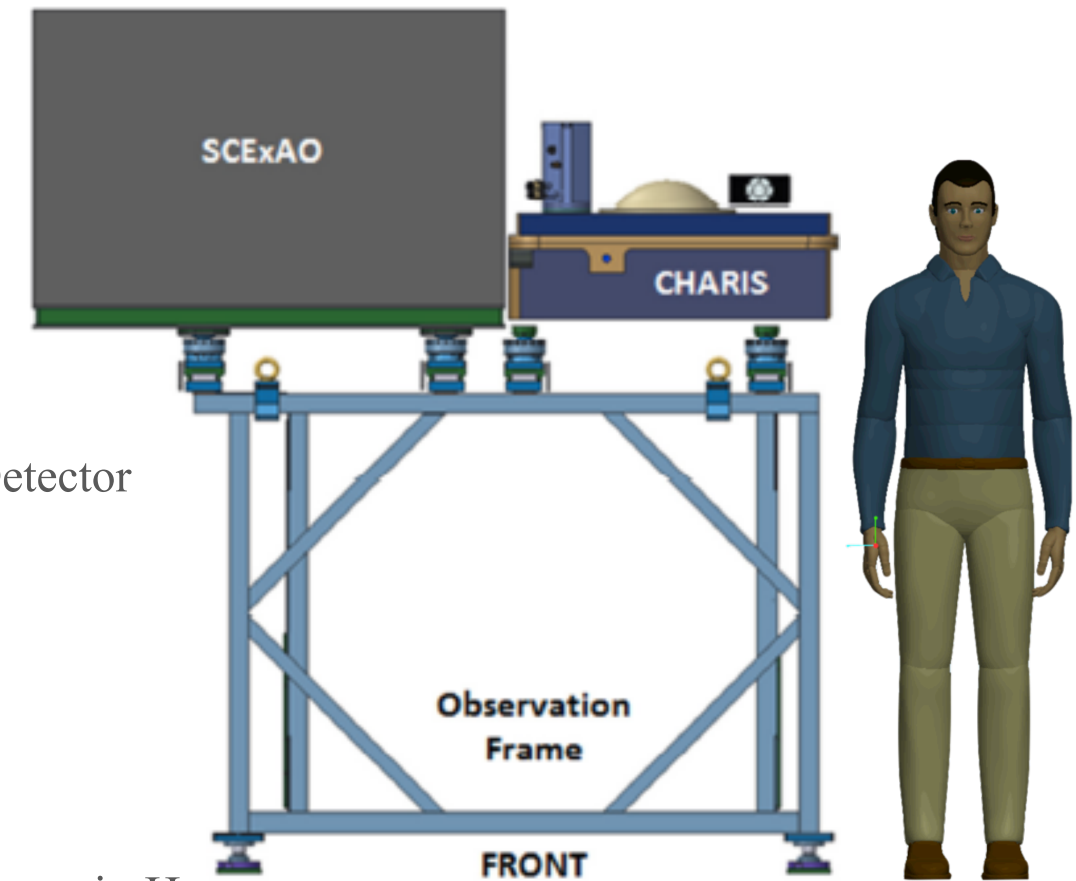


- CHARIS instrument requirements
  - High Contrast
  - High sensitivity
  - Spectral Characterization across J, H, and K (low and high resolution)
  - Diffraction Limited
  - Moderate Field of View

CHARIS will take advantage of the high-contrast system on Subaru AO188+SCExAO to achieve small IWA and contrasts of 10^{-5} to 10^{-6}.

CHARIS + SCExAO

- IWA = 2 λ/D = 80 mas
- Contrast ~10^{-5} to 10^{-6}
- 2.07”x2.07” FOV
- Nyquist sampled at 1.15 μm
- R~19, J+H+K Band
  - 65-70% Throughput
  - 15% (10% K) Atmosphere ➔ Detector
- R~70-90: J,H, and K Bands
  - 55-60% Throughput
  - ~15% Atmosphere ➔ Detector
- Crosstalk Mitigation
- 1hr point source sensitivity of 22 mag in H
- 3 mas astrometric precision
- 0.06 mag photometric precision



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Detection: Sensitivity to Exoplanets

Mode	1 hr Point Source Sensitivity
Low Resolution	28
J	27
H	26
K	24

- CHARIS 1 hour point source sensitivities are unlikely to limit the search sensitivity, even for nearby star forming regions

Target	Distance (pc)	Age (Myr)	Sensitivity (10^5)		Sensitivity (10^6)		Projected Separations Probed (AU)
Ursa Majoris	20	500	17.3	< 30	19.8	< 20	1.2-20
Beta Pic	30	12	18.2	< 5	20.7	< 3	1.8-30
Columba	40	30	18.8	< 10	21.3	< 7	2.4-40
AB Dor	40	100	18.8	< 12	21.3	< 7	2.4-40
TW Hydrae	45	8	19.1	< 3	21.6	< 1	2.7-45
Rho Oph	120	3	21.2	< 2	23.7	< 1	7.2-120
Taurus-Aurigae	145	3	21.6	< 2	24.1	< 1	8.7-145

Assumes Sun-like star and Baraffe et al. 2003 DUSTY models

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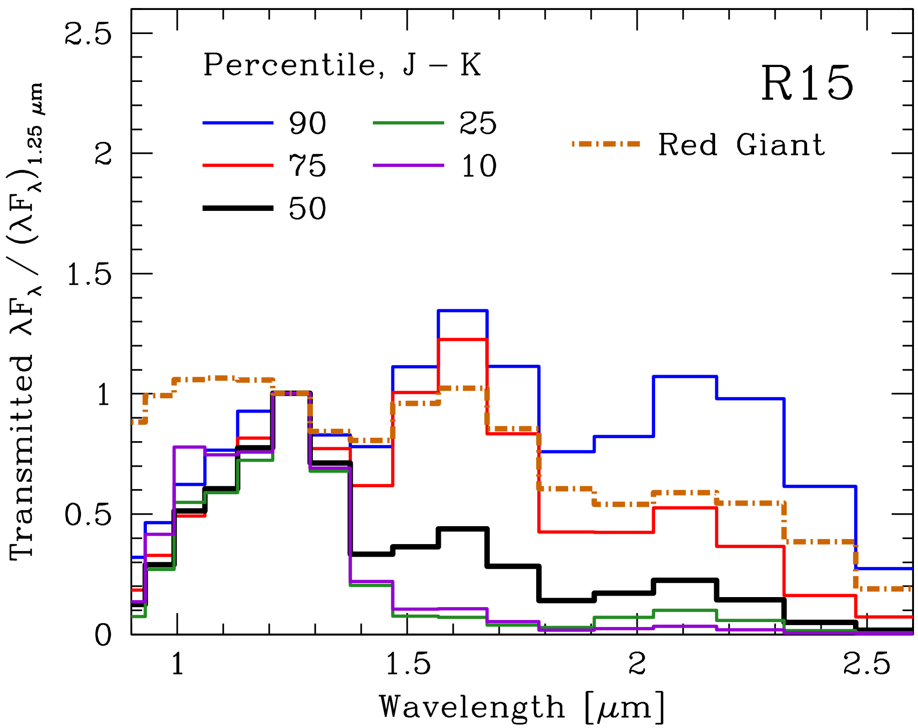
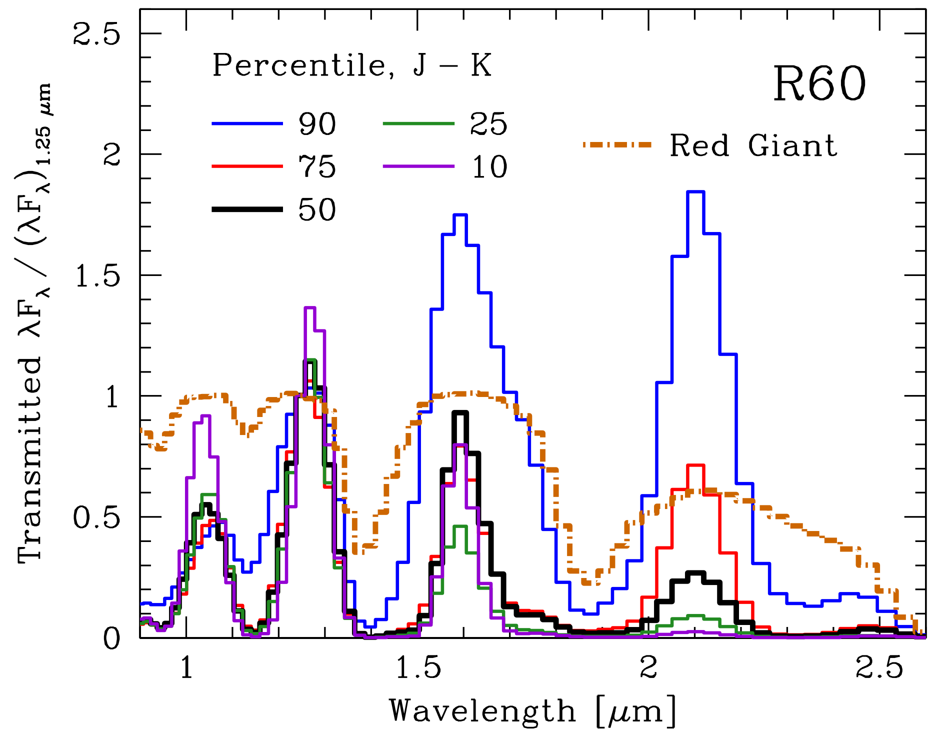
Simulated Spiegel & Burrows Spectra

Sample at CHARIS Low Resolution

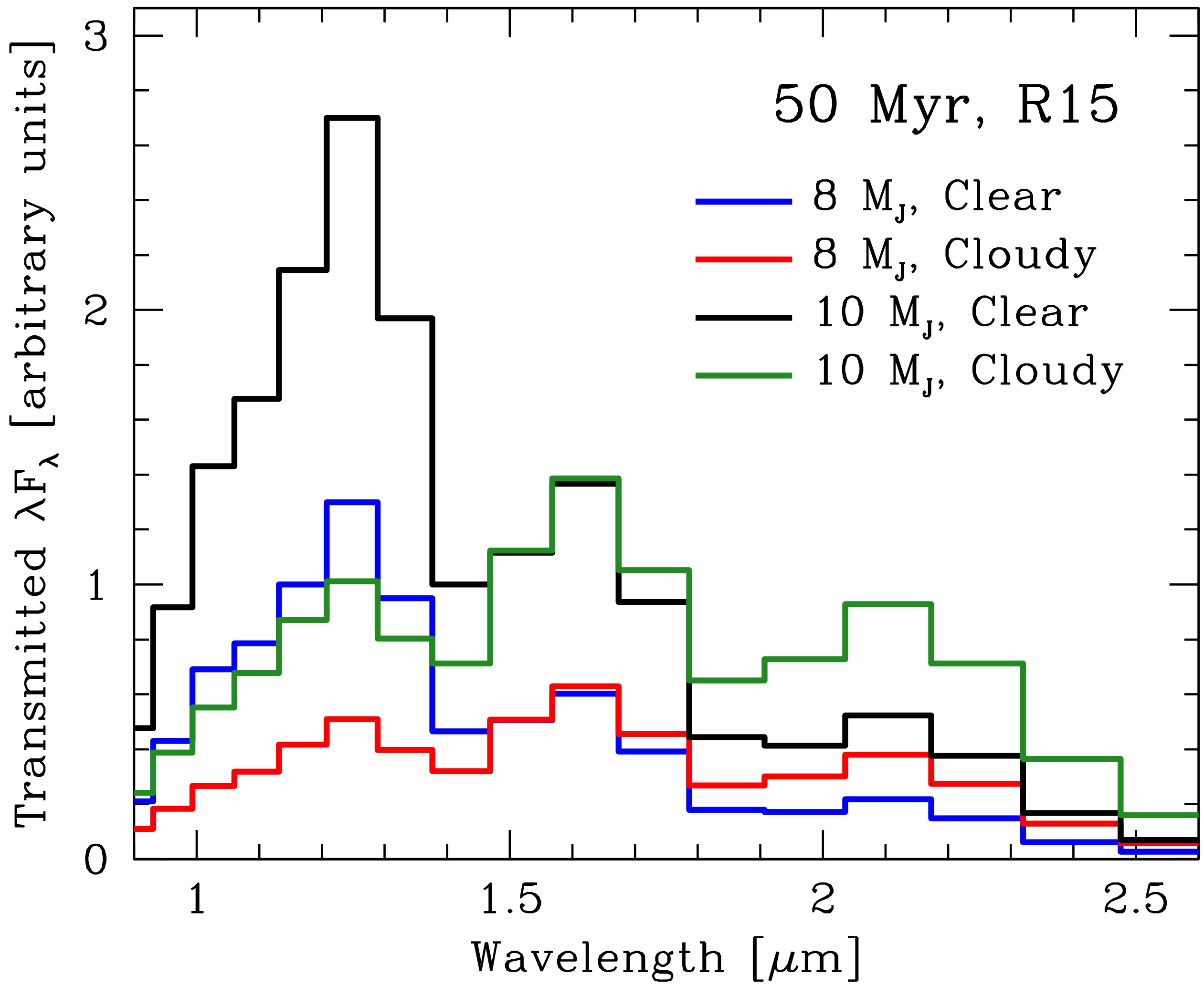


Sample at CHARIS High Resolution



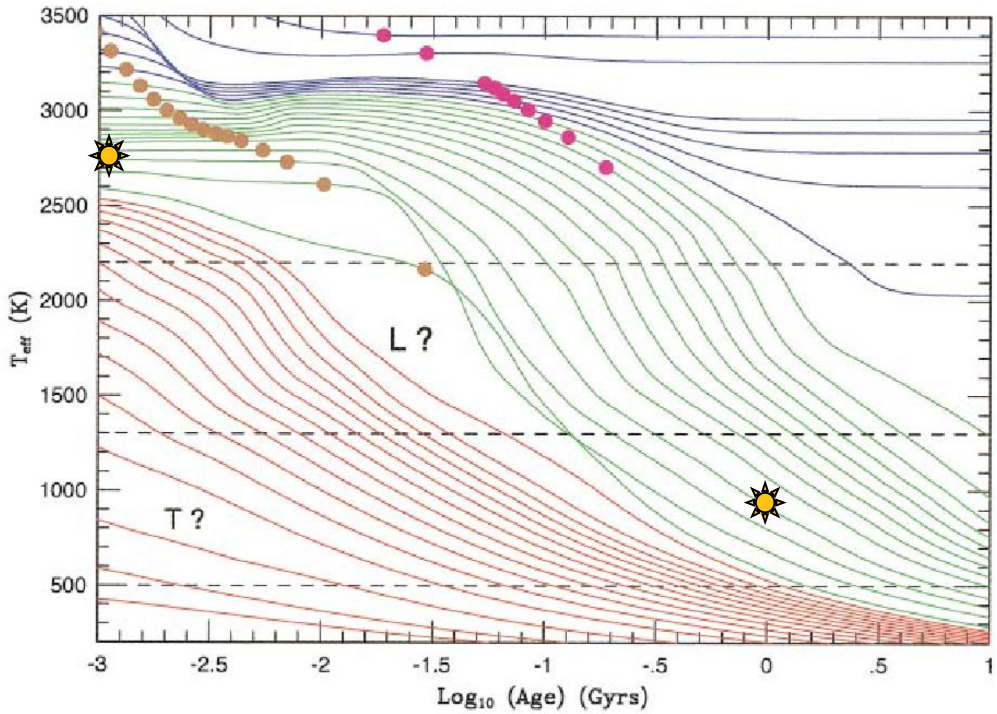
Giant Planet Characterization, differentiate population models.

Known Age Provides Unique Model



Substellar Evolution

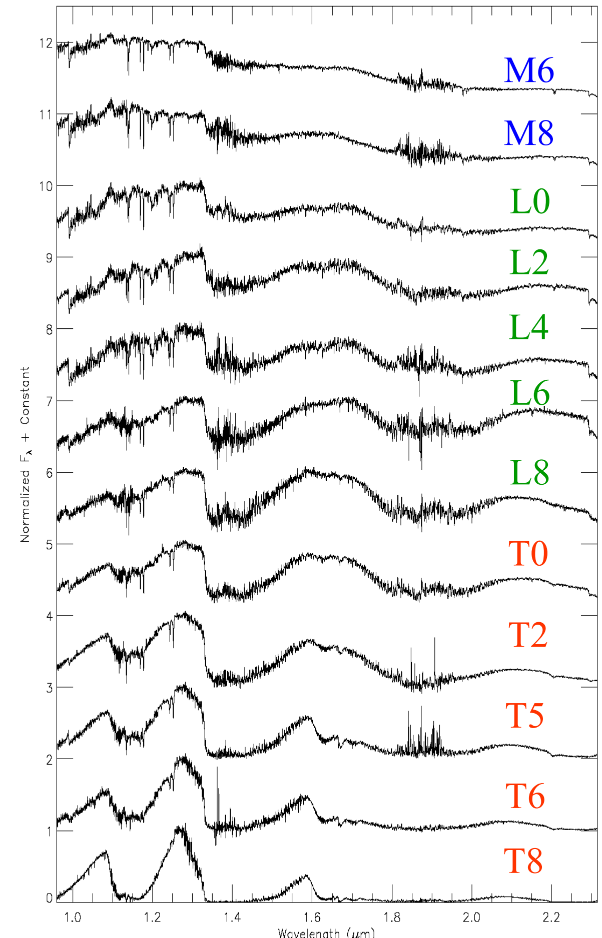
Theoretical T_{eff} vs. Log (Age)



Burrows et al. 2001

20 M_{Jup} object
@ 1 Myr old – SpT ~ M8, T ~ 2700K
@ 1 Gyr old – SpT > T6, T ~ 1000K

Keck NIRSPEC BDSS data



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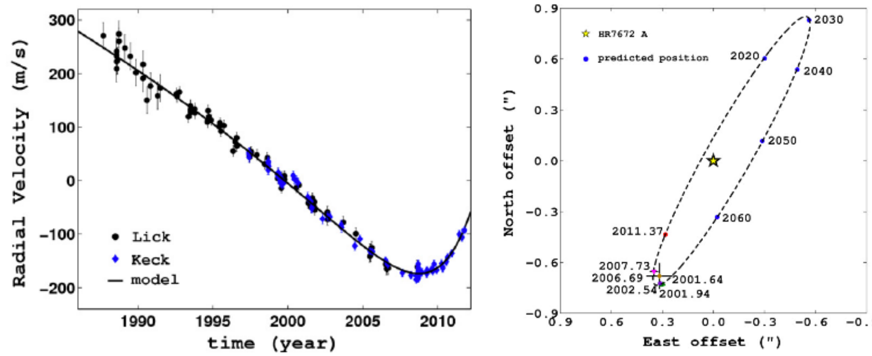
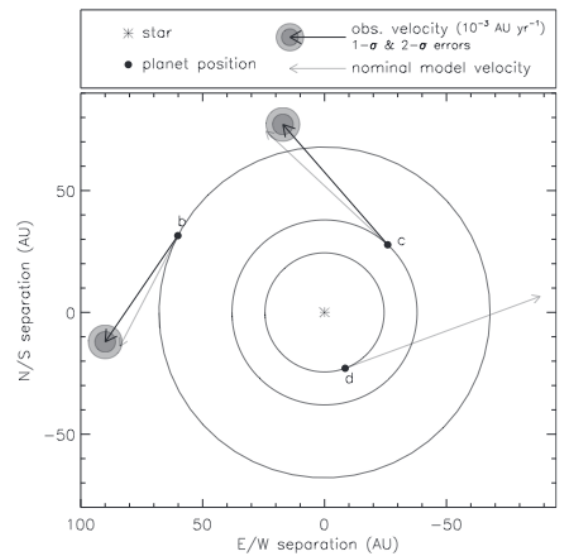
Characterization: Astrometric Motion

- Common proper motion will be used to determine physical association with the host star. The slowest moving objects within 100 pc have proper motions of about 15 mas/yr. The CHARIS astrometric precision of 3 mas will enable confirmation within a year.
- Astrometric observations can constrain planetary orbits
  - For a survey, eccentricity distributions could constrain formation mechanisms
  - For systems with RV data, imaging orbital information can be used to derive a dynamical mass. Subaru/IRD and CHARIS may be an excellent platform for these studies.
  - For systems with multiple planets, the orbital solutions constrain masses due to dynamical stability arguments (e.g., HR 8799 b,c,d).
- GAIA may be able to provide complimentary astrometric data on discovered exoplanets.



From Crepp et al. 2012



From Fabrycky & Murray-Clay 2010

Planet Formation Scenarios

- Planetary masses will be calculated based on the measured luminosities and the age of the system
- Compare to theoretical models to determine how 'hot' the start was during the formation period.
- A SCExAO + CHARIS survey will be more sensitive and probe smaller inner working angles than SEEDS.
  - SEEDS had a much larger field of view sensitive to planets on wide orbits, making the surveys very complimentary.
- The spectral diagnostics will be used to understand the evolution of planets.

Image credit: Meg Stalcup

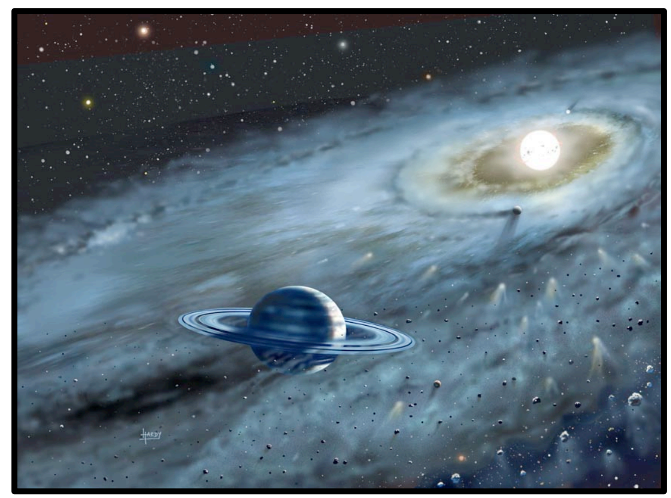
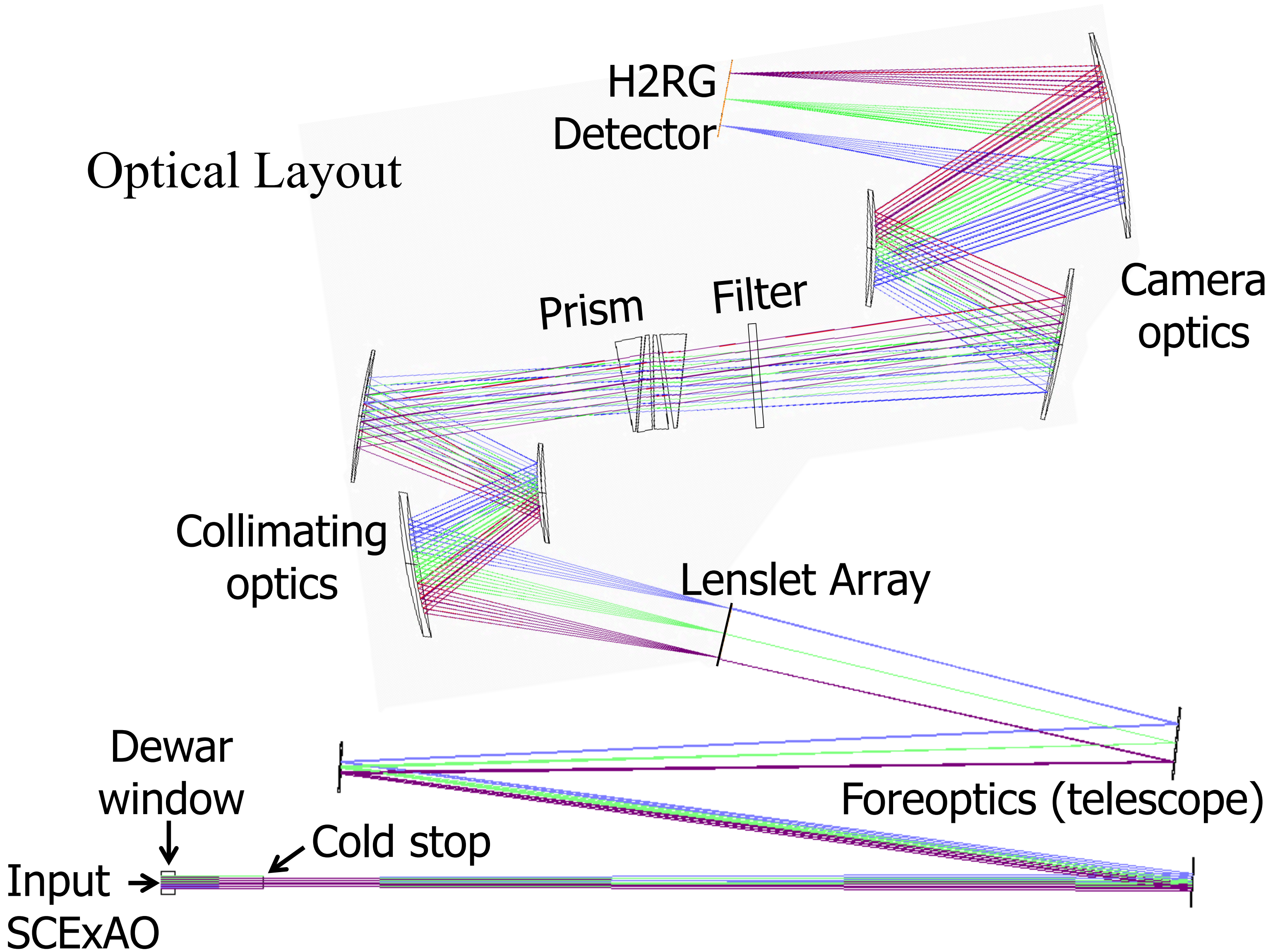
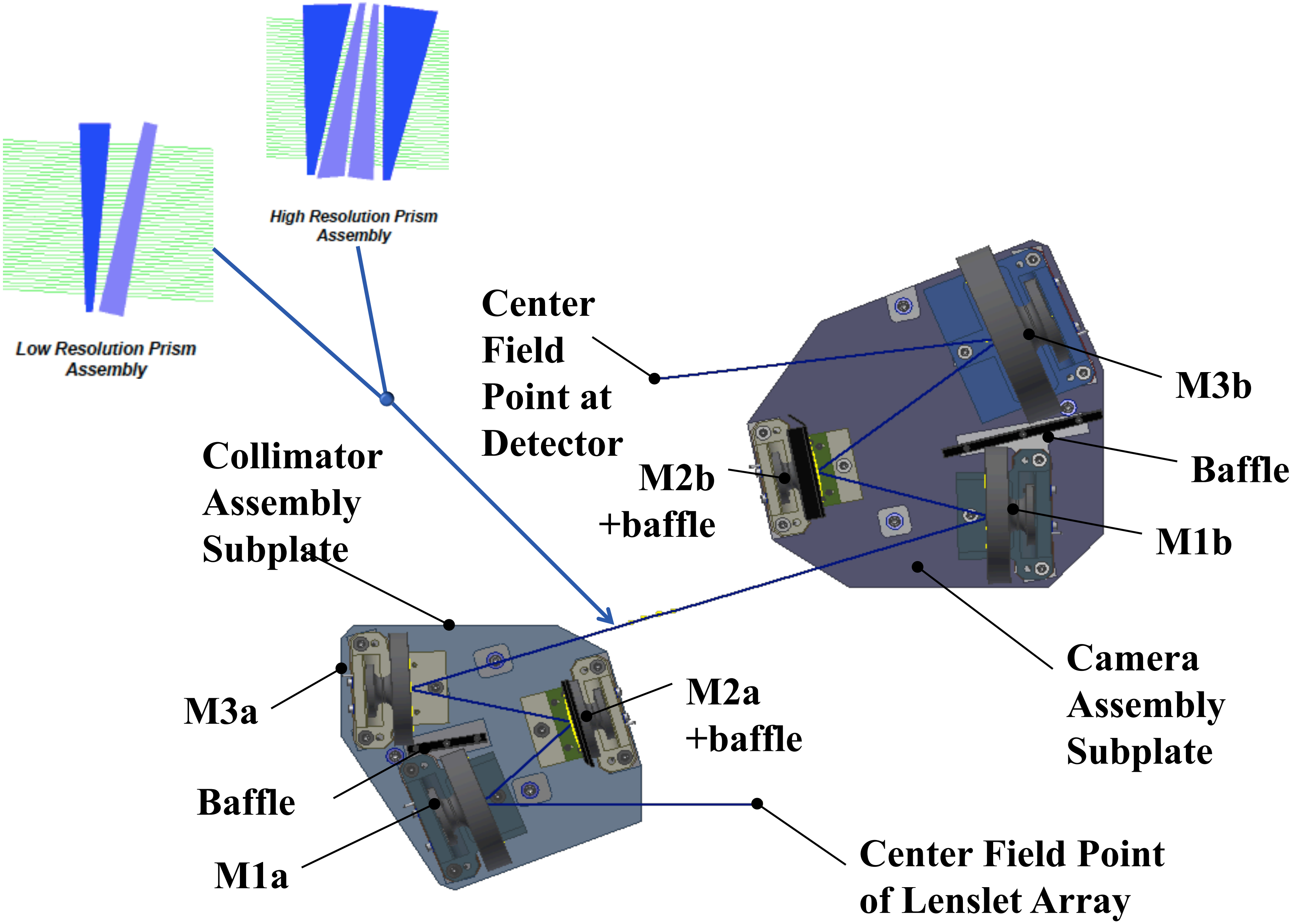


Image credit: David A. Hardy

CHARIS Instrument Design

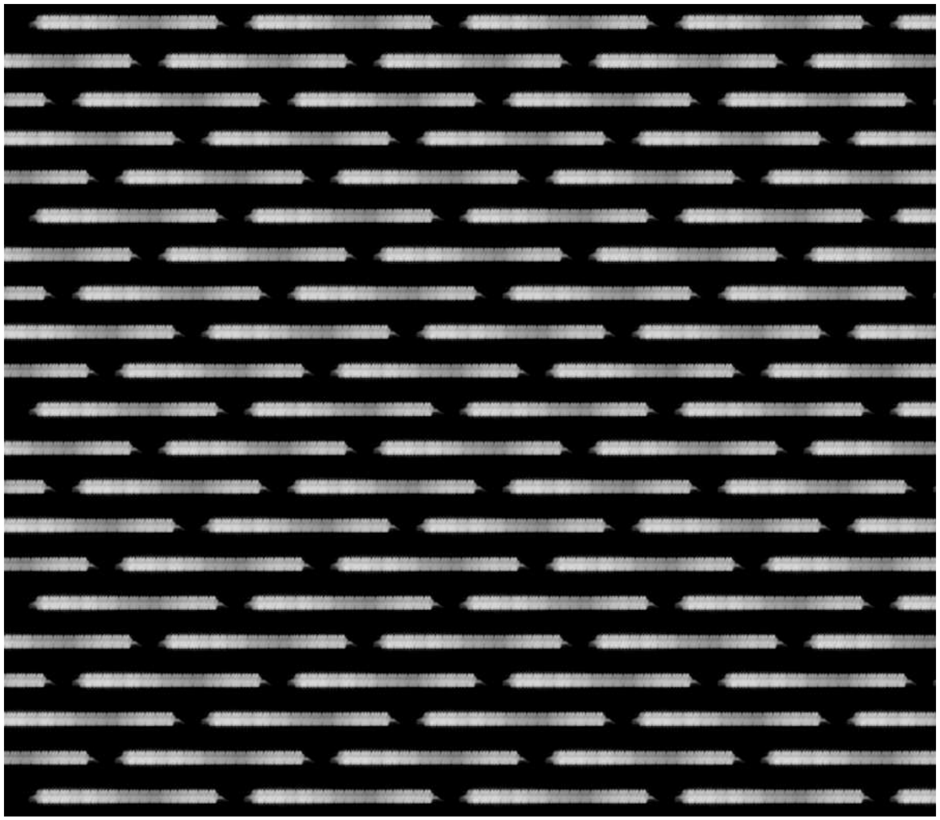


L3-SSG Relay Optics

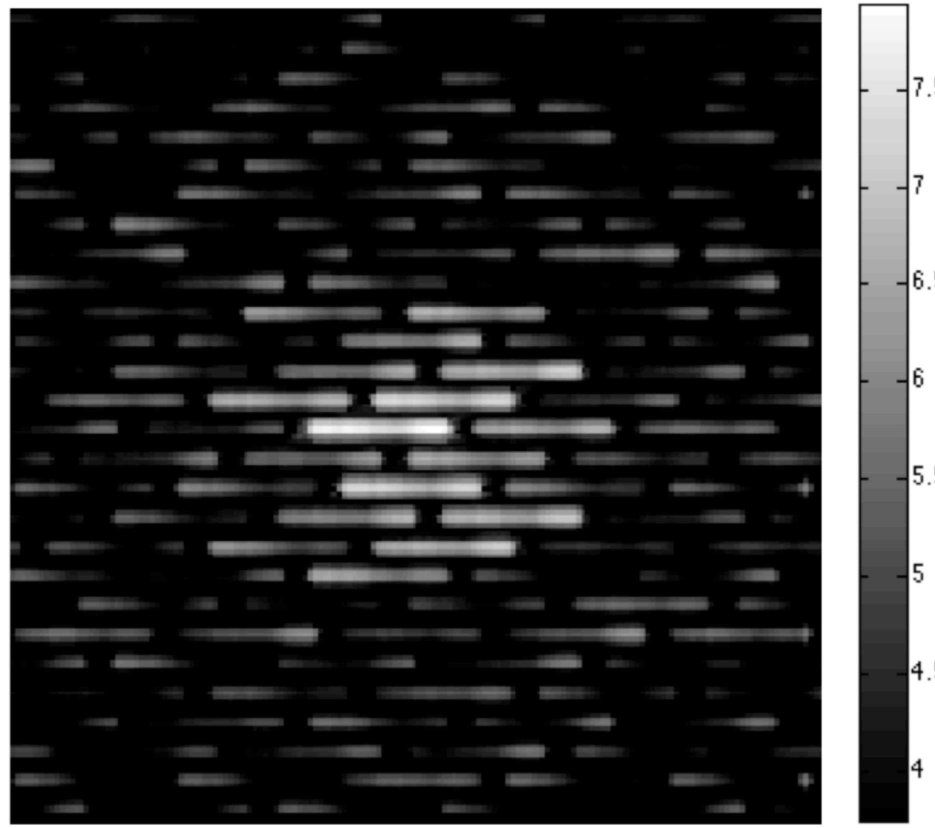


Simulated Images

Example Flat Field



200mas × 200mas H-band Image



Three major challenges:

- Spectral Uniformity
- Cross-talk
- Wavefront Quality

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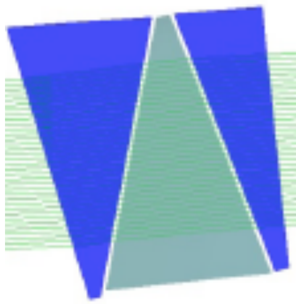
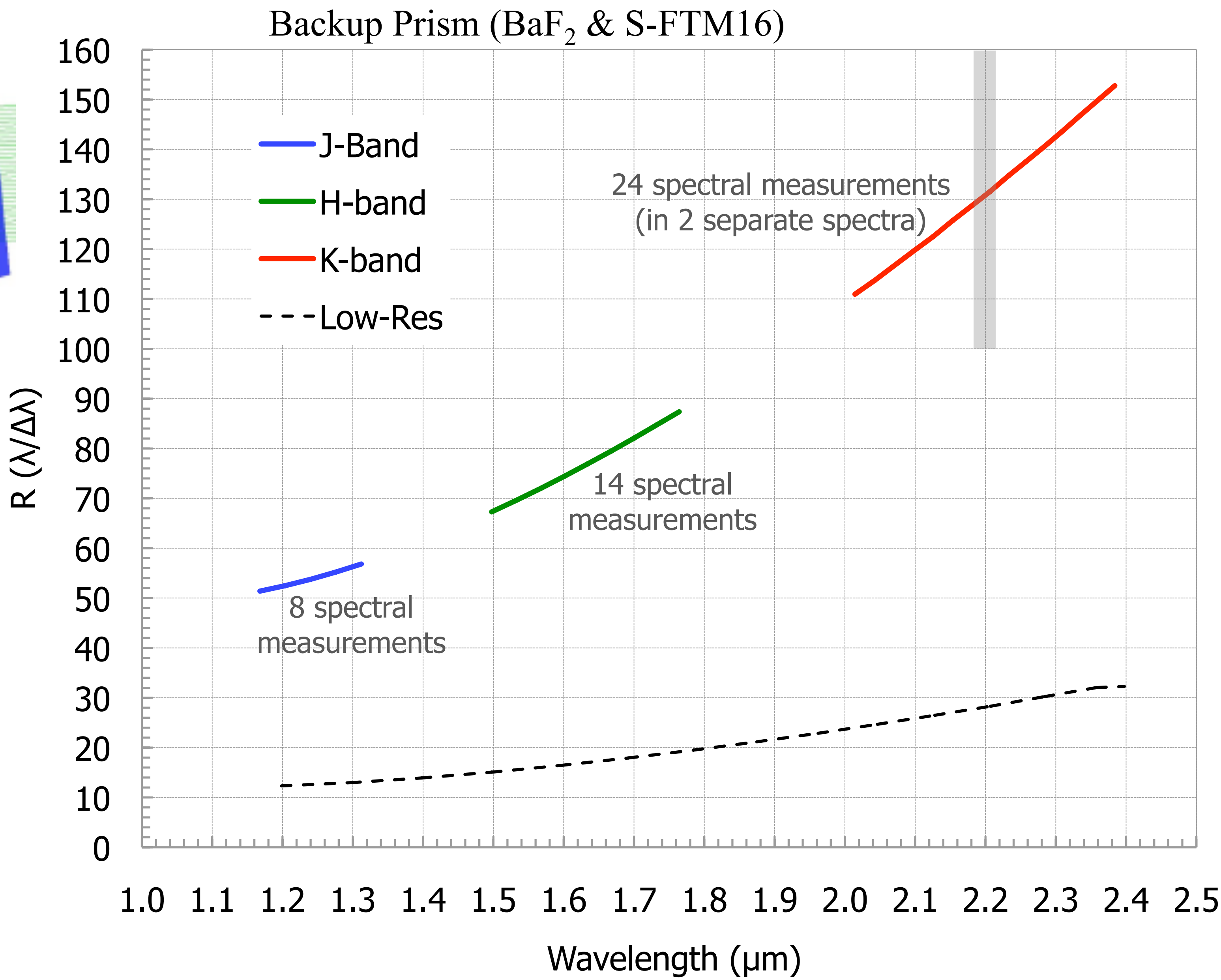
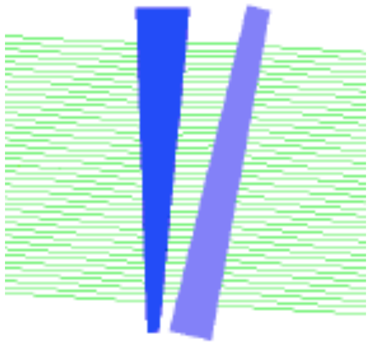
The "classic" choice: S-FTM16 Prism

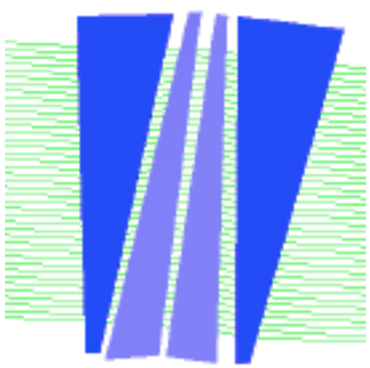




L-BBH2 Prism

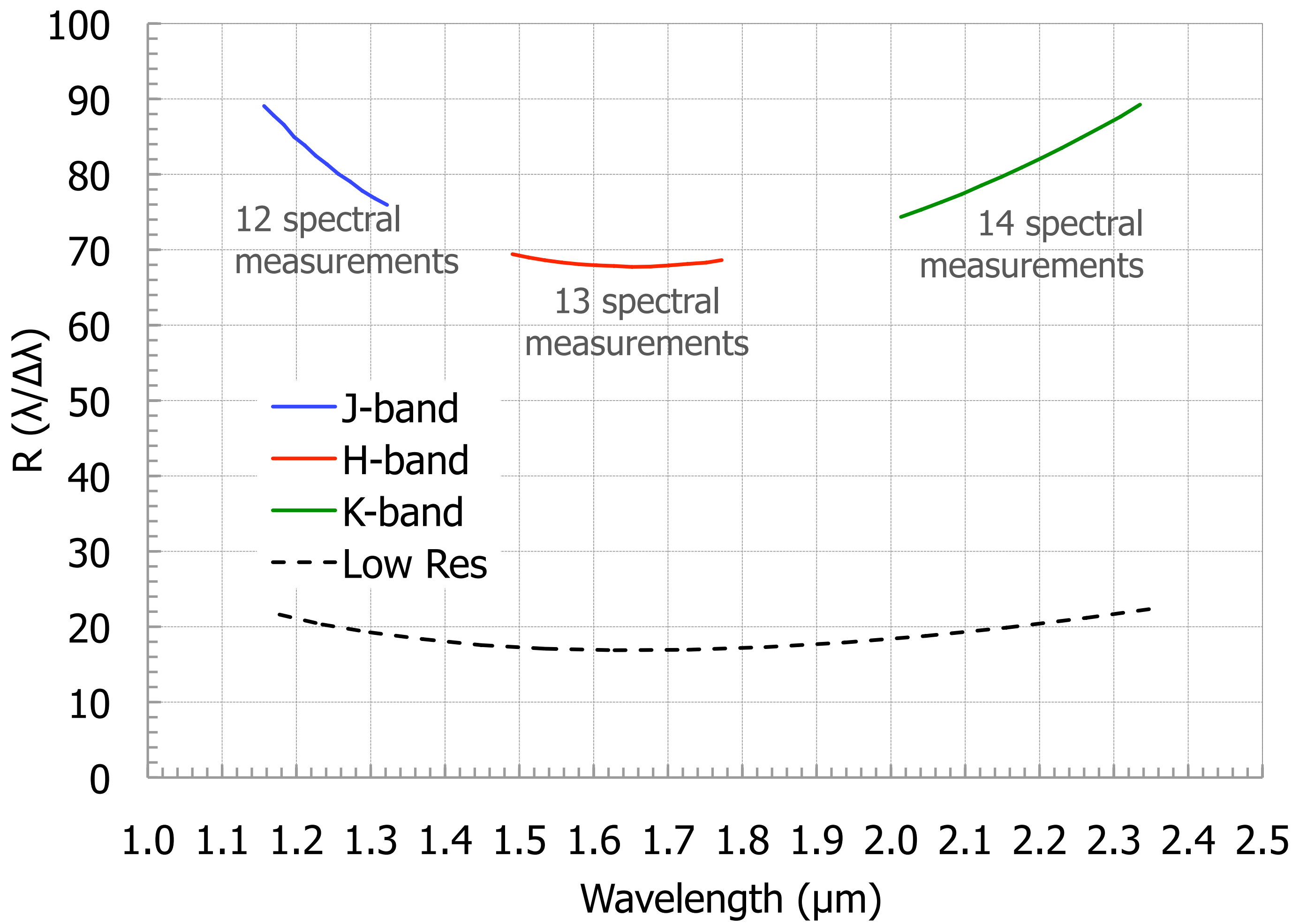


Low Resolution Prism Assembly



High Resolution Prism Assembly

Baseline Prism (BaF_2 & L-BBH2)



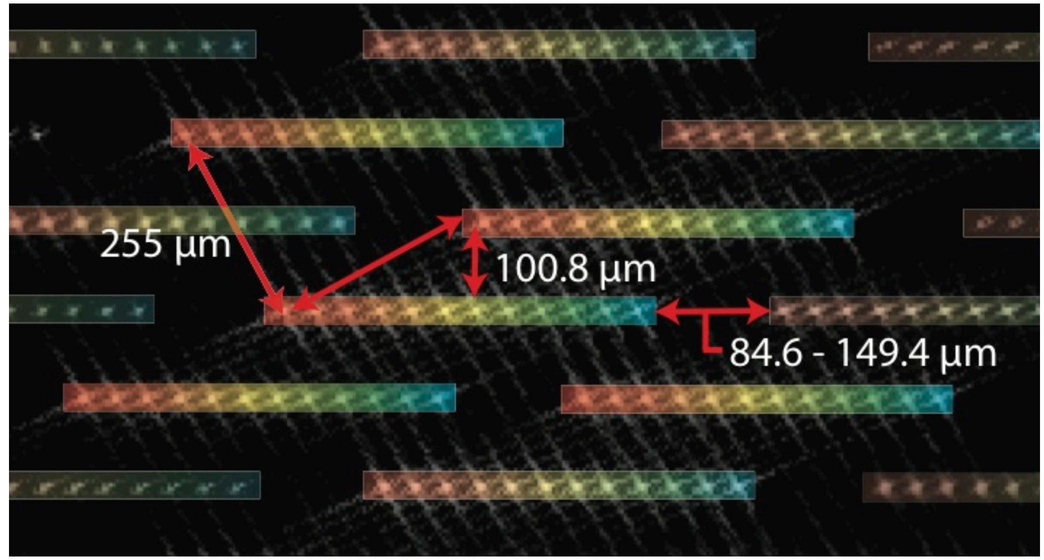
Cryogenic CTE and Index tests beginning soon at Goddard Space Flight Center.

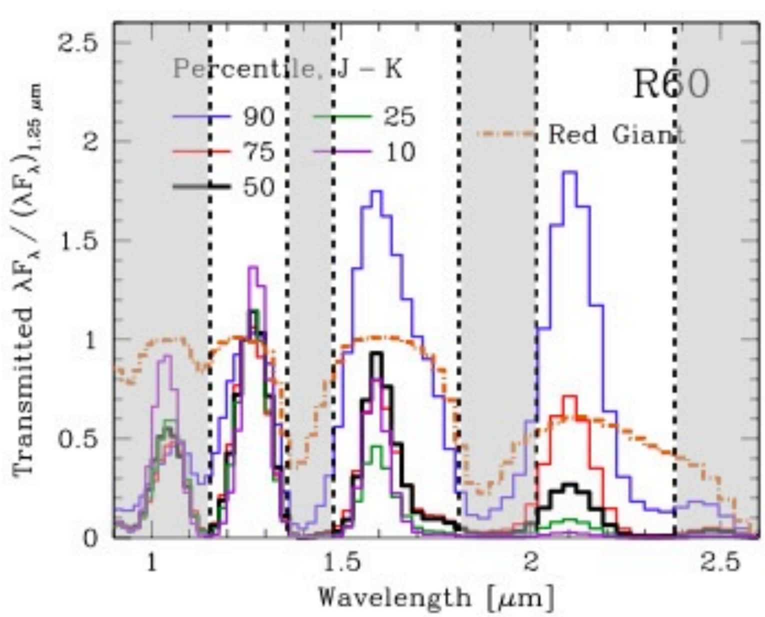
Spectral Contamination - Crosstalk

4 Lenslets Nyquist Sample PSF
➔ 4 adjacent spectra per planet
➔ Self-contamination

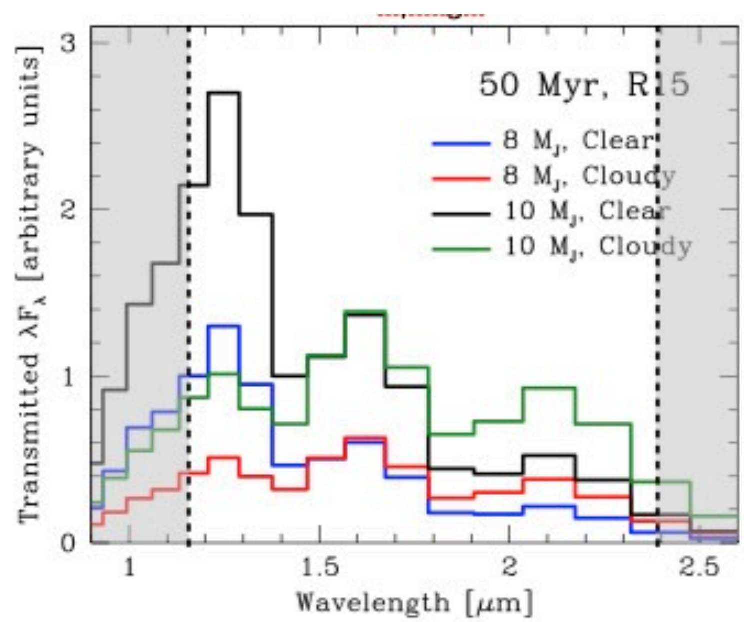
Adjacent speckles contaminate signal

<u>90 micron radius</u>



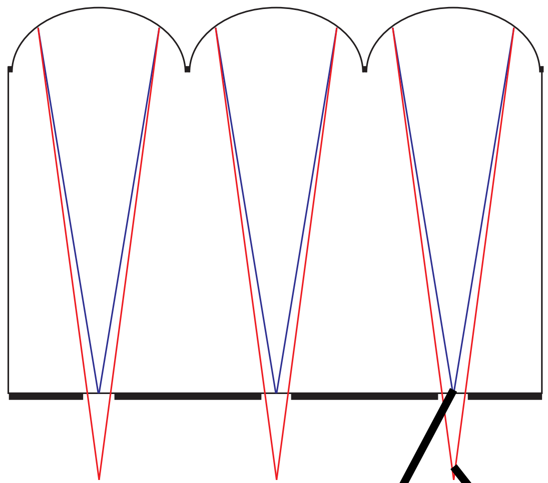


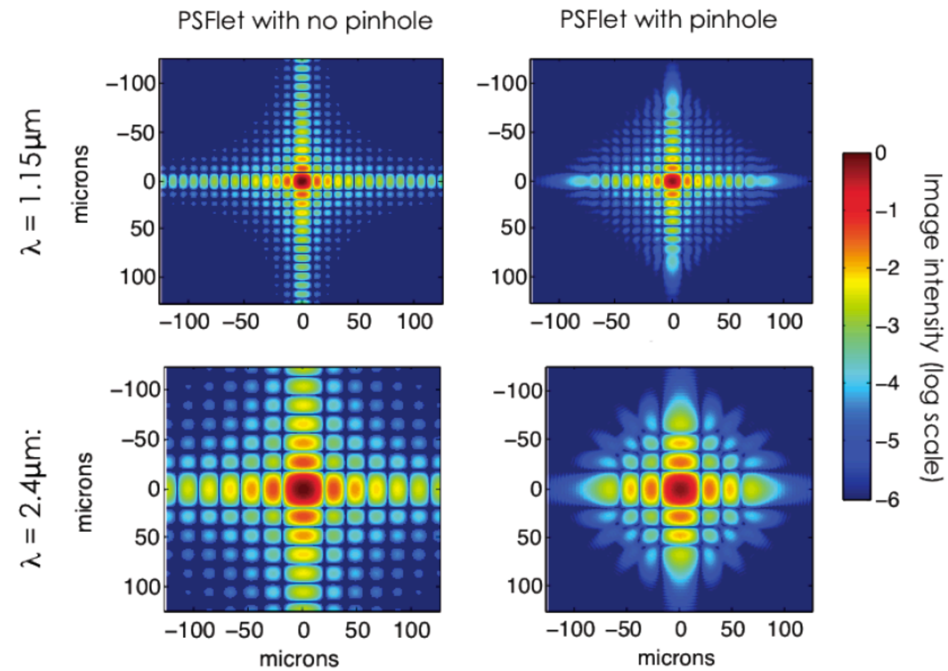
Any band varies by ~factor of 10.

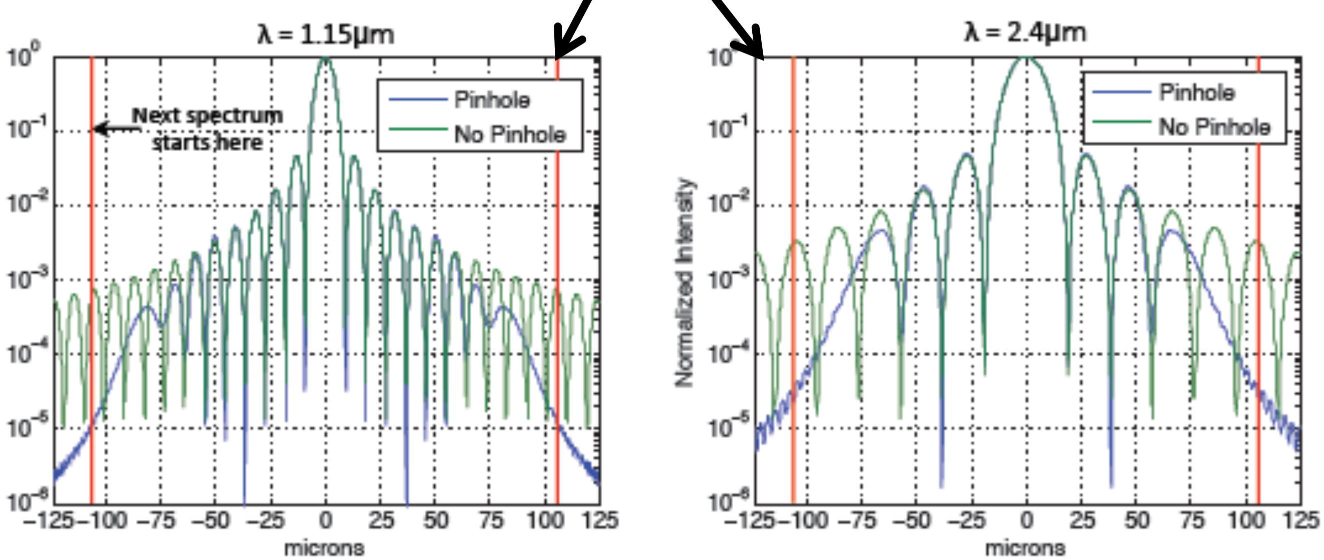


Mitigating Crosstalk at Lenslet Array

Field stop array
clips diffractive contamination lenslets



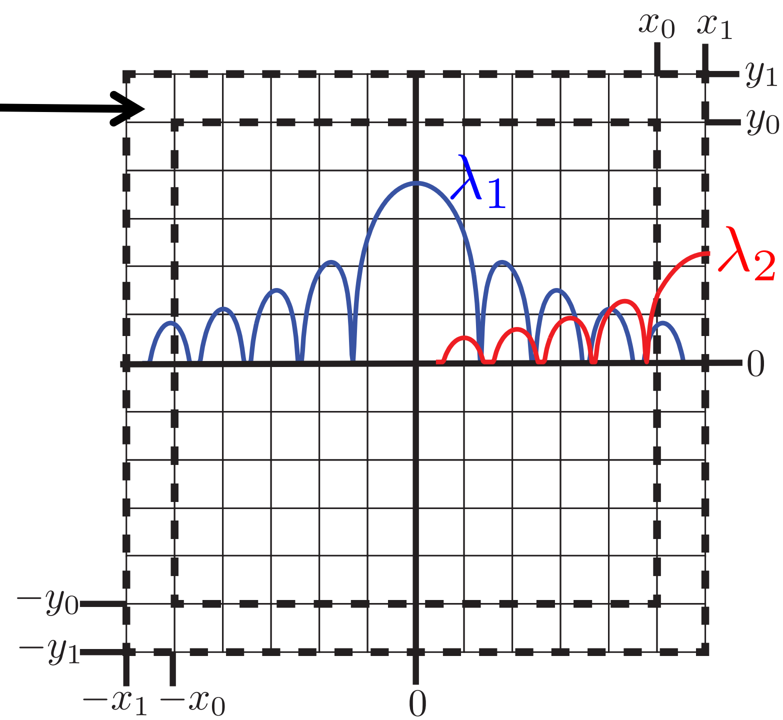




Ensquared Energy requirement on L3 optics maintains diffraction limited crosstalk.

Ensquared Energy as Proxy to Contrast

- Assume all remaining energy outside x_0 falls in annulus



- Define max relative intensity

$$C_{max}(x_0) = \epsilon_{max} \frac{I_{\lambda_2}(x_1)}{I_{\lambda_1}(0)}$$

- Assuming $\frac{I_{\lambda_2}(x_1)}{I_{\lambda_1}(0)} = 0.1$

ε	0.1%	0.5%	0.8%	1%
Min. EE	99.6%	98.2%	97.2%	96.5%

Wavelength [nm]	Design-Level EE		
	HR	LR	No Prism
1150	0.997	0.997	0.996
1650	0.972	0.972	0.972
2400	0.951	0.951	0.951

$$EE_{min}(x_0) = 1 - \frac{C_{max}}{EE_0 \Delta x \Delta y}\left[\int_{-x_1}^{x_1}\int_{-y_1}^{y_1} \mathrm{d}x\mathrm{d}y - \int_{-x_0}^{x_0}\int_{-y_0}^{y_0} \mathrm{d}x\mathrm{d}y\right].$$

Wavefront Requirement

- SCExAO has ~44x44 actuator Boston Micromachines 2k DM.
  - Used for high order wavefront correction & speckle suppression at focal plane
  - Controllable Limit of 22 cycles/aperture
- 3 control scenarios for quasi-static speckle suppression
  - Speckle sensing and control at the CHARIS science detector
  - Speckle sensing using a combination of CHARIS & SCExAO detectors
  - Speckle sensing using only SCExAO detector (**Limiting Case**)
- Maintaining dark hole despite non-common path
  - Suppression region must maintain 1×10^{-5} contrast floor
  - All non-common path optics are post-occulter

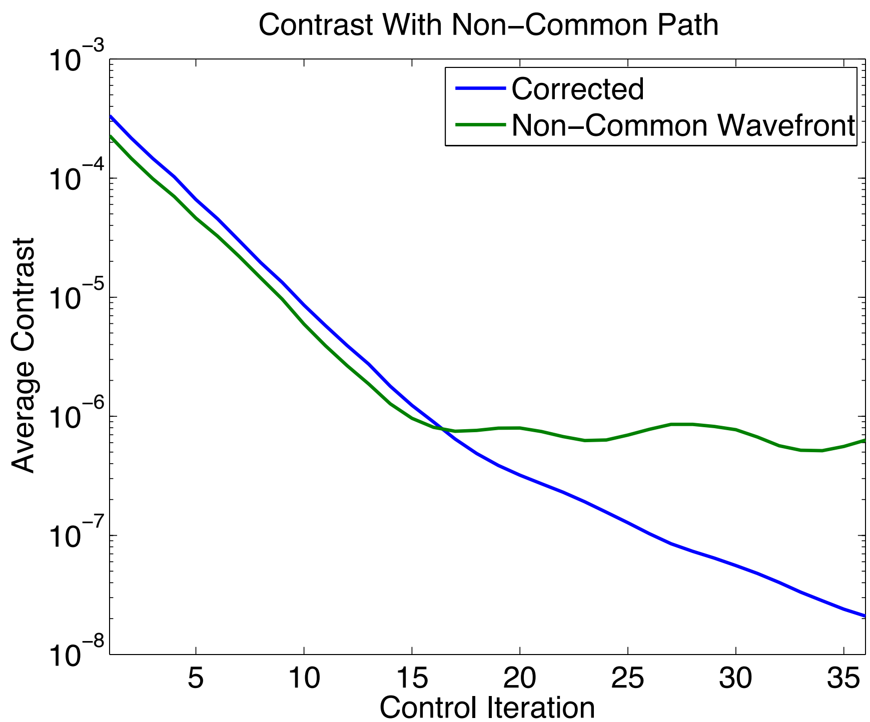
SCExAO dichroic	Window	F/420 Imager	Filter	Prism	L3 relay optics
$\lambda/10$	$\lambda/20$	$\lambda/20$	$\lambda/5$	$\lambda/5$	$\lambda/5$

Simulation Final Results

- Sum of two λ/5 surfaces from expected L3-SSG wavefront, scaled by √2
  - L3-SSG relay optics, prism, filter, SCExAO dichroic, F/420 Imager
  - ≤ λ/10 dichroic/beamsplitter
  - ≤ λ/20 for F/420 Imager

  } Allows for Relaxed Prism and Filter

- Non-common path limits SCExAO's ability to maintain high contrast at 1×10^{-6}
  - True even at the inner working angle for the example coronagraph
  - Simulation is order of magnitude below first generation detection limit



Defining Technologies of CHARIS

- Strict definition and tolerancing to mitigate crosstalk in a high-contrast image
  - Pinhole Array on the back side of the lenslets (Woodgate et al. 2006, Bonfield et al. 2008)
  - Clear aperture requirements
  - Ensquared energy requirements
  - Wavefront requirements based on coronagraphic residuals

- L-BBH2
  - Never been used as a prism material before
  - Index uniformity tests with Ohara
  - Thermal expansion tests at Goddard Space Flight Center at 77K
  - Cryogenic characterization of index of refraction over full bandpass at Goddard
    - Material changes are promising based on -40C measurements by Ohara
  - Unprecedented dispersion uniformity across the 1.15-2.37 micron instrument bandpass
    - Avoids overdispersion in K-band
    - High uniformity in H-band
    - Avoids splitting high-resolution K-band
    - Avoids cutting bandpass in the low-resolution imaging mode

Summary

- CHARIS will build upon SEEDS survey by characterizing known objects and discovering new ones, as well as enhancing the disk science.
- CHARIS+SCExAO will be the only Northern Hemisphere spectrograph for high-contrast science, complementing GPI and SPHERE in the South
- CHARIS advances the science and technology of integral field spectroscopy
  - All reflective design with low wavefront error
  - Minimize crosstalk in hardware
  - New prism material for uniform spectral distribution
- CHARIS is on track to be delivered to Subaru in early 2016
  - Science grade detectors delivered and in test
  - L3 CDR in October 2013 and manufacturing begun
  - CHARIS CDR on December 5-6, 2013
  - Cryostat material ordered
  - Prism material ordered and will begin testing soon