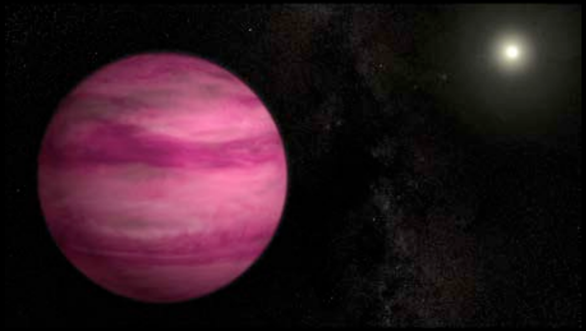

The Promise and Challenges of Multiplex Spectroscopy for Exoplanet Science

Wide-Field InfraRed Surveys: Science and Techniques

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November 18, 2014

Roman Technology Fellow

Goddard AFTA Study Scientist

Exo-C Science and Technology Definition Team

Goddard Space Flight Center

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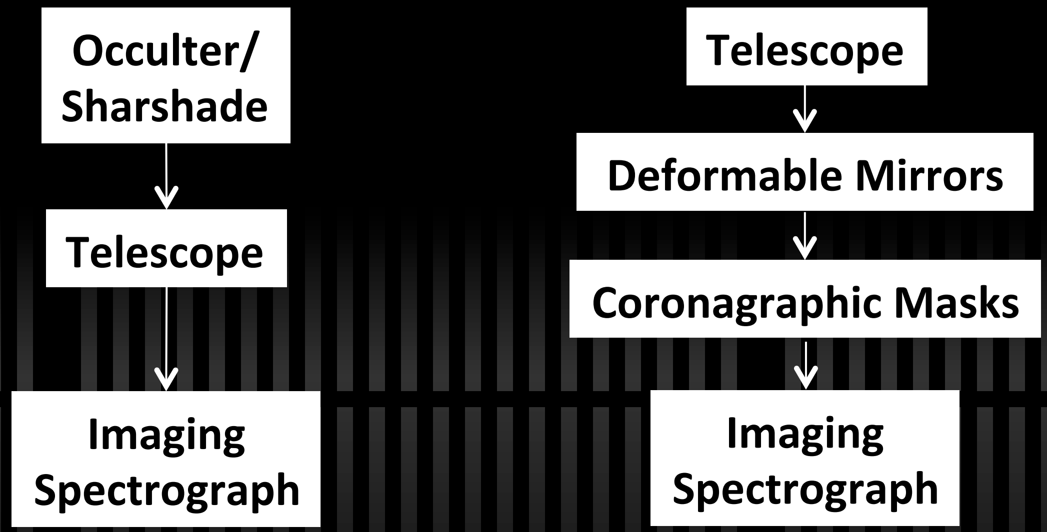
SEEDS: Motohide Tamura (PI), Joe Carson, Thayne Currie, Markus Feldt, Miwa Goto, Carol Grady, Olivier Guyon, Thomas Henning, Klaus Hodapp, Markus Janson, Ryo Kandori, Jungmi Kwon, Masayuki Kuzuhara, Taro Matsuo, Ryuji Suzuki, Christian Thalmann, John Wisniewski, + ~60 others

Primary AFTA-C Exoplanet Imaging Spectrograph Design Goals

Specifications	AFTA-C
Spectrograph Field of View	< 48 λ/D × 48 λ/D (TBR) 2.5”×2.5” at 600 nm
Spatial Sampling	0.3 λ/D at 600nm (TBR)
Spectral Range	600-970 nm 18% at λc 720, 840, 970
Spectral Resolution	R=70
Detector Read Noise	< 1e-3 e-/frame (TBR)
Detector Dark Current	< 1e-4 e-/pix/s (TBR)

*See Wilkins, McElwain, Norton, Rauscher, et al. 2014 SPIE for detector characteristics

Imaging Spectrographs Required

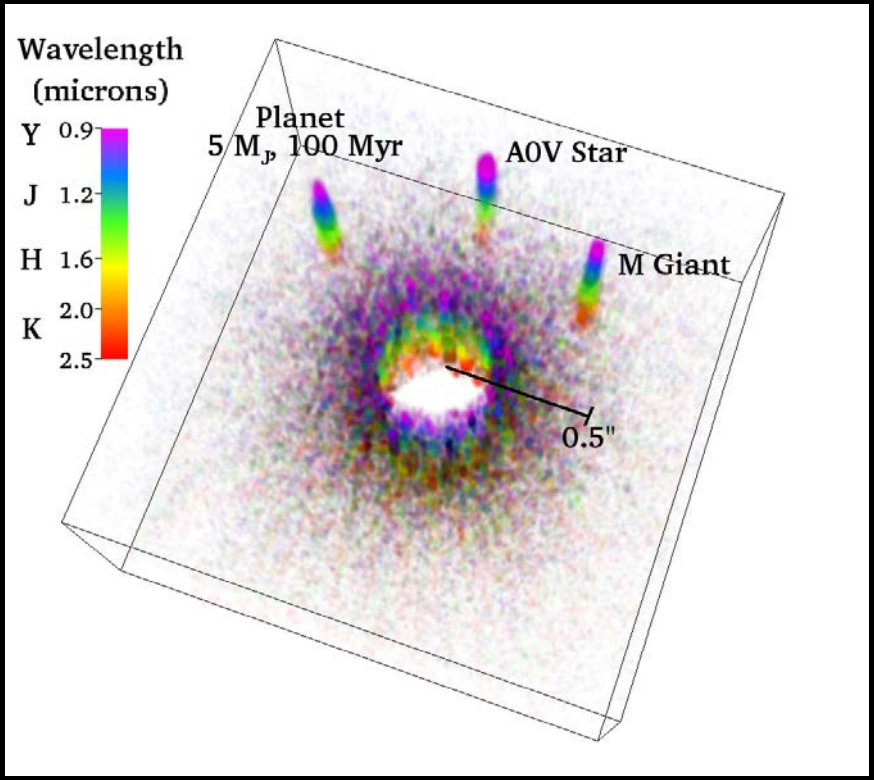


*Imaging spectrograph requirements could be met by an **integral field spectrograph (IFS) with a large format conventional detector (e.g., CCD, EMCCD)** OR an energy discriminating detector (e.g., MKID, TES, STJ)*

- Energy discriminating detectors currently are low TRL, have small formats, low QE, limited by fundamental physics to low spectral resolutions (R<100), must be very cold (few K) which is especially challenging for large formats, and cooling to few K poses jitter risks.

***See Roberge talk at this conference**

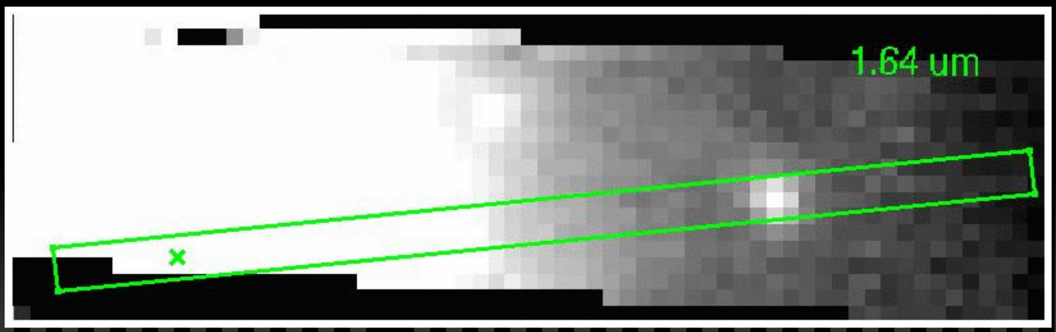
Imaging Spectrographs



McElwain, M., Brandt, T., Janson, M. et al., 2012, Proc of the SPIE, 8446

IFS Multiplexing for High Contrast Science

Keck AO + OSIRIS GQ Lup B



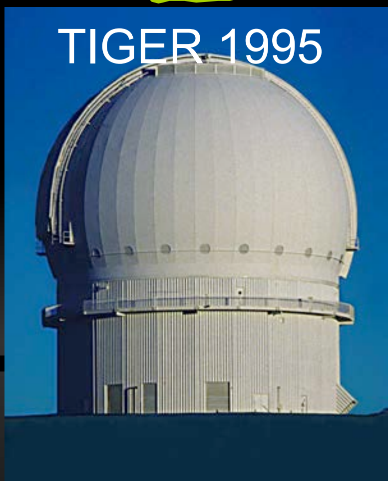
elevation,
differential refraction

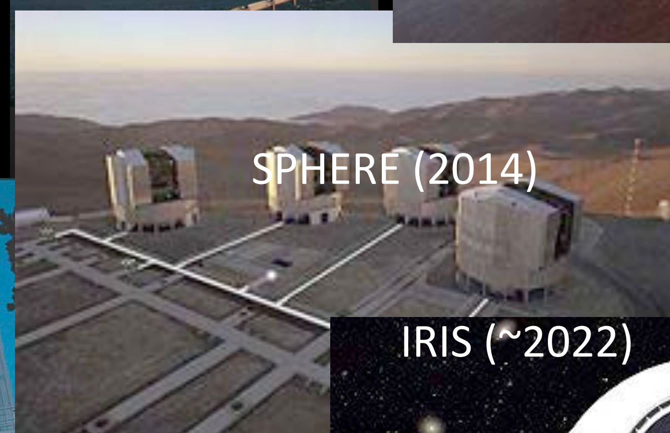
H-band
53 mas-wide slit
GQ Lup A/B aligned on slit

- AO slit spectroscopy
  - slit width (40–100 mas), PSF (40–80 mas) comparable to pointing precision (~20–40 mas)
- AO IFS spectroscopy
  - No slit losses due to centering on slit
  - No slit losses due to differential refraction
  - Speckle suppression in post processing

McElwain et al., 2007, ApJ, 656, 505

Lenslet-based IFSs on Ground-based Observatories





A Brief History of High Contrast IFSs

- 2005: OSIRIS first light at Keck II
- 2005 CorSpec Study (PI Heap, NASA Goddard)
- 2008: Direct imaging discovery of HR 8799 bcd
- 2008: Project 1640 first light at Palomar
- 2012: PISCES Roman Concept Study
- 2013-16: PISCES Roman Development Effort
- 2013: AFTA-Coronagraph Working Group Formed
- 2013: GPI first light at Gemini
- 2013: Exo-C STDT Started
- 2014-?? AFTA-Coronagraph Exoplanet Spectrograph (ACES) study
- 202? ATLAST Earth and Gas Giant Imaging Spectrograph (AEGIS)

Exoplanet Science Papers with IFSs

Author	Title	Year
McElwain	First High-Contrast Science with an Integral Field Spectrograph: The Substellar Companion to GQ Lupi	2007
Thatte	Very high contrast integral field spectroscopy of AB Doradus C: 9-mag contrast at 0.2arcsec without a coronagraph using spectral deconvolution†	2007
Close	New Photometry and Spectra of AB Doradus C: An Accurate Mass Determination of a Young Low-Mass Object with Theoretical Evolutionary Tracks	2007
Janson	Integral field spectroscopy of L449-1. A test case for spectral differential imaging with SINFONI	2008
Bowler	Near-infrared Spectroscopy of the Extrasolar Planet HR 8799 b	2010
Hinkley	Discovery and Characterization of a Faint Stellar Companion to the A3V Star ζ Virginis	2010
Zimmerman	Parallactic Motion for Companion Discovery: An M-Dwarf Orbiting Alcor	2010
Lafrenière	The Directly Imaged Planet around the Young Solar Analog 1RXS J160929.1-210524: Confirmation of Common Proper Motion, Temperature and Mass	2010
Barman	Clouds and Chemistry in the Atmosphere of Extrasolar Planet HR8799b	2011
Pueyo	Constraining Mass Ratio and Extinction in the FU Orionis Binary System with Infrared Integral Field Spectroscopy	2012
Hinkley	High Resolution Infrared Imaging & Spectroscopy of the Z Canis Majoris System During Quiescence & Outburst	2012
Hinkley	The κ Andromedae System: New Constraints on the Companion Mass, System Age, and Further Multiplicity	2013
Oppenheimer	Reconnaissance of the HR 8799 Exosolar System. I. Near-infrared Spectroscopy	2013
Konopacky	Detection of Carbon Monoxide and Water Absorption Lines in an Exoplanet Atmosphere	2013
Chilcote	The First H-band Spectrum of the Massive Gas Giant Planet beta Pictoris b with the Gemini Planet Imager	2014
Ingraham	Gemini Planet Imager Spectroscopy of the HR 8799 Planets c and d	2014
Pueyo	Reconnaissance of the HR 8799 Exosolar System II: Astrometry and Orbital Motion	2014
Perrin	Polarimetry with the Gemini Planet Imager: Methods, Performance at First Light, and the Circumstellar Ring around HR 4796A	2014
Reggiani	Discovery of a Companion Candidate in the HD 169142 Transition Disk and the Possibility of Multiple Planet Formation	2014
Currie	Direct Imaging and Spectroscopy of a Candidate Companion Below/Near the Deuterium-burning Limit in the Young Binary Star System, ROXs 42B	2014
Galicher	Near-Infrared Detection and Characterization of the Exoplanet HD 95086 b with the Gemini Planet Imager	2014

Integral Field Spectrographs are demonstrated instruments for high contrast spectroscopy.

Characterizing a Directly Detected Companion: GJ 758 B

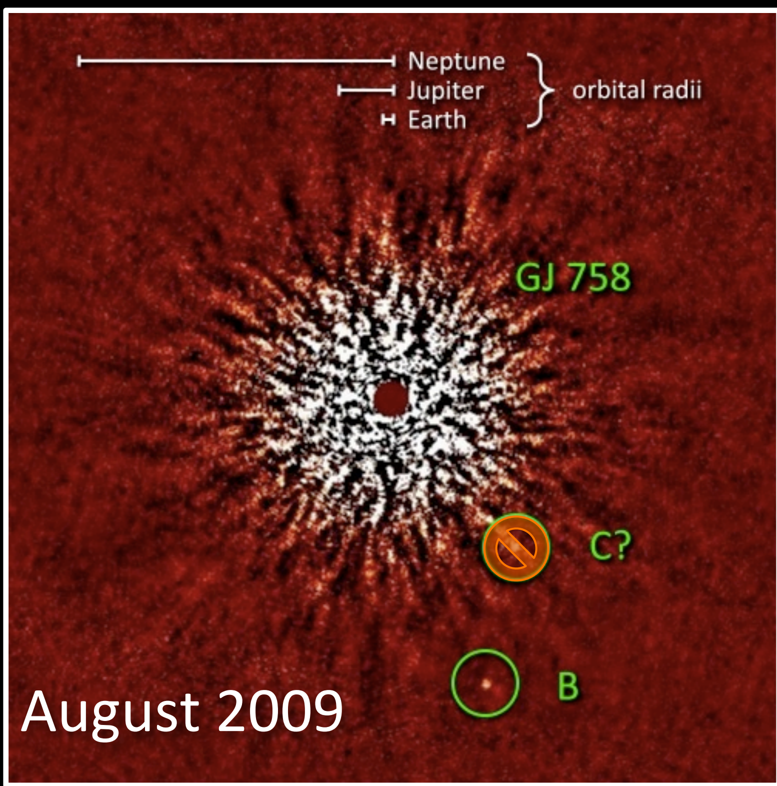
TIME

The Top 10 Everything of 2009

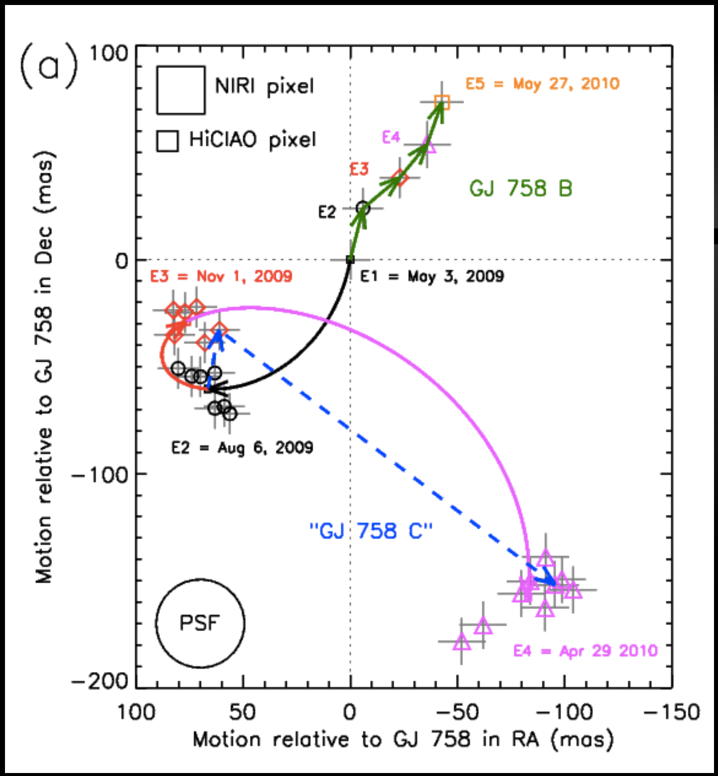
TIME charts the highs and lows of the past year in 50 wide-ranging lists

Top 10 Scientific Discoveries

10. A New Planet (or Brown Dwarf?) Discovered

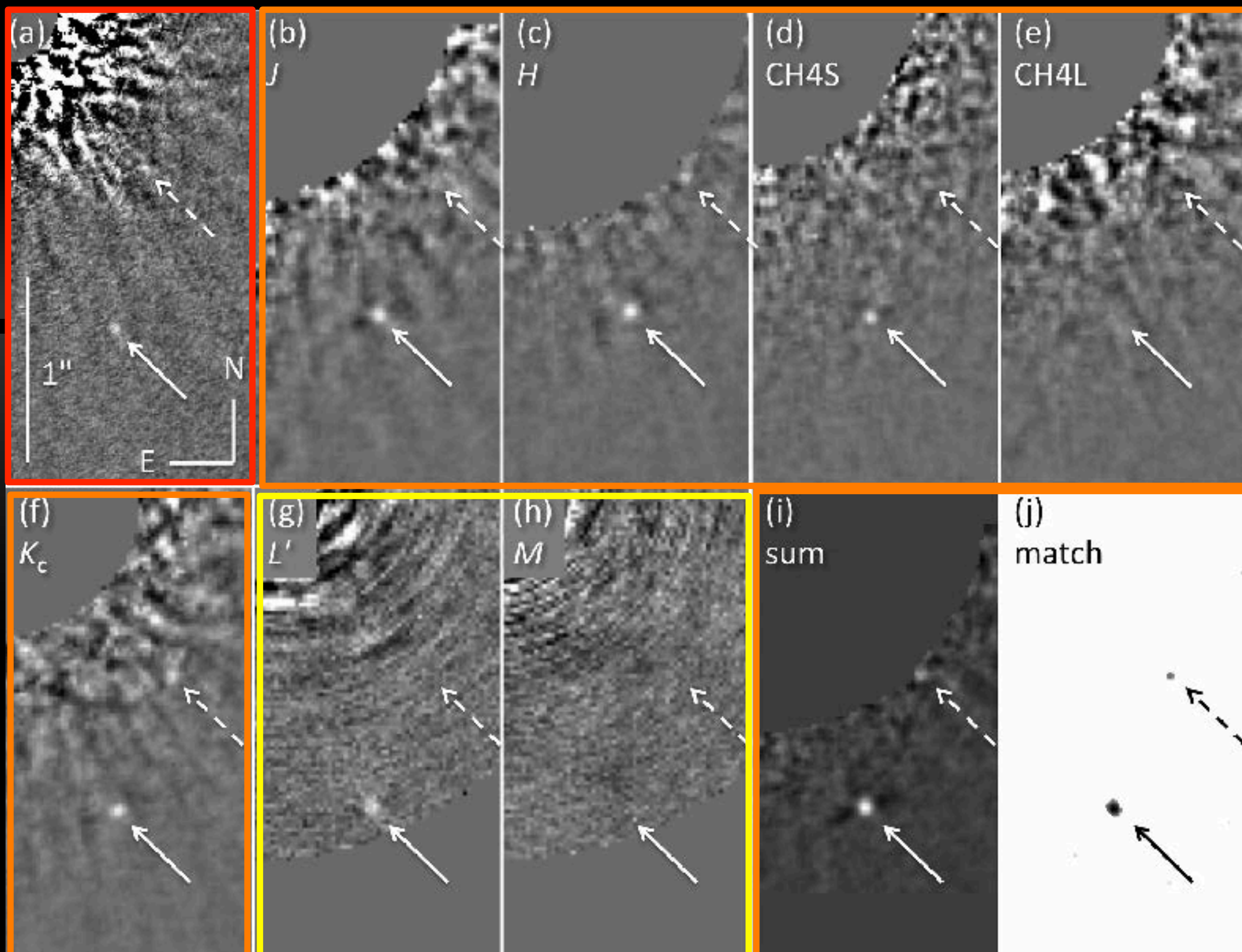


S/N Map Scaling [-1σ, 5σ]



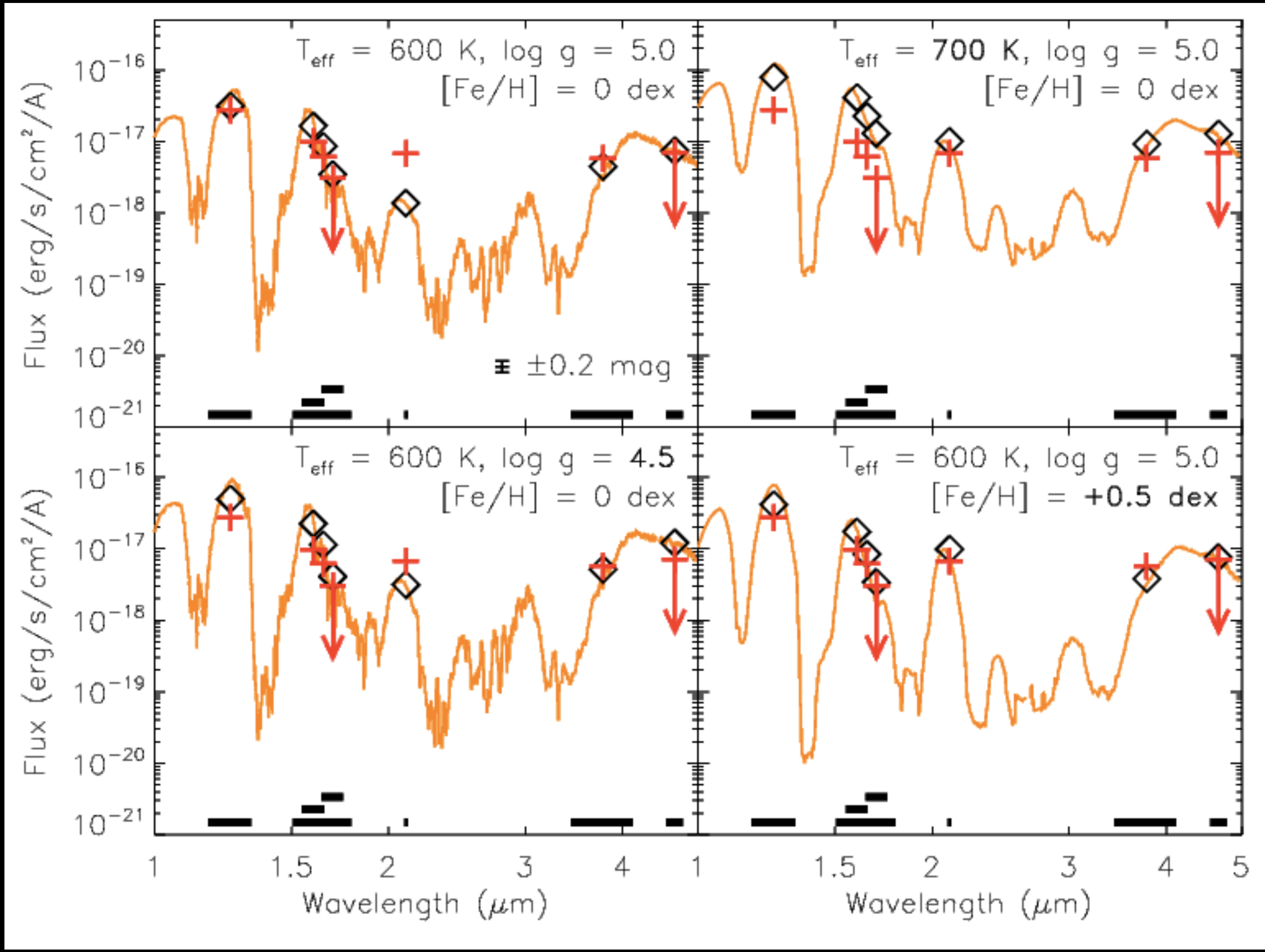
See Thalmann, …, McElwain, et al. 2009, ApJL, 707, L123

GJ 758 B Multiband Photometry



See Janson, …, McElwain et al. 2010, ApJL, 728, 85

GJ 758 B Comparison to Theoretical Models



See Janson, …, McElwain et al. 2010, ApJL

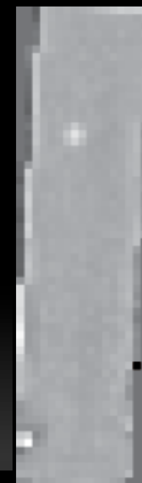
Path to Understanding GJ 758 B

Date	Event
May 2009	Candidate Discovery
Aug. 2009	Common Proper Motion Confirmation
Sep. 2009	Multiband Imaging Proposals Submitted
Aug. 2010	Currie et al. L-band paper posted on astro-ph
Aug. 2010	Multiband Imaging Campaign Completed
Nov. 2010	Janson, …, McElwain, et al., ApJ, 728, 85 (this work)

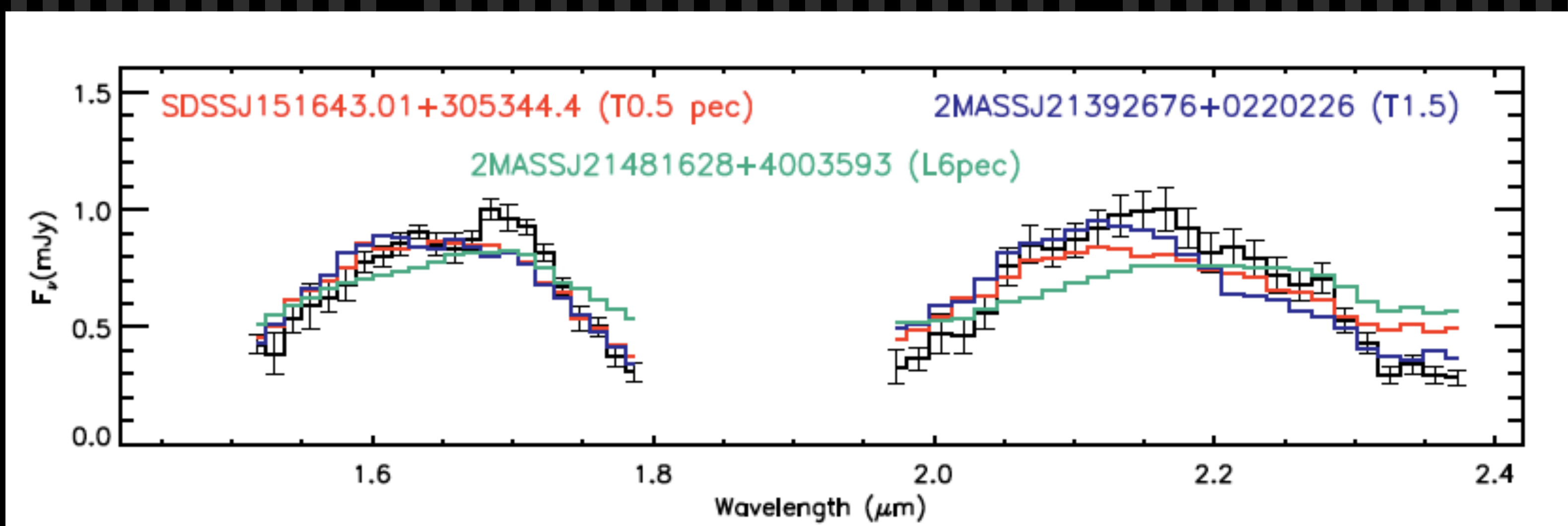
Data taken over 9 nights on 3 telescopes ≥ 8 m.!

OSIRIS HR 8799 b Spectroscopy

Reduced median collapsed
H-band cube



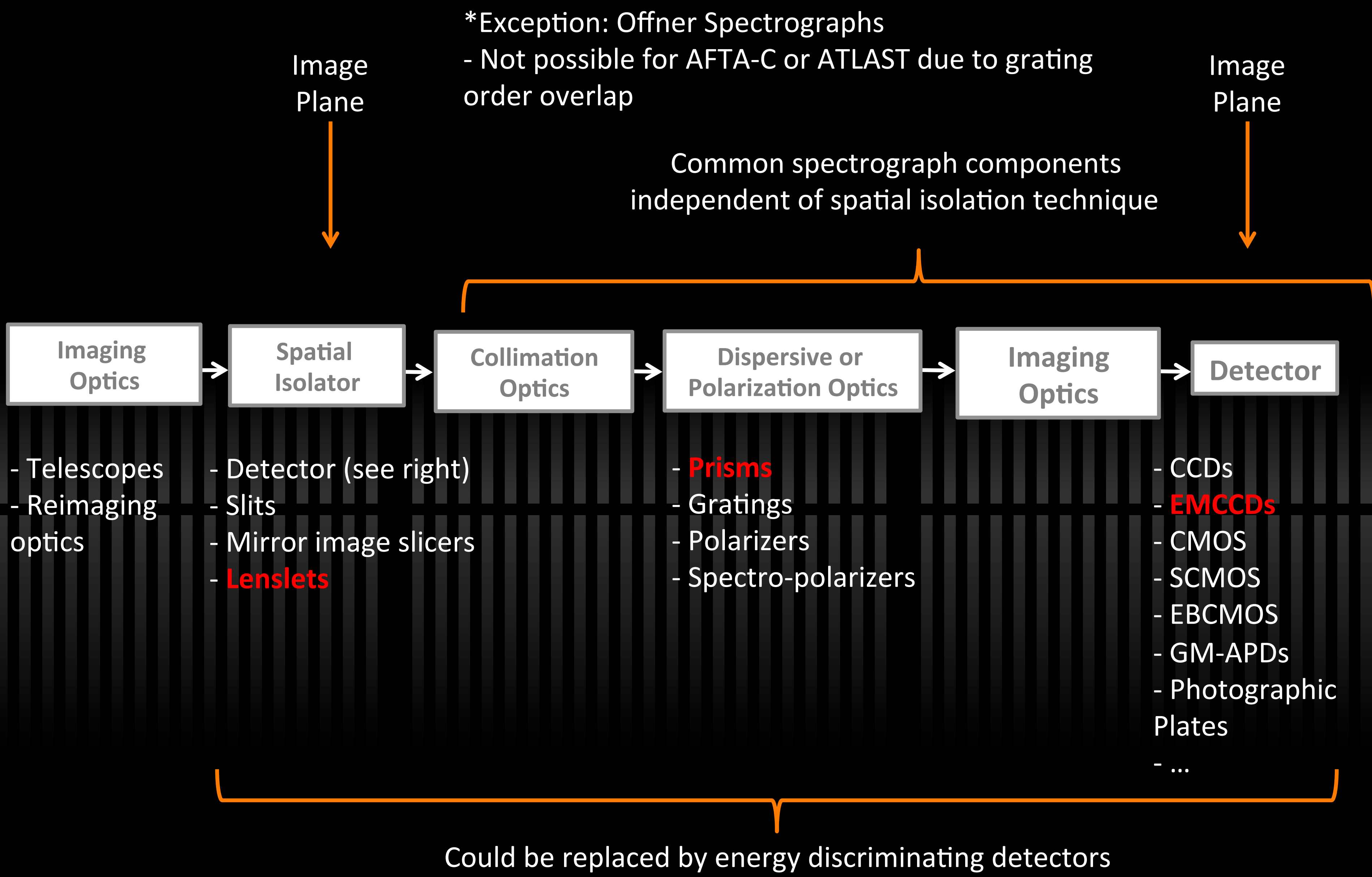
Speckle suppresed median
collapsed
H-band cube



***See Bowler talk at this conference**

Barman et al. 2011, ApJ, 733, 65

Basic Spectrograph Layout



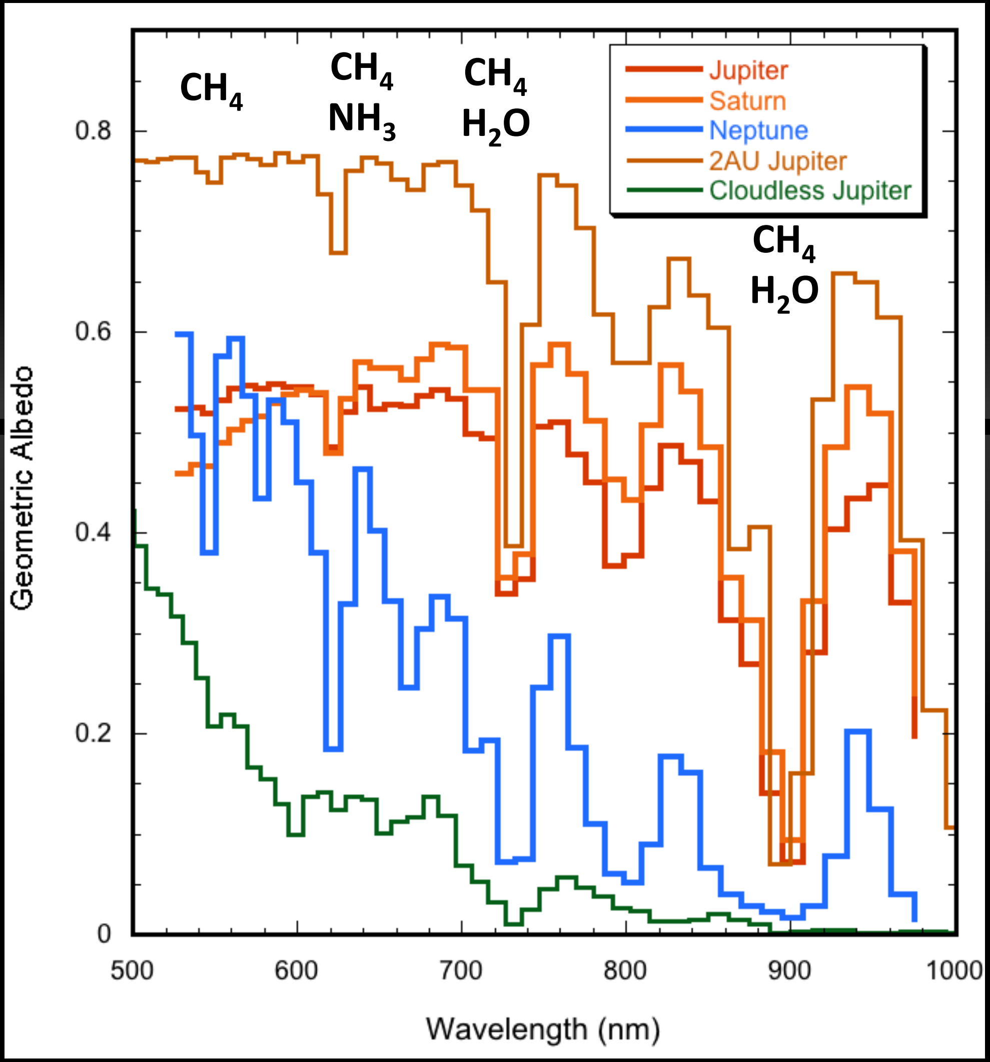
PISCES: IFS Demonstration at the HCIT

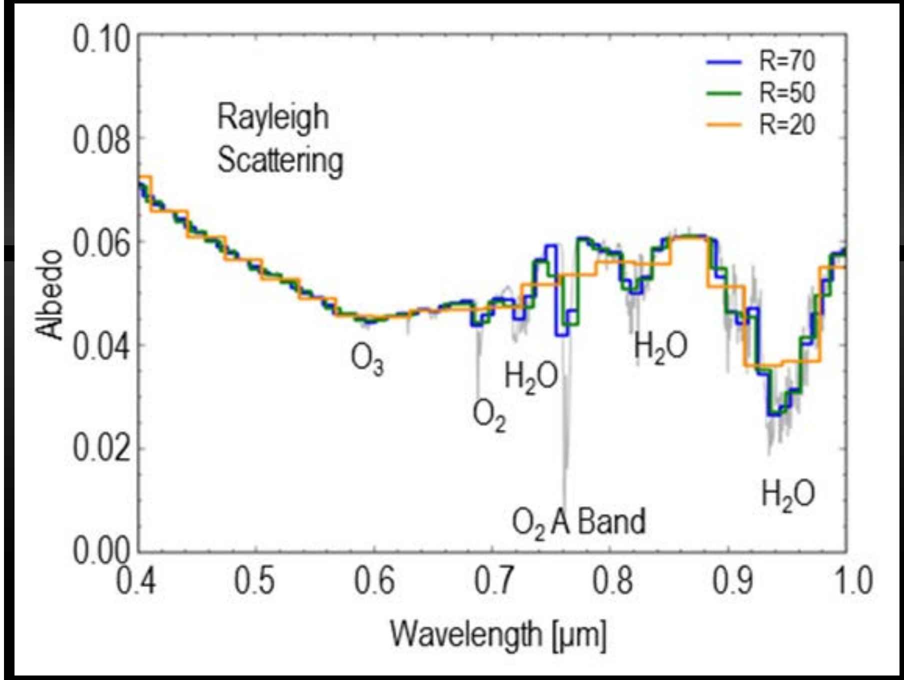
Prototype Imaging Spectrograph for Coronagraphic Exoplanet Studies

- Raise TRL of an exoplanet science camera for flight
- Advance TRL of the HCIT system
- Diagnostic tool for HCIT chromatic performance
- Improve WFS&C algorithms
- Flight-like data reduction and analysis
- Enable realistic post-processing demonstrations

1. High Contrast Lenslet-based IFS's will be TRL 5 before FY18
2. A PISCES-like camera is the baseline science camera for AFTA-C, Exo-C, Exo-S, and ATLAST.

Reflected Light Exoplanet Spectroscopy with R~70





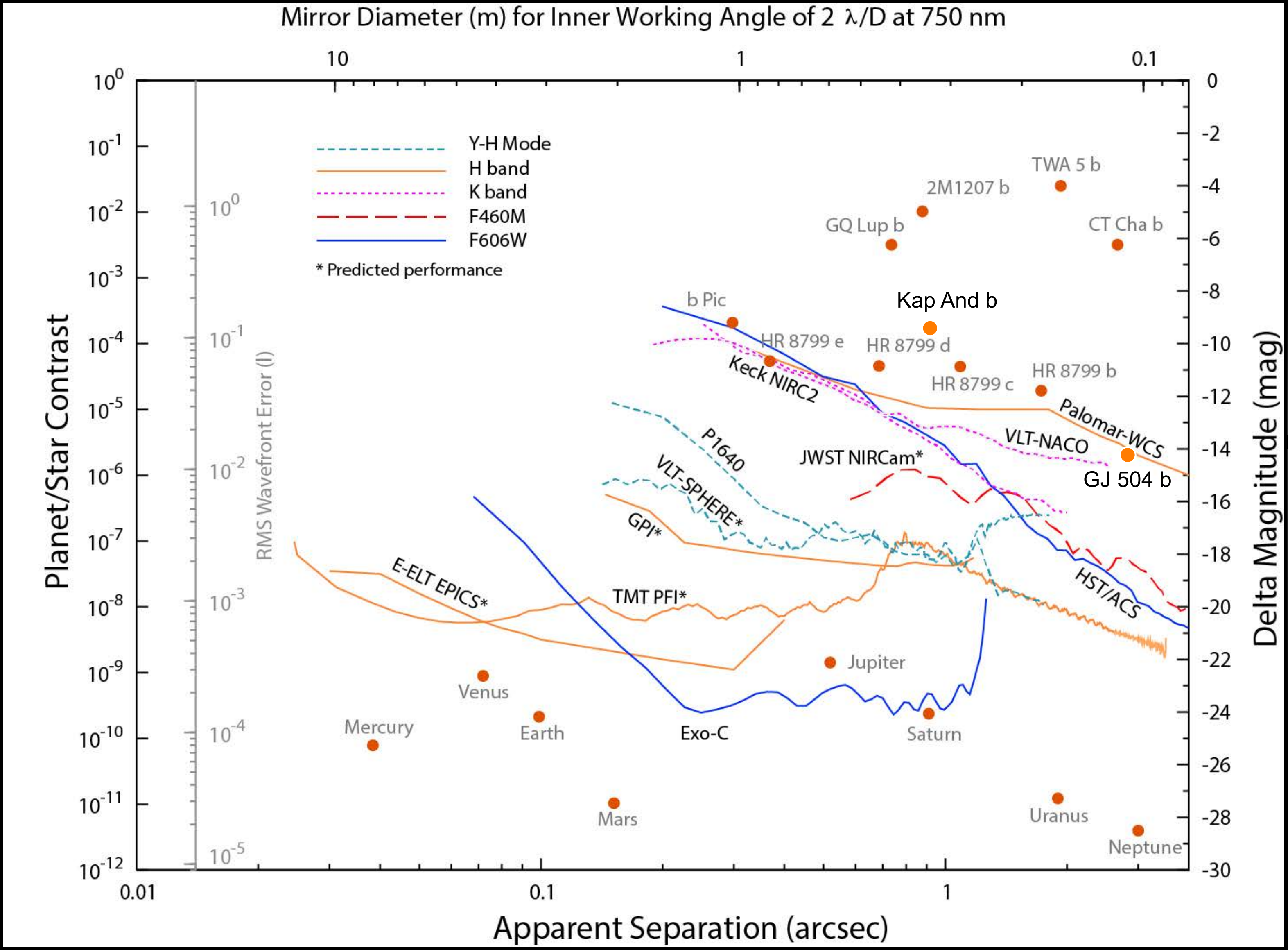
*See Morley talk at this conference

See Exo-C STDT Interim Report

Preliminary High Contrast IFS Instrument Requirements on the Ground and in Space

Specification	Subaru/CHARIS	HCIT/PISCES	Exo-C/IFS	AFTA-C/ACES	ATLAST/AEGIS
Spatial Sampling	2x at 1.15μm 15mas	3x at 0.60μm	2x at 0.40μm 36mas	3x at 0.60μm 41mas	2x 0.50 μm?
Field of view	133 x 133 2"x2"	76x76 25λs/D x 25λs/D	76x76 2.2"x2.2"	76x76 TBR	TBR
Spectral Resolution	20, 75	70	70	70	100-500
Instantaneous Spectral Bandpass	20%, 70%	18%	18%	18%	TBR
Instrument Spectral Bandpass	1.15-2.40μm	0.60-0.97μm	0.40-1.00 μm	0.60-0.97 μm	0.3-2.5μm
Spectrophotometric Precision	0.06 mag (5%)	0.06 mag (5%)	0.06 mag (5%)	TBR	TBR
Astrometric Precision	3 mas	TBR	TBR	TBR	TBR

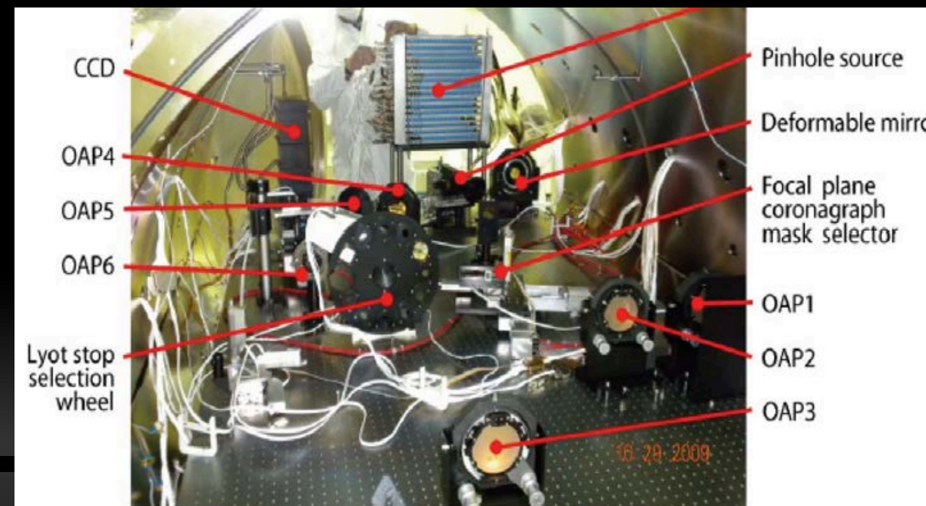
High Contrast Imaging Snapshot



See Exo-C STDT Interim Report

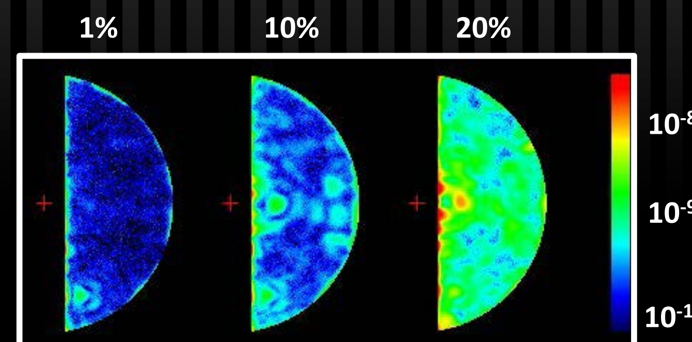
Status of High Contrast Imaging Technology Demonstrations: Coronagraphs I

- Several coronagraph testbeds throughout the NASA community, including JPL (HCIT I, HCIT 2, APEP), Goddard/VNC, Ames/ACES, Princeton/HCIL
- HCIT is the standard for non-VNC demonstrations – Ames/ACES and Princeton/HCIL demonstrate technologies before ExEP HCIT
- Goddard/VNC and JPL/APEP are standalone laboratories since their architecture is different.



JPL HCIT

Xinetics Deformable Mirror

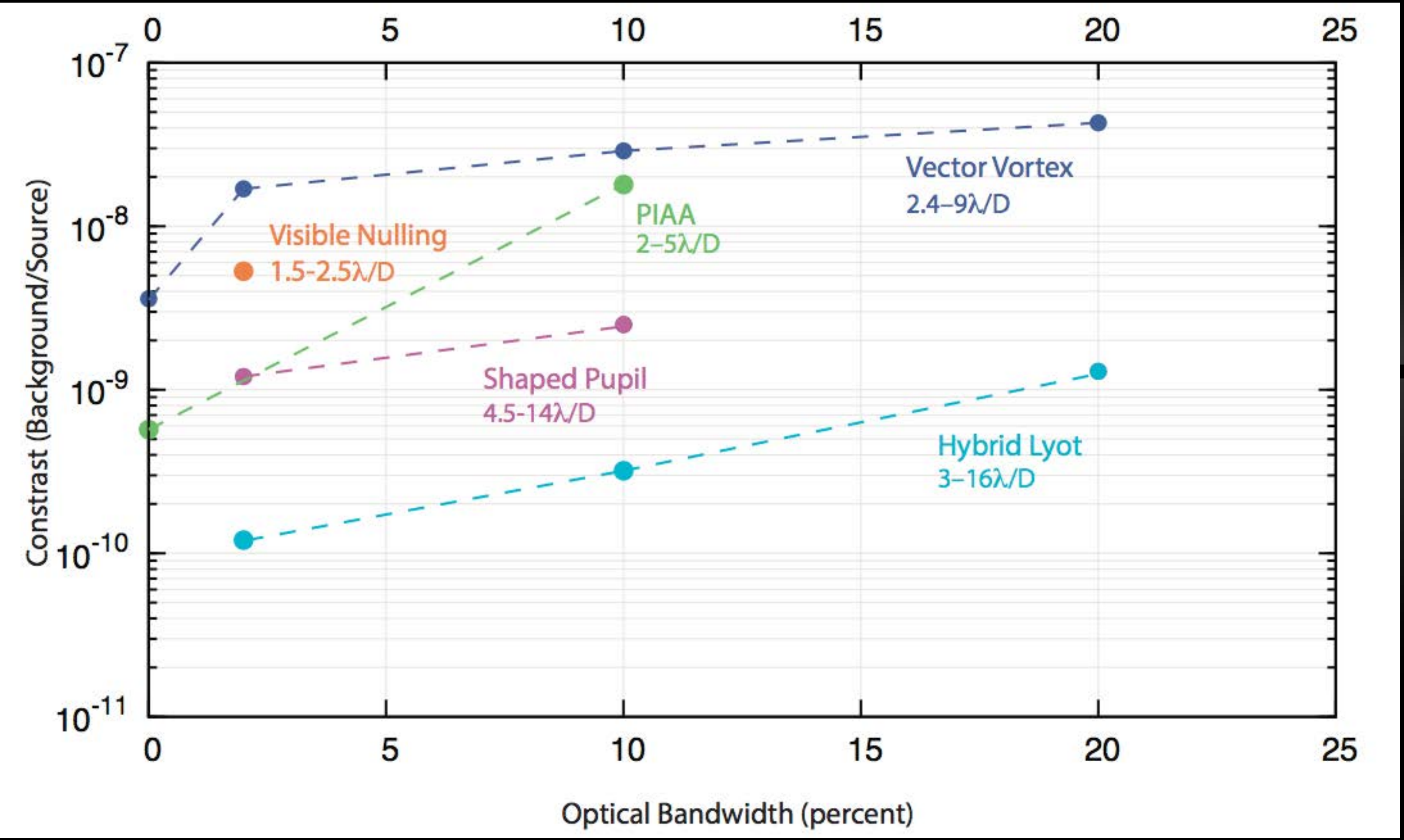


HCIT Demonstration

*See Poberezhskiy talk at this conference

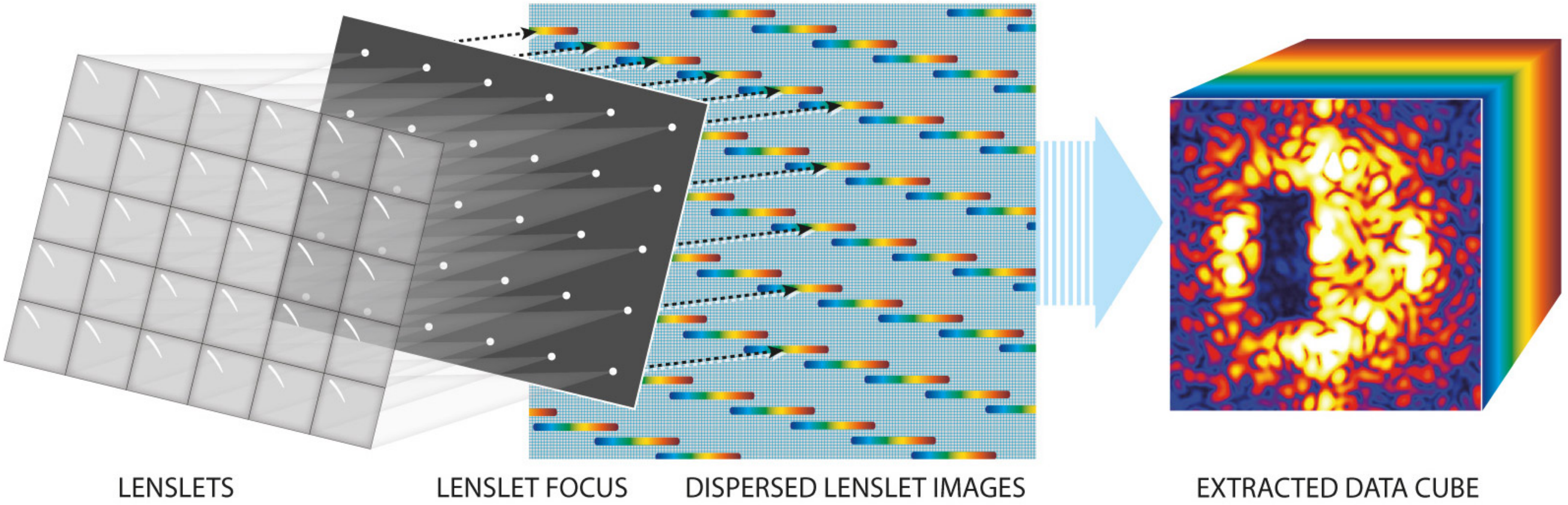
See Exo-C STDT Interim Report

Status of High Contrast Imaging Technology Demonstrations: Coronagraphs II

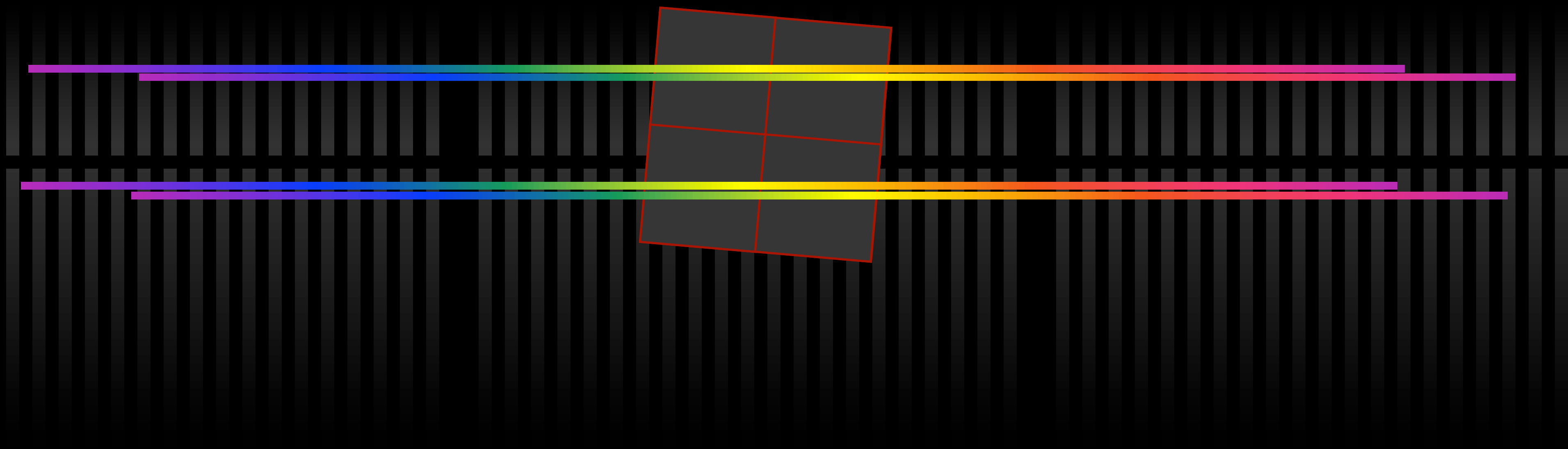


ExEP 2014 Technology Plan

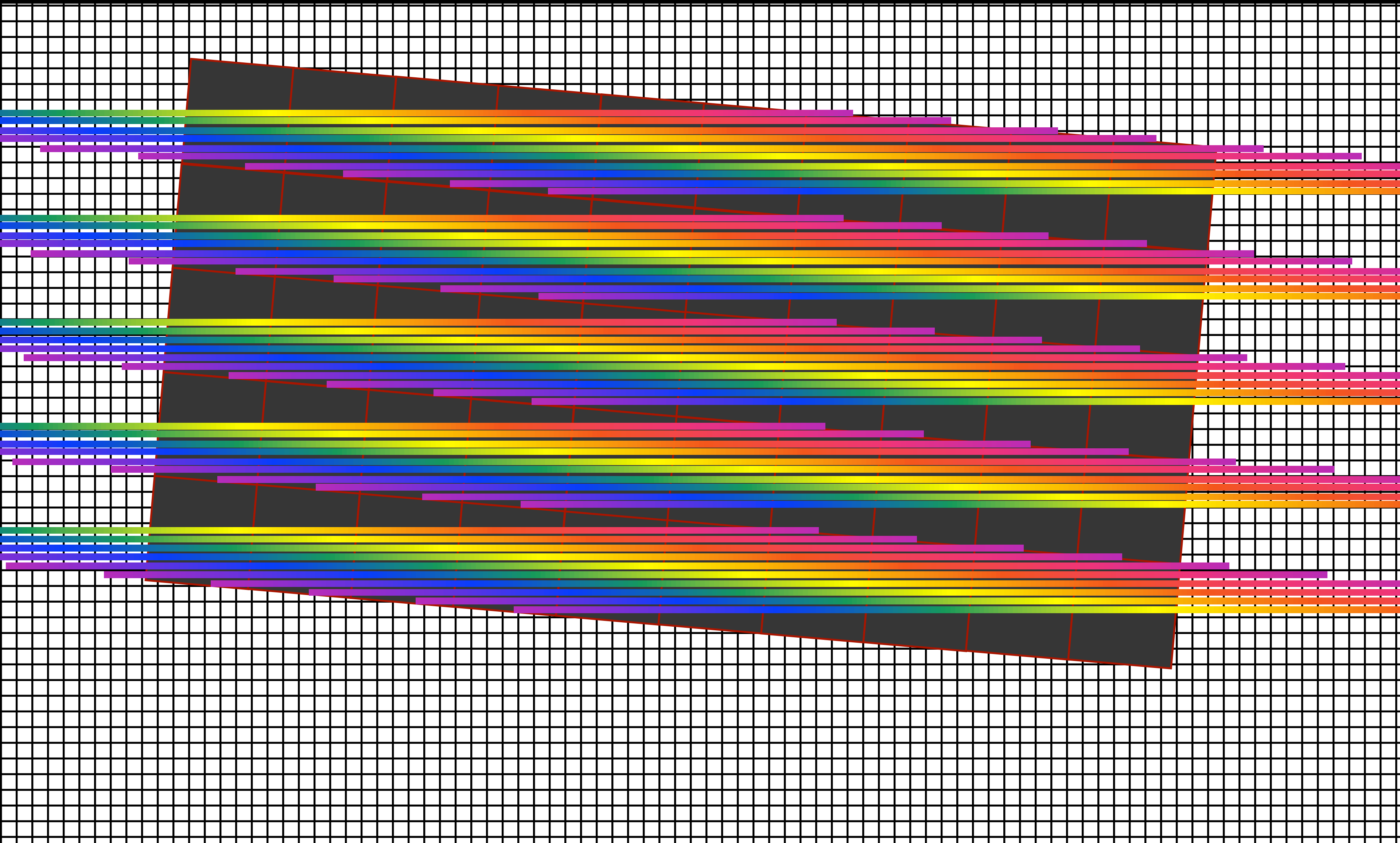
How an Integral Field Spectrograph Works



Dispersing Lenslet Spots



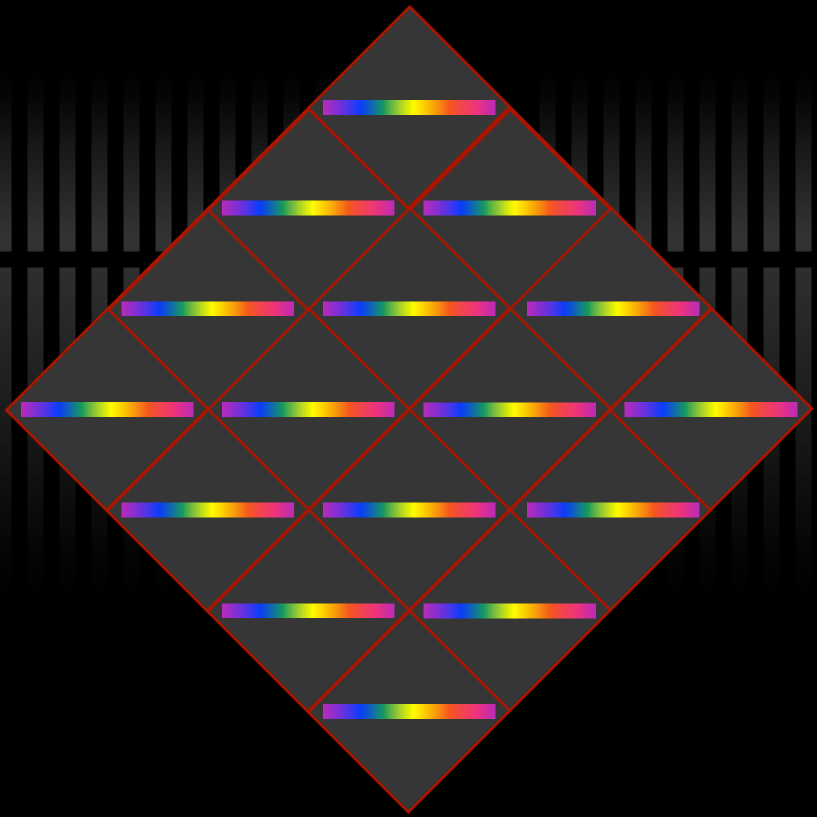
Dispersing Lenslet Spots



IFS Optical Relationships

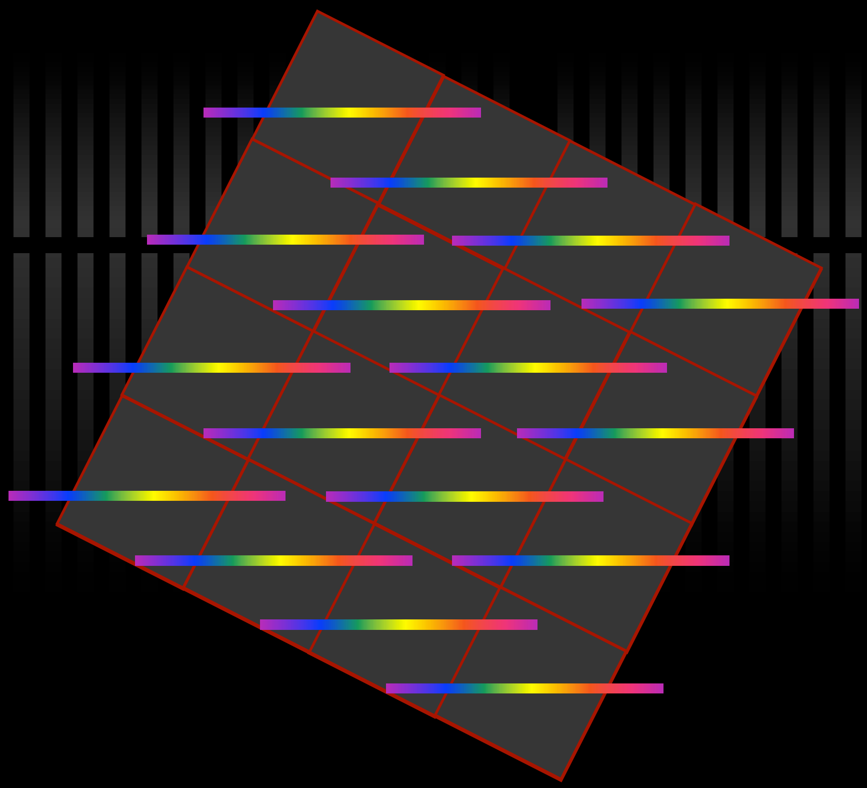
- ***λ=wavelength of interest in microns***
- ***D=Telescope diameter in microns***
- T=Telescope paraxial focal length at the lenslet array in microns
- F=Effective paraxial focal ratio at the lenslet array (F=T/D)
- θ_{diff}=Diffraction limited angular resolution
- ι = Lenslet pitch in microns
- f=Lenslet focal length in microns
- Ψ=Lenslet focal ratio (Ψ=f/ι)
- θ=Angular sampling of the lenslet array in radians on the sky
- d=diffractive lenslet spot diameter produced by the lenslet in microns
- s=Sampling ratio of the lenslet compared to the diffraction limit (s=2 implies Nyquist sampling)
- ***q=Detector pixel pitch in microns***
- ***L=Length of each spectrum in pixels***
- ***w=Center-to-center spacing of neighboring spectra perpendicular to the dispersion axis in pixels***
- F=Focal ratio at the detector
- ***A=Detector array width in pixels***
- R=Spectral resolution (λ/Δλ)
- B=Spectral bandwidth of each full spectrum (Δλ/λ)
- N=Number of spatial samples along each axis
- V=One dimensional field of view

Interlacing 1: More Spatial Samples but Shorter Spectra



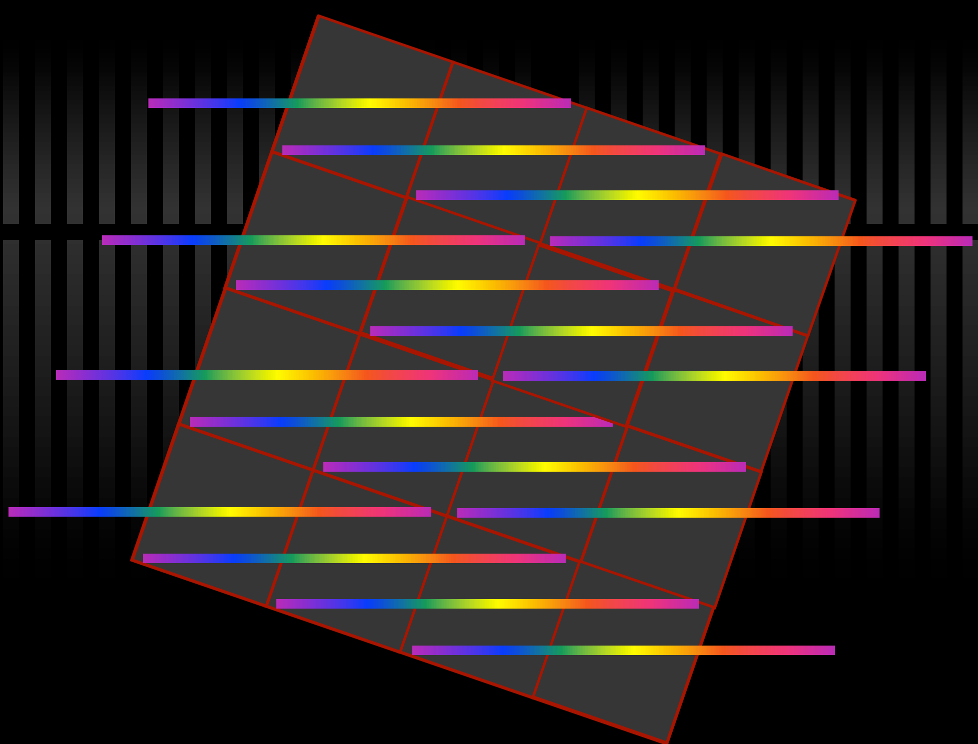
Parameter	Value
Lenslet pitch	110 microns
Lenslet Rotation	45.0 deg
Spectral Length	8 pix
Gap between spectra	4
Gap perpendicular between spectra	≥ 5
Field of view	120 x 120 lenslets assuming 13.3 mm detector

Interlacing 2: Fewer Samples and Longer Spectra



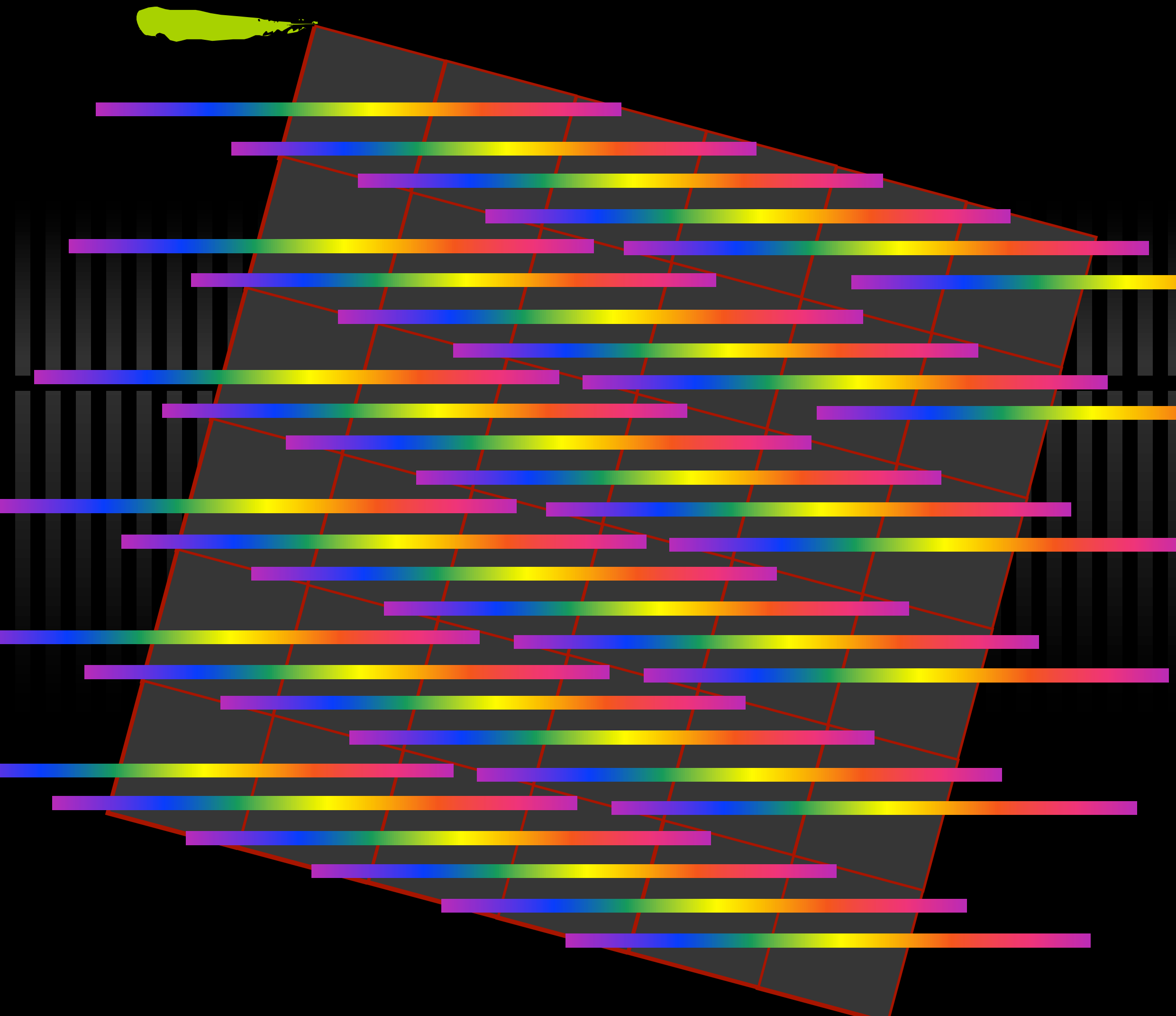
Parameter	Value
Lenslet pitch	174 microns
Lenslet Rotation	26.6 deg
Spectral Length	26 pix
Gap between spectra	4
Gap perpendicular between spectra	≥ 5
Field of view	76 x 76 lenslets assuming 13.3 mm detector

Interlacing 3: Even Fewer Samples and Even Longer Spectra



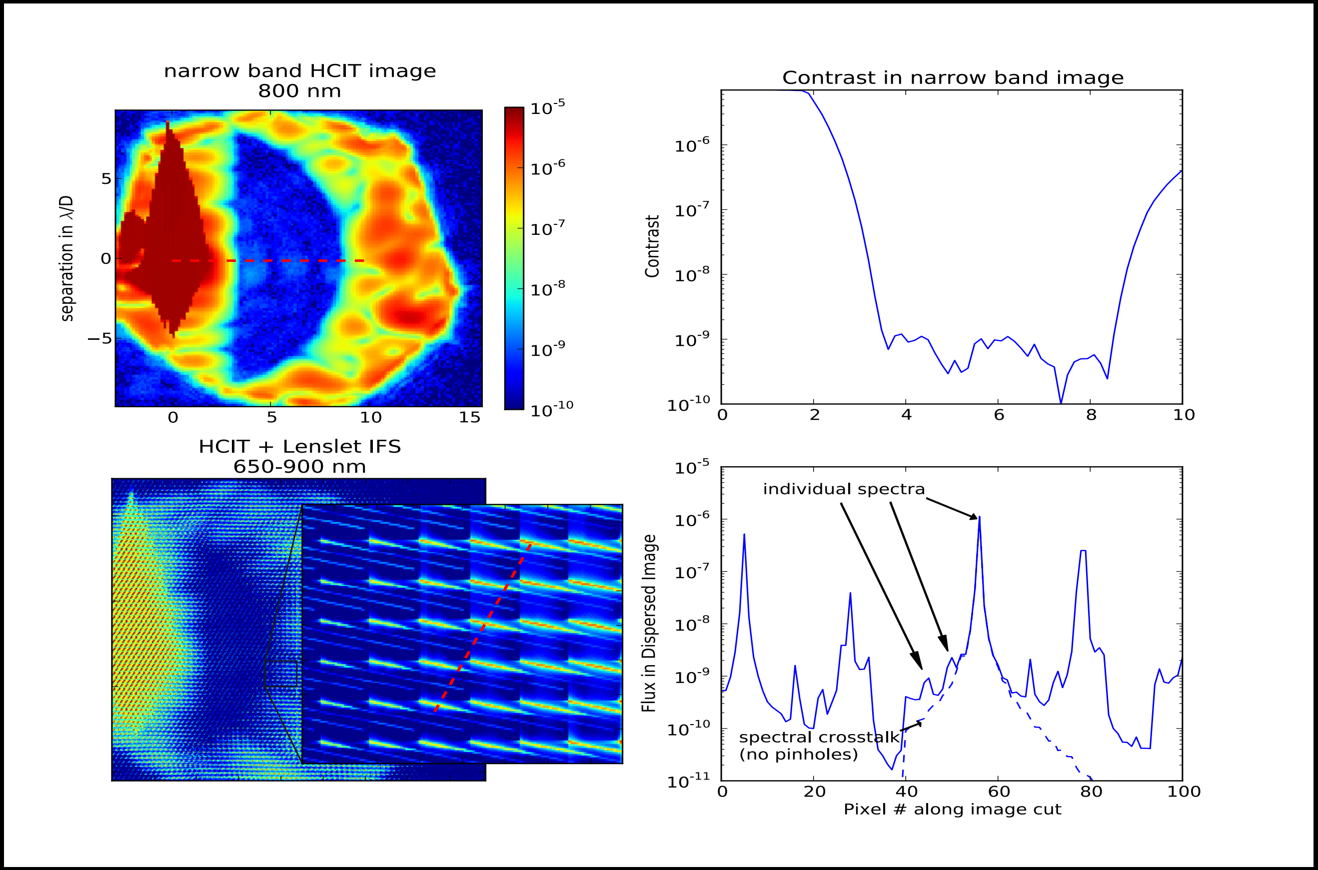
Parameter	Value
Lenslet pitch	244 microns
Lenslet Rotation	18.4 deg
Spectral Length	56 pix
Gap between spectra	4
Gap perpendicular between spectra	≥ 5
Field of view	54 x 54 lenslets assuming 13.3 mm detector

Interlacing 4: Even Fewer Samples and Even Longer Spectra



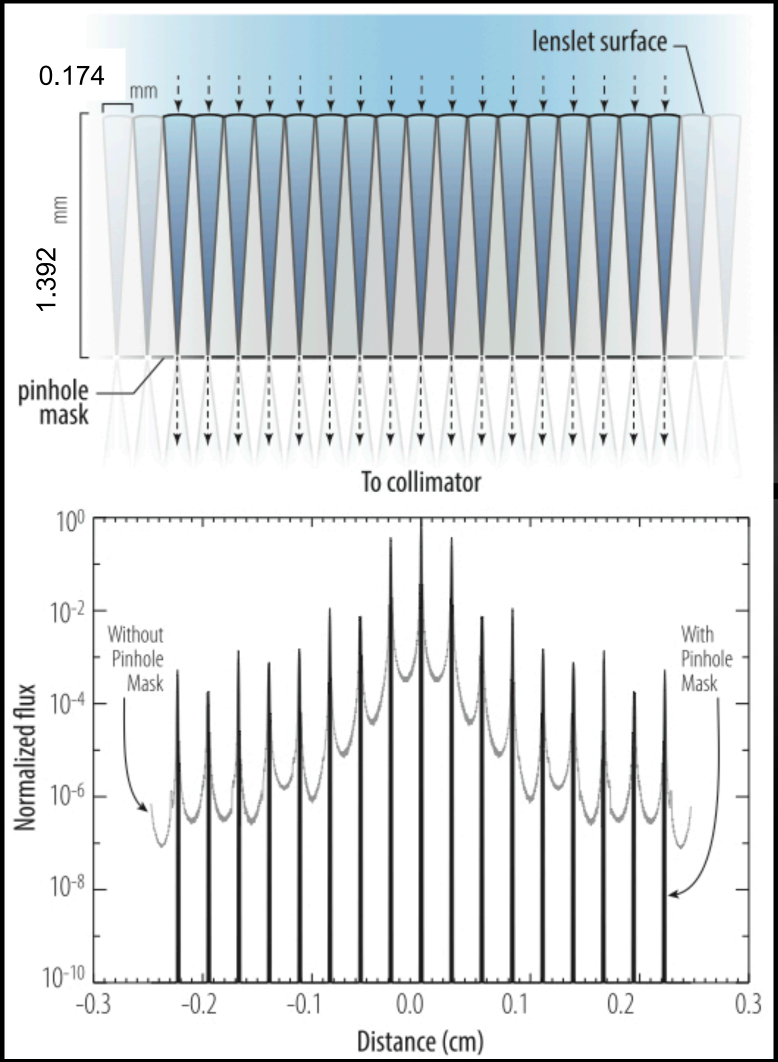
Parameter	Value
Lenslet pitch	322 microns
Lenslet Rotation	14.0 deg
Spectral Length	98 pix
Gap between spectra	4
Gap perpendicular between spectra	≥ 5
Field of view	41 x 41 lenslets assuming 13.3 mm detector

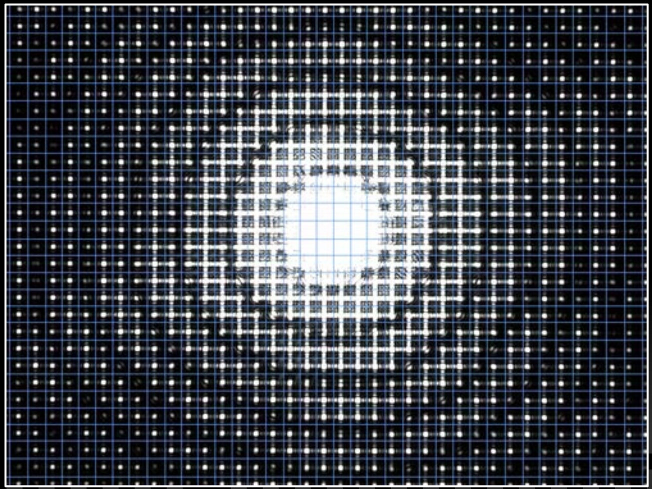
Spectral Crosstalk on Detector

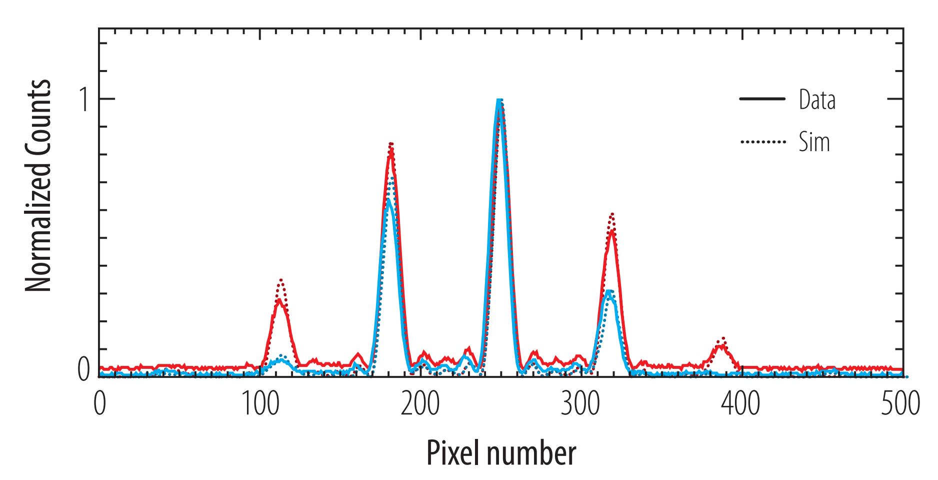


McElwain, M., Perrin, M. D., Gong, Q. et al., 2013, Proc of the SPIE, 8864

High Contrast Lenslets Reduce Crosstalk

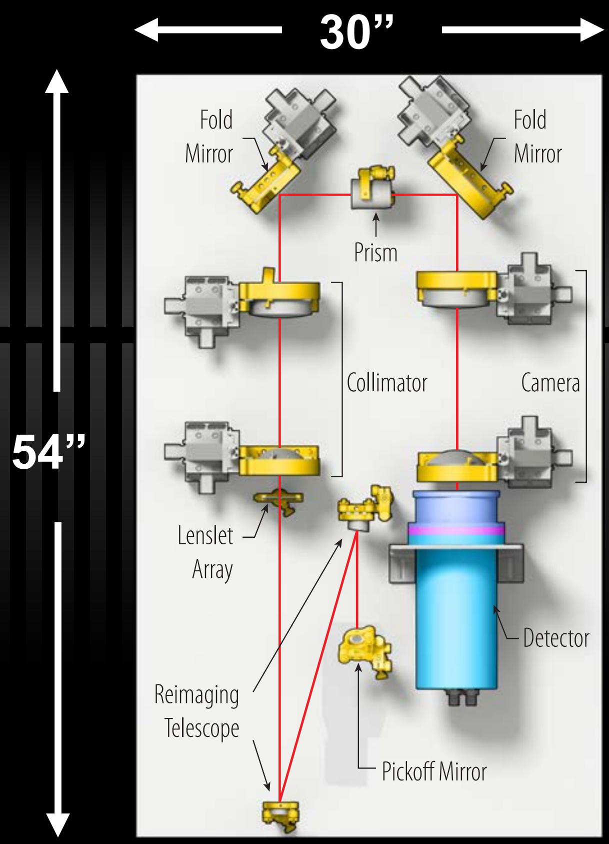


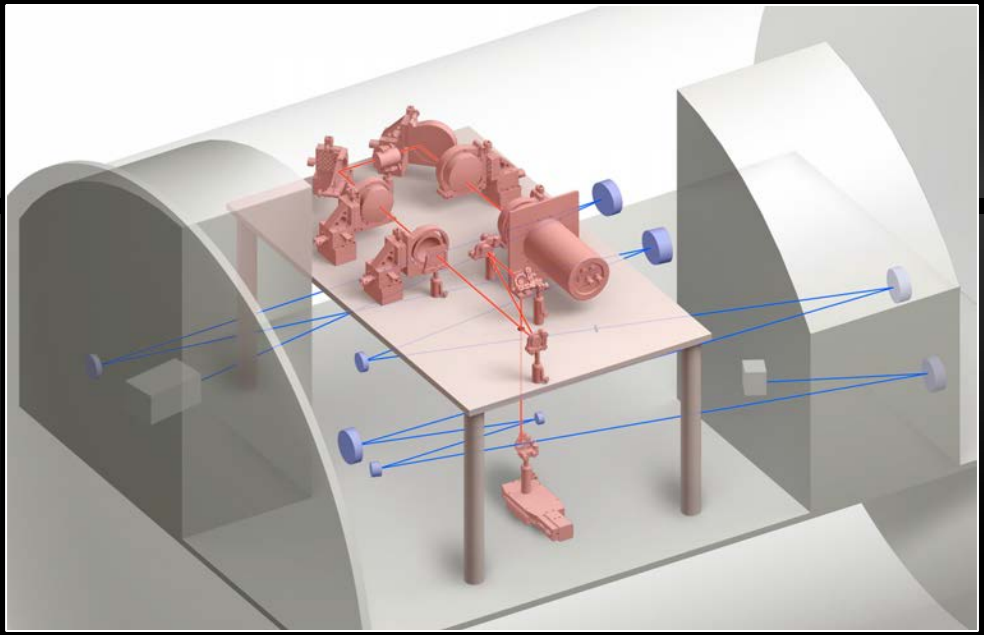




McElwain, M., Perrin, M. D., Gong, Q. et al., 2013, Proc of the SPIE, 8864
Contract in place with Jenoptik to procure a high contrast lenslet

PISCES: Roman Technology Fellowship Critical Design





FY12 GSFC IRAD: Development of an Integral Field Spectrograph to Advance High Contrast Imaging Technologies
2012 Roman Technology Fellowship Concept Study
2013 Roman Technology Fellowship Development Effort

High Contrast IFS Challenges

- High contrast lenslet array
  - Ghosting effects
- Wavefront sensing and control techniques
- Post processing speckle suppression techniques
  - Point source coherence testing
  - Speckle aliasing
- Calibration
  - Flat fielding
  - Wavelength calibration
- Chromatic effects when covering a large bandpass
- Detector properties (Read Noise, Dark Current, Traps, Charge Transfer Efficiency, Radiation Damage, etc.)

The End