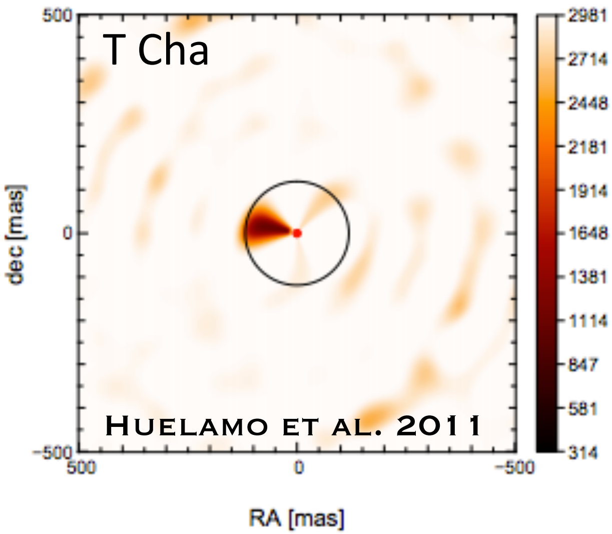
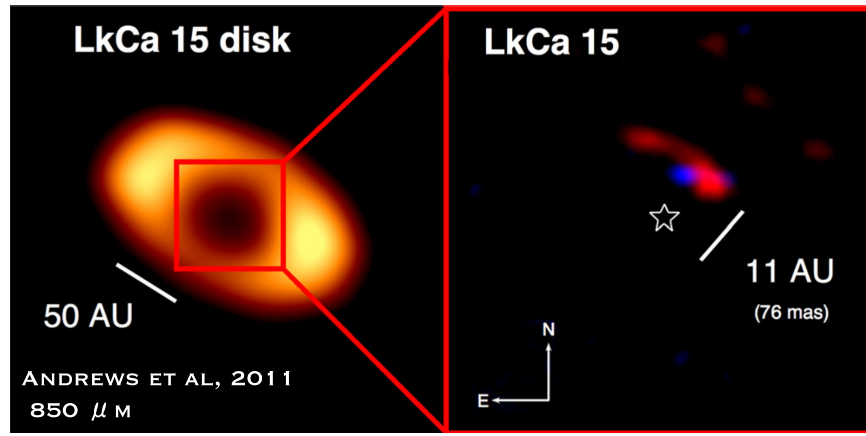
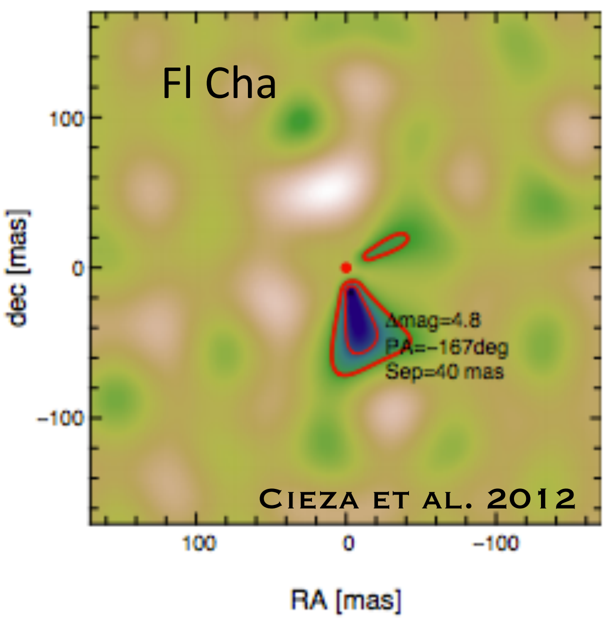
POP: Inside the gap with NRM

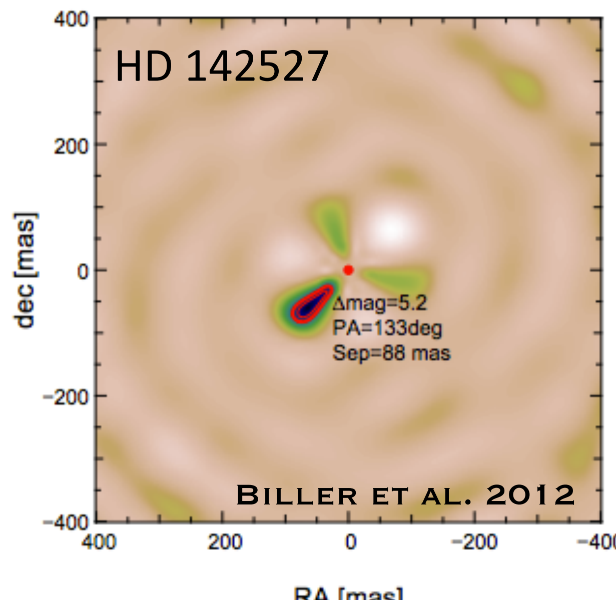
Alexandra Greenbaum
Johns Hopkins University





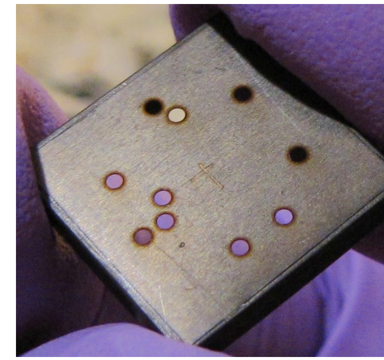
Kraus & Ireland 2012





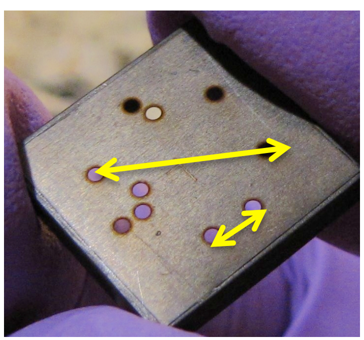
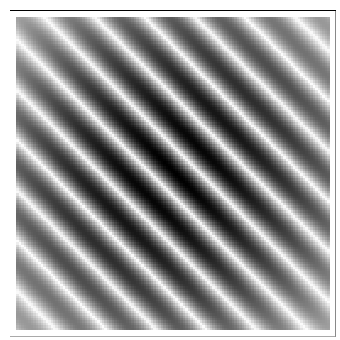
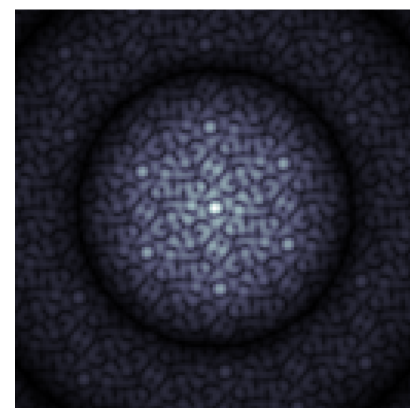
Inside the gap with NRM

NRM – **Non-Redundant mask interferometry**
Splits up the pupil into a set of unique baselines to measure interference fringes



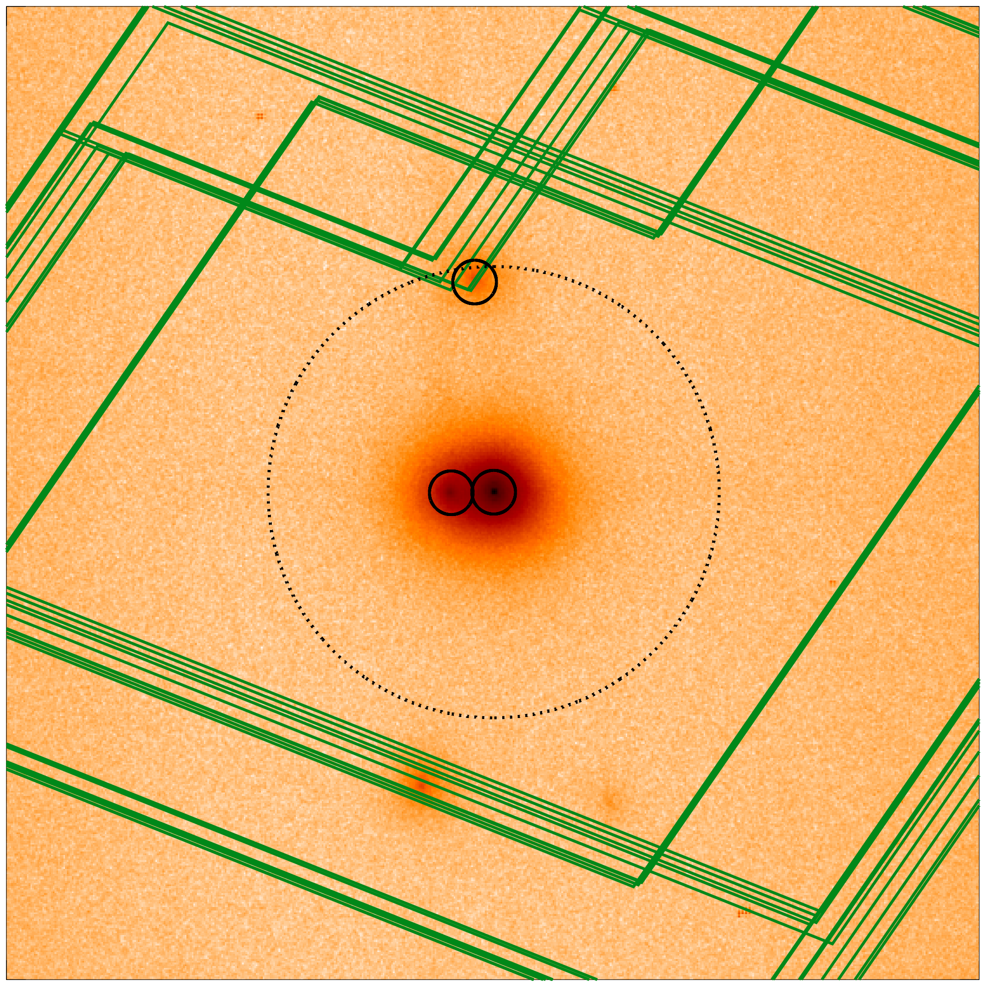
GPI 10-hole mask

- 0.5 λ/D resolution (~ 30 mas in GPI H band)
- **Interferometric technique**, pushes a more aggressive inner working angle

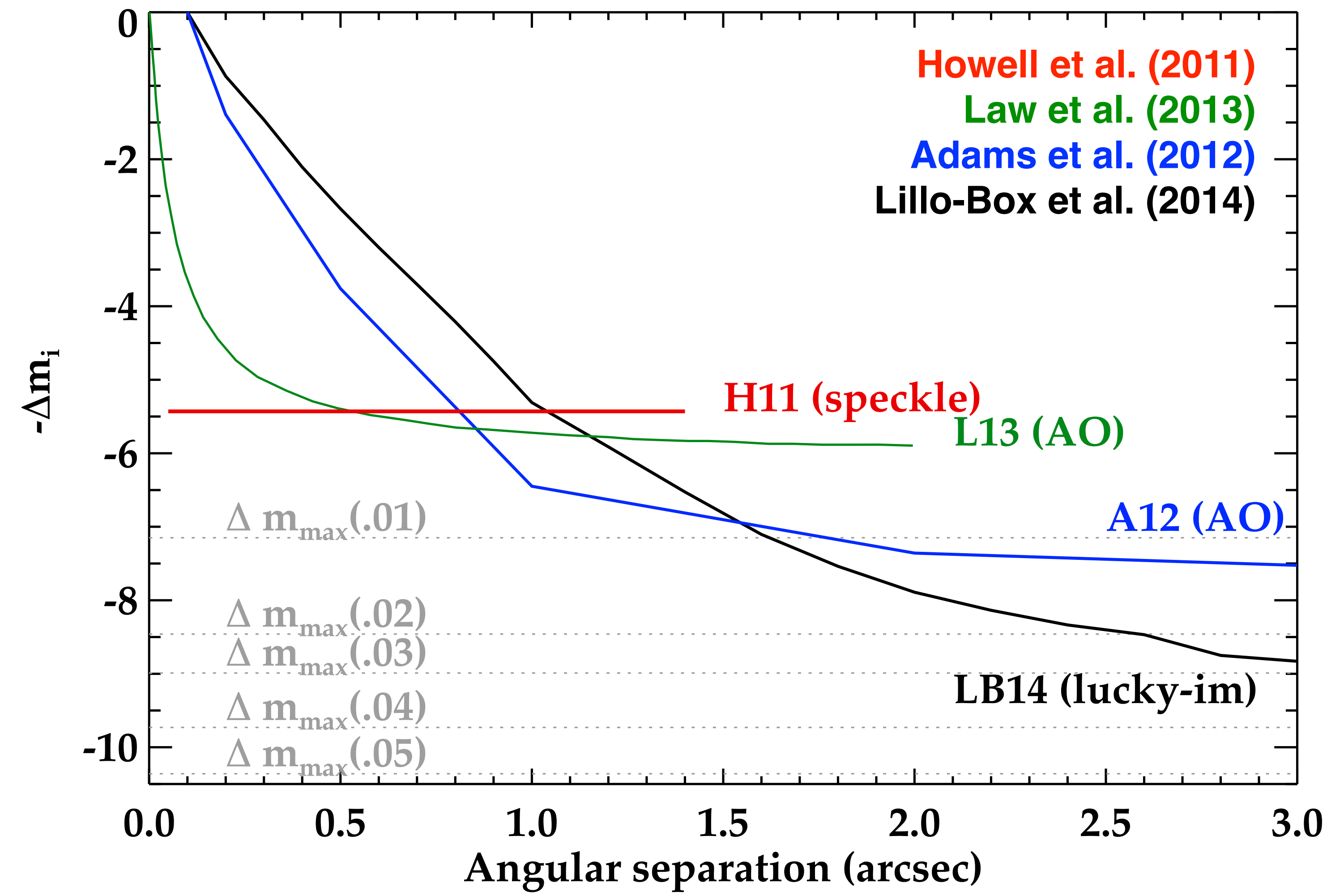
$\sum$  $\rightarrow$ $\sum$  $=$ 

- Probes contrasts down to $10^2 – 10^3$ @ 5-15 AU scales
- Excellent tool for studying planet formation

Blended Source Confidence: a framework to compare high-spatial resolution techniques



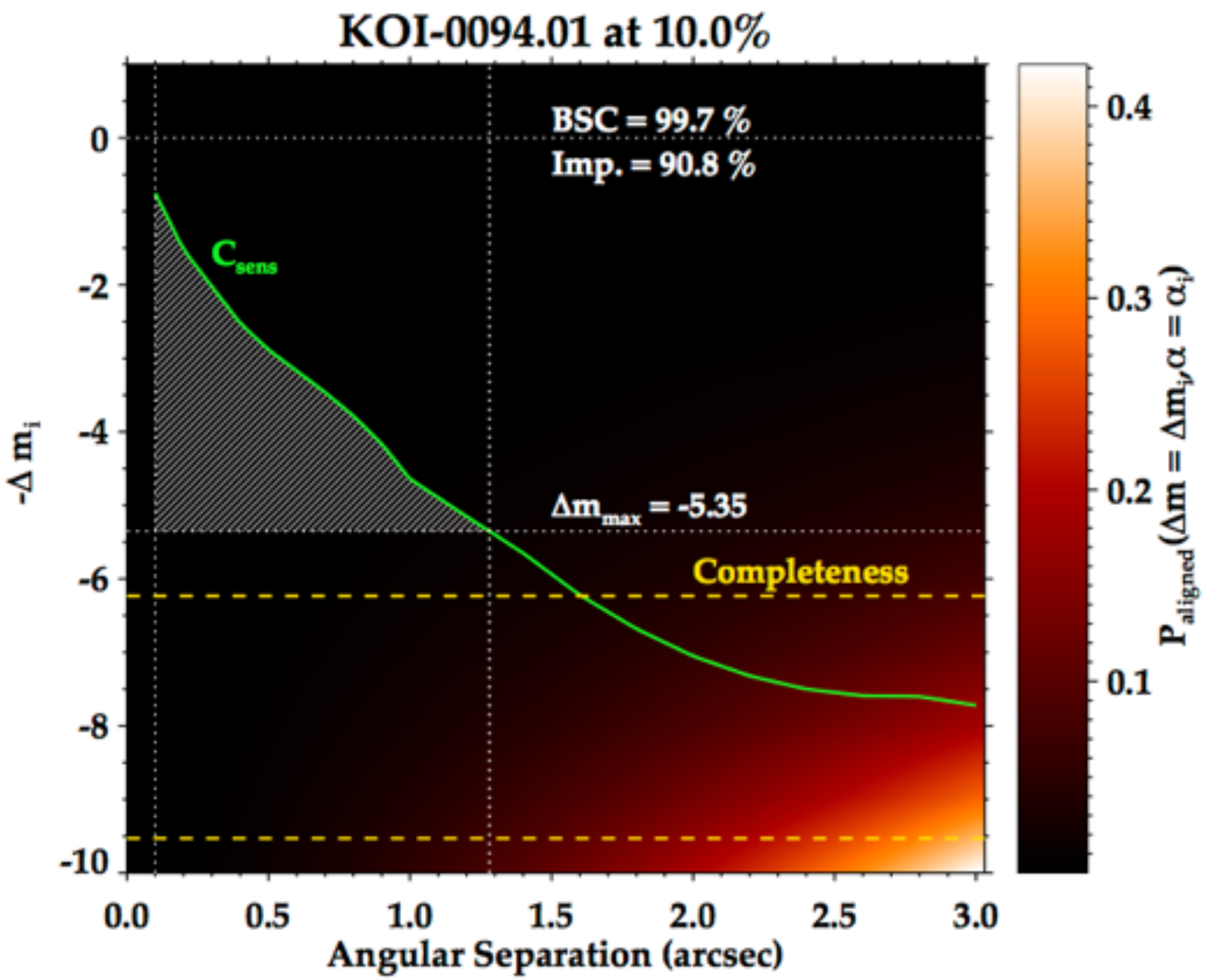
High-resolution image of KOI-1546 obtained with AstraLux at Calar Alto Observatory (Almería, Spain).



Sensitivity curves for the candidate planetary system KOI-0082 obtained with different techniques.

High-resolution follow-up observations of planet candidates are crucial in the confirmation process. An exhaustive analysis of these images is necessary to quantify how they improve the quality of the candidate. The **Blended Source Confidence (BSC) parameter** provides this **quantification** and allows **comparison** between different techniques.

Blended Source Confidence: a framework to compare high-spatial resolution techniques



Lillo-Box et al. (2014)

$$P_{BS,0} = \int_{0''}^{3''} 2\pi\alpha\rho(b, m_i, \Delta m_{max})d\alpha =$$

$$= 9\pi\rho(b, m_i, \Delta m_{max})$$

Density of stars with magnitudes between **m** and **m+Δm** at galactic latitude **b**

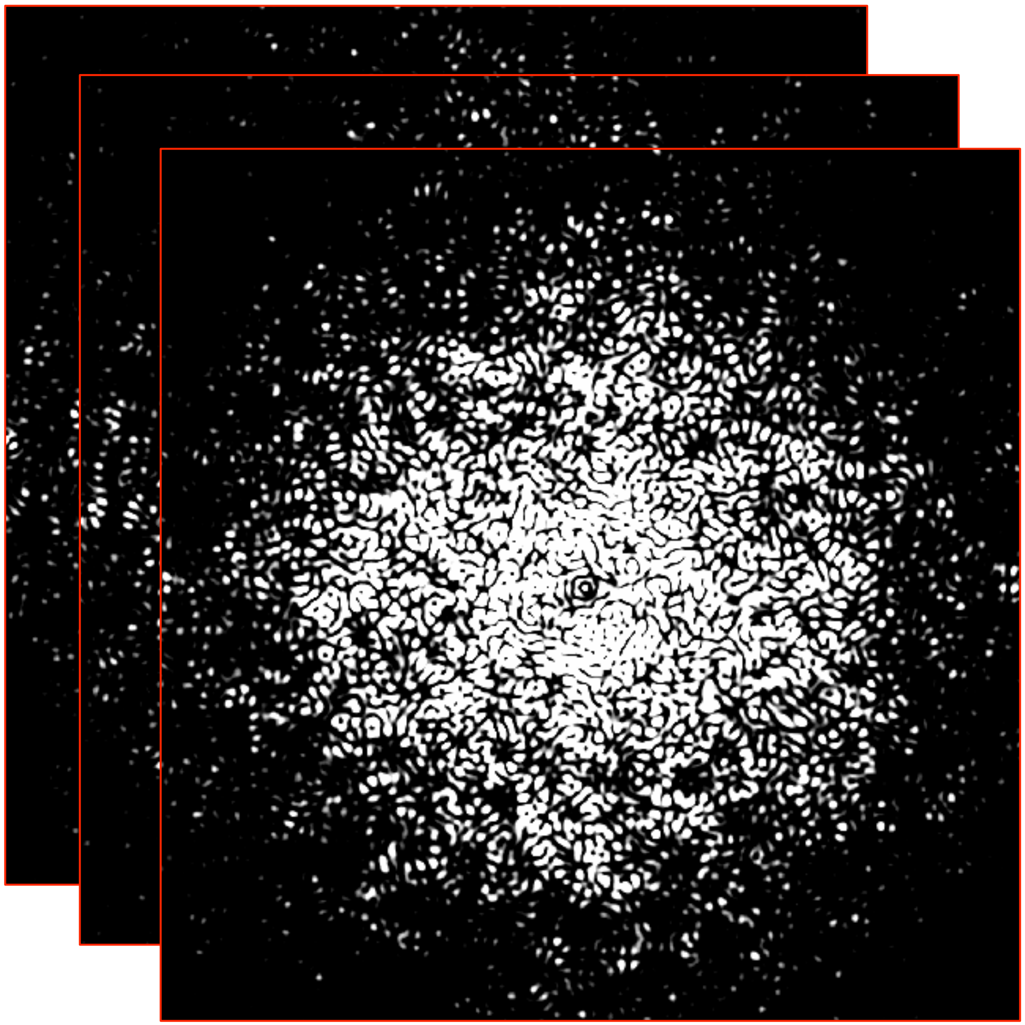
$$P_{BS} = P_{BS,0} - \int_{0''}^{3''} 2\pi\alpha \times \rho[b, m_i, \Delta m_0(\alpha)]\, d\alpha$$

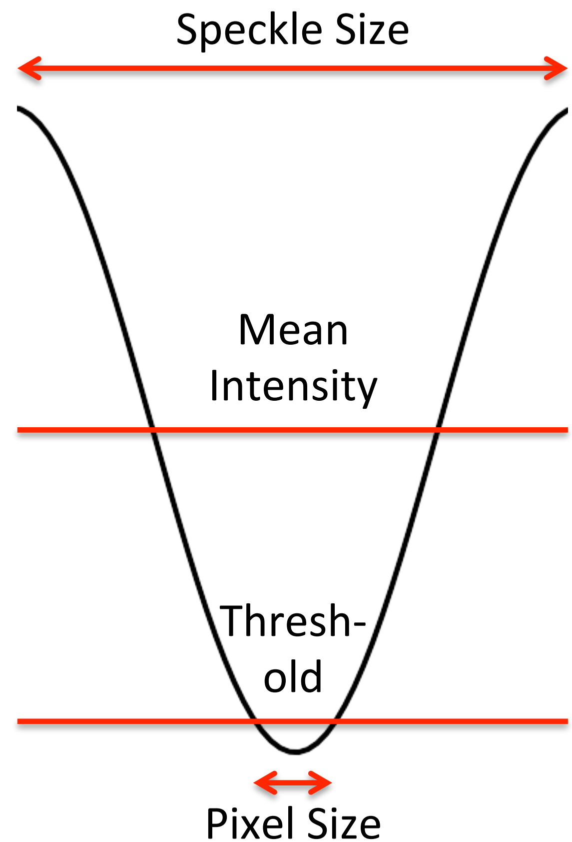
Now we remove the region where our high-resolution images have not detected any companion from the $\mathbf{P_{BS,0}}$.

$$\boxed{BSC = 1 - P_{BS}}$$

The BSC is an easily computable parameter given the sensitivity curve of a high-resolution image so that different methods can be compared. In **Lillo-Box et al. (2014)**, we have obtained it for the 301 *Kepler* candidates observed with lucky imaging, improving the probability of being isolated in more than 50% for the 62% of the studied candidates. Comparison to other works show that **our optical high-resolution survey combines a large number of observed sources with a high quality of the observations**, reflected in the low BSC obtained for most of them.

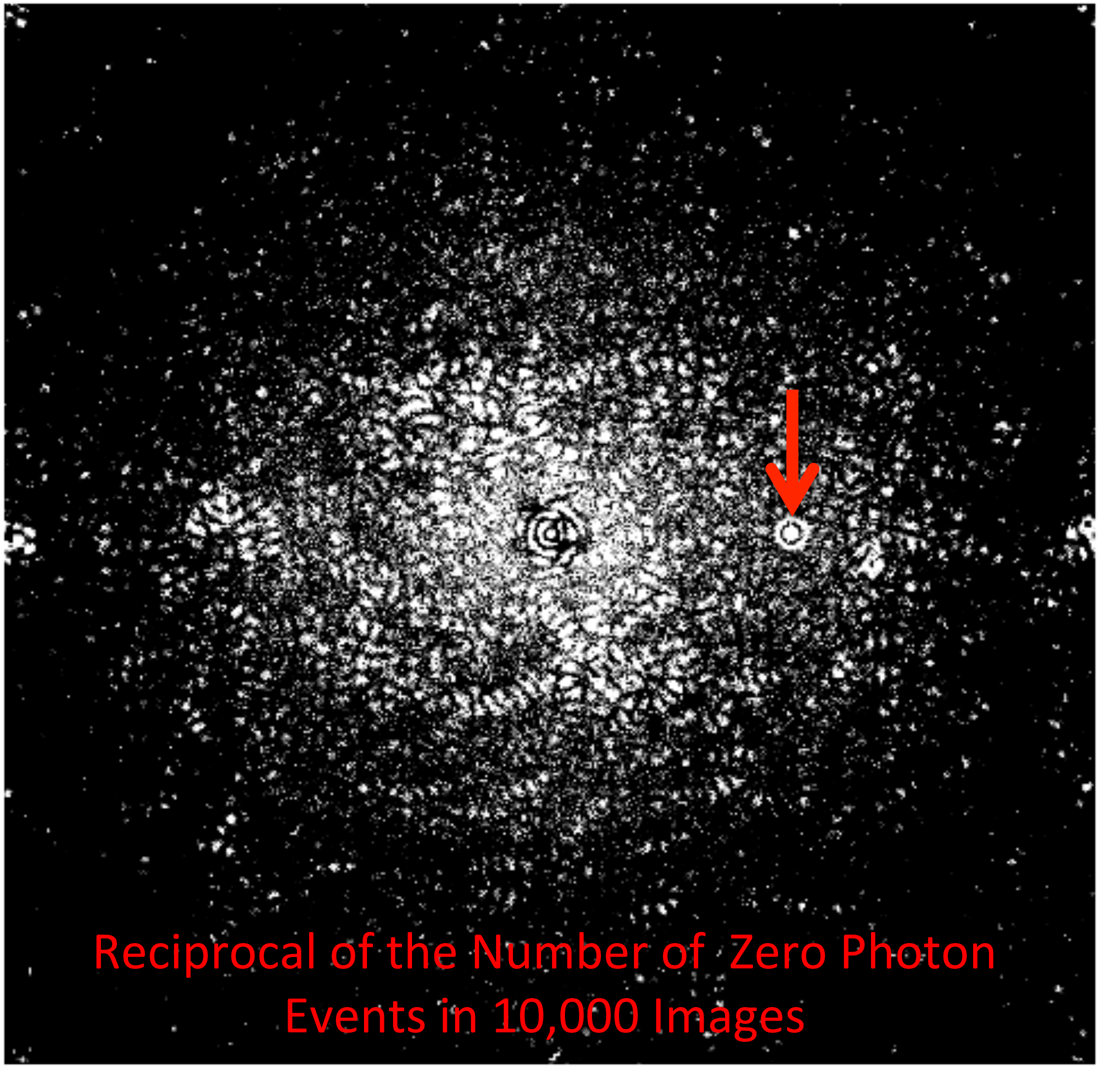
Dark Speckle Statistics





See Labeyrie 1995 and Boccaletti et al 1998

The DS Method Requires a Photon Counting Detector



Low Background Counts
Fast Exposures
Small Pixels

- **Detector:** Microwave Kinetic Inductance Detectors (MKIDS)
- **AO:** PALM-3000 at Palomar 200”
- **Coronagraph:** P1640 and SDC

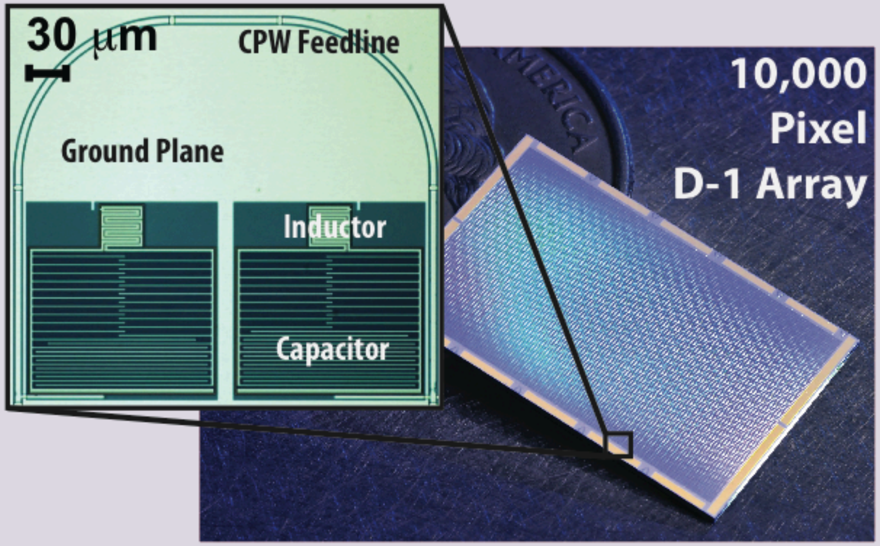
DARKNESS: A MKID based IFS for high-contrast imaging at Palomar

MICROWAVE KINETIC INDUCTANCE DETECTORS

- Operating principle[1]: photons break Cooper pairs in lithographed superconducting resonator. Broken Cooper pairs -> Inductance shift -> Resonance shift -> Phase shift in readout tone

- **Measures individual photon arrival times to few μs and photon energy to ~10%**

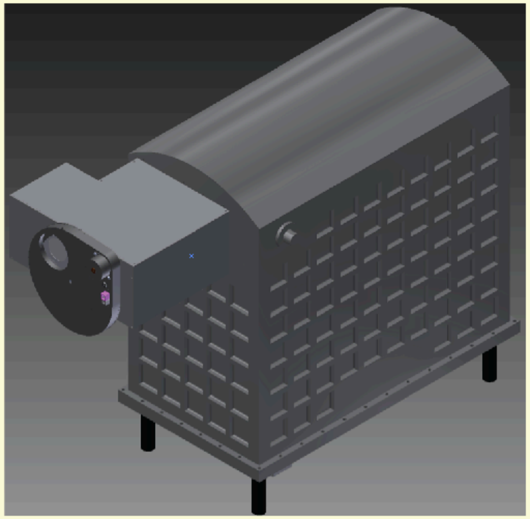
- **Optimized for 0.7-1.4 μm photons for DARKNESS**

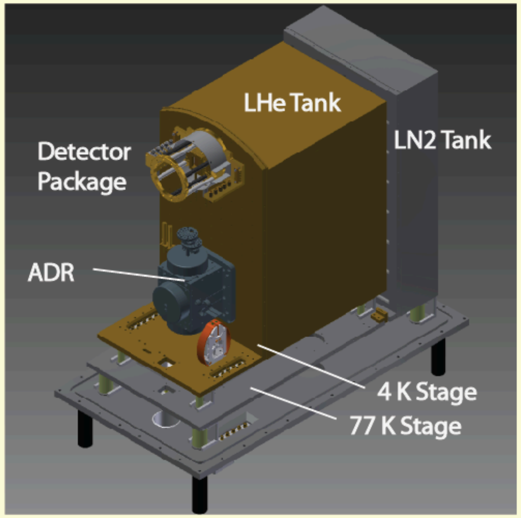


MECHANICAL DESIGN

- LN2/LHe pre-cooled Adiabatic Demagnetization Refrigerator: **Operating temperature = 100 mK**

- Dewar fits PHARO envelope for easy **integration with Palm-3000 AO system, Project 1640 coronagraph, and Stellar Double Coronagraph (SDC)**



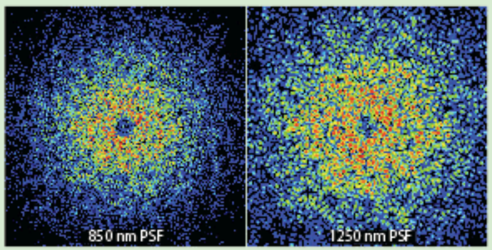


DARKNESS: A MKID based IFS for high-contrast imaging at Palomar

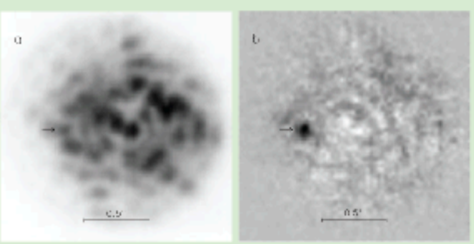
SIMULATED PERFORMANCE

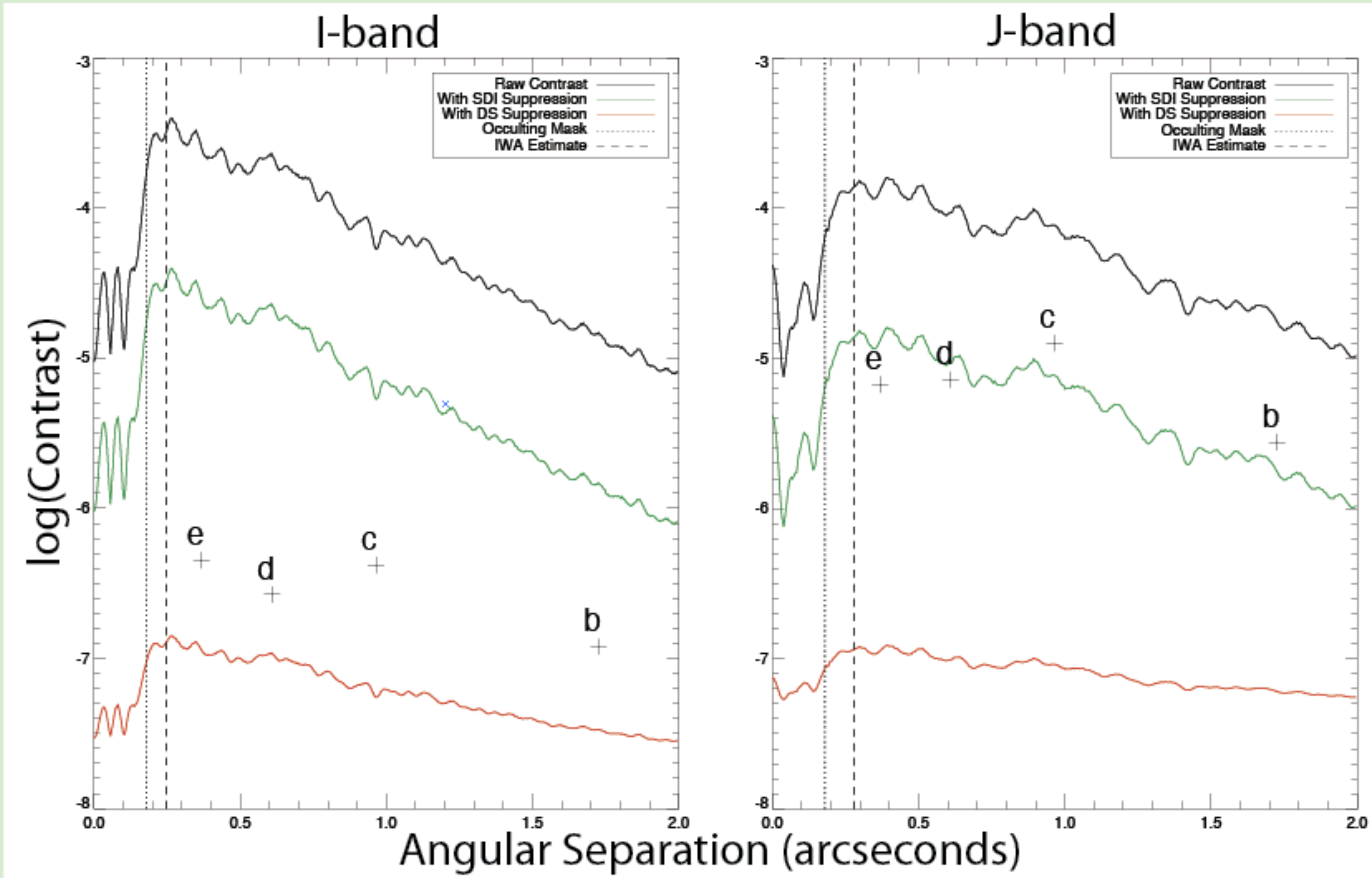
- Project 1640 simulated with PROPER
- Includes residual WFE from P3K AO and P1640 optical aberrations

- Energy Resolution -> post processing with **Spectral Differential Imaging (SDI)**



- Photon Counting -> post processing with **Dark Speckle Imaging (DS)**

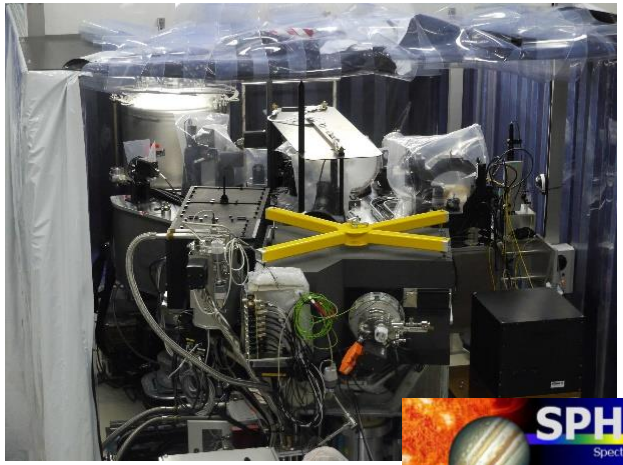




STORY OF A NEW METHOD …

CONTEXT

- PhD
- From September 2009 to December 2012
- Two laboratories ONERA & IPAG



IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

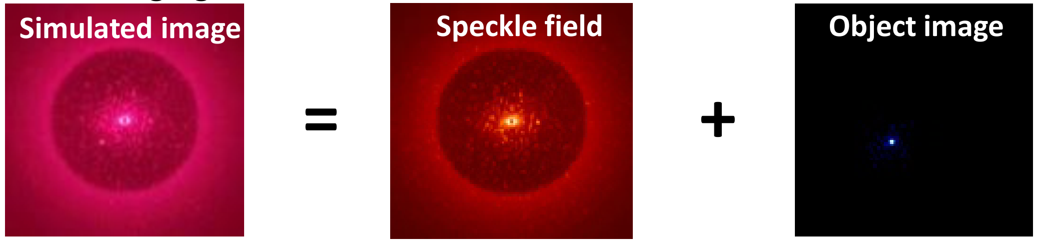
SPHERE
Spectro-Polarimetric High-contrast Exoplanet REsearch

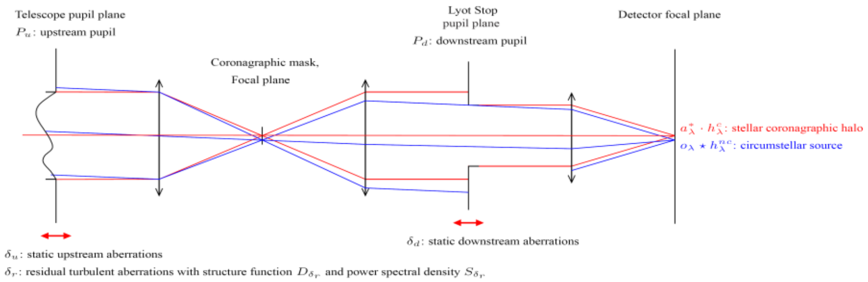
ONERA
THE FRENCH AEROSPACE LAB

PEOPLE

IDEA

- Spectral « deconvolution » **[Sparks and Ford, 2002]**
- + imaging model **[Sauvage et al., 2010]**



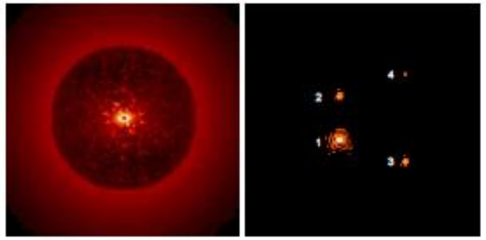


A NEW METHOD IS BORN

- Evolutive method:
  - Diverse type of instruments
  - Diverse type of objects (planets, disks, brown dwarfs …)
  - Detection and characterization
  - Combination of spectral and temporal information possible
- All-in-one method:
  - Joint estimation of aberrations and object of interest: paves the way for calibration by post-processing
- Joint design

THE STORY CONTINUES …

RESULTS



(a) Simulation.

(b) Joint estimation.

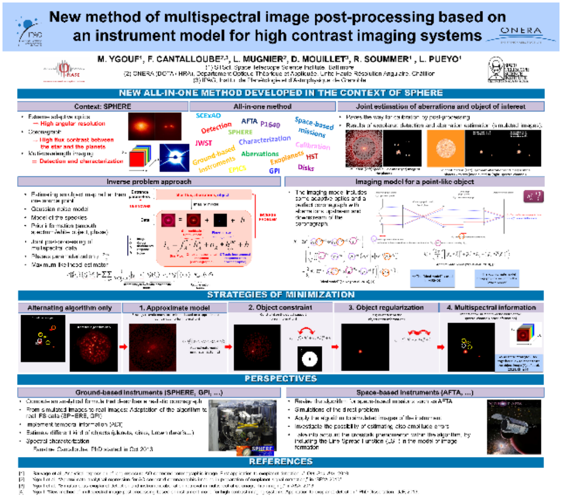
NEW HORIZONS

- Post-doc - Marie Ygouf
  - From September 2014
  - STScI
  - AFTA project
- Second PhD - Faustine Cantalloube
  - From September 2013
  - Two laboratories ONERA & IPAG
  - See Faustine's POP & Poster

FOR MORE INFORMATION ABOUT..

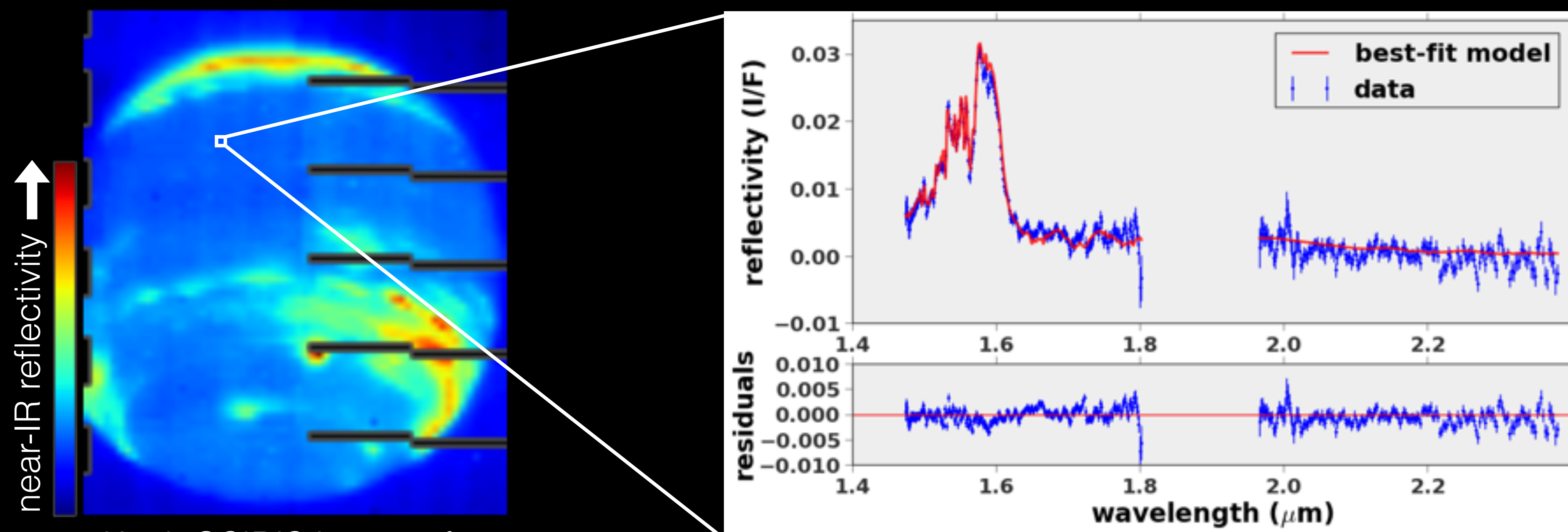
- The model used
- The criterion we minimize
- Strategies of minimization
- Perspectives
- References

SEE MY POSTER!



A retrieval approach to modeling giant planet spectra

Statia H. Luszcz-Cook[1], M. Ádámkovics[2], K. de Kleer[2]



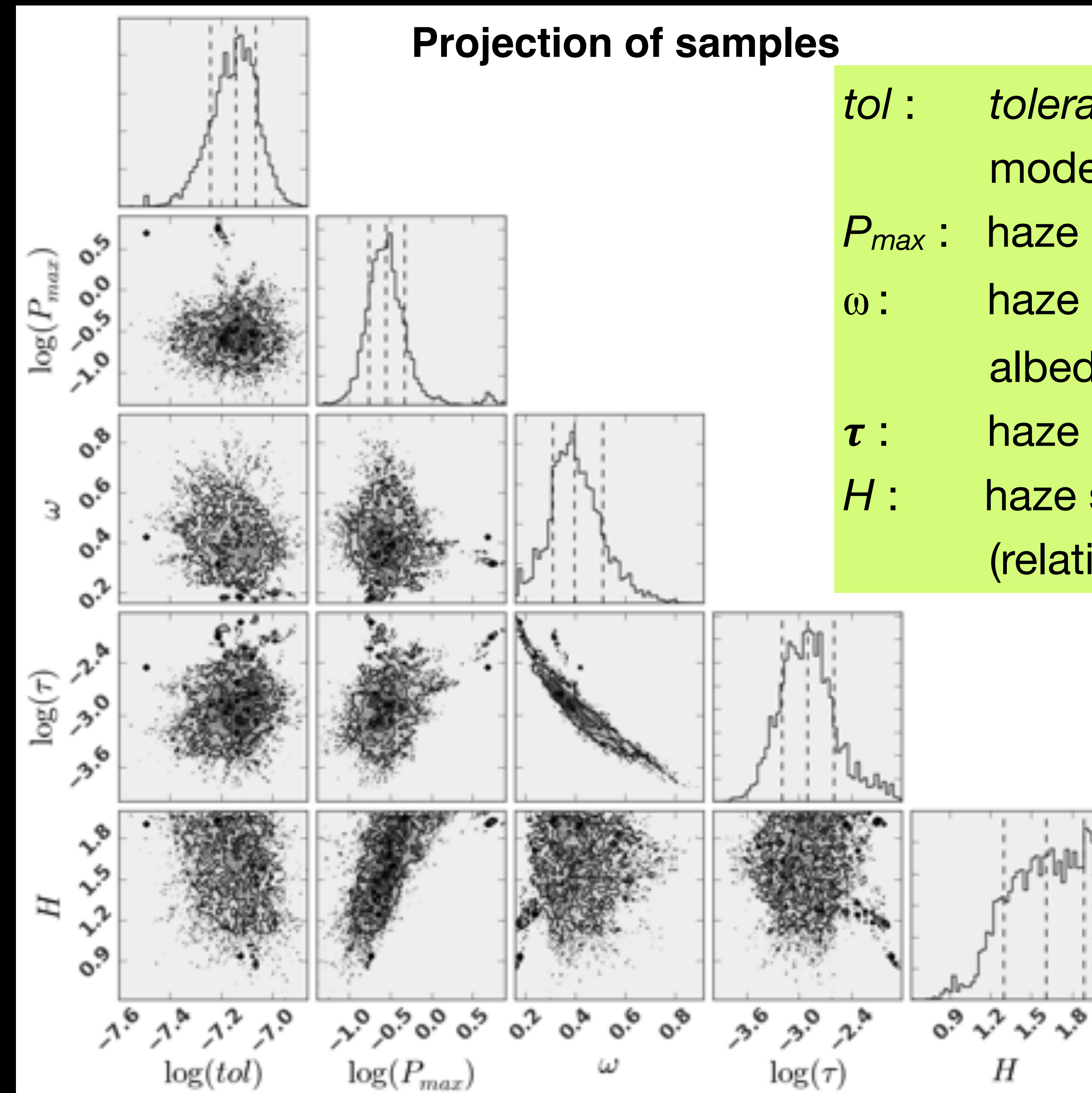
Keck OSIRIS image of Neptune, July 2009

Forward model: a flexible, python-based radiative transfer code

Retrieval: *emcee.py* — an affine invariant MCMC ensemble sampler by Dan Foreman-Mackey (NYU)

[1]AMNH [2]UC Berkeley
contact me: shcook@amnh.org

Example retrieval:



tol : *tolerance* (measure of model errors)

P_{max} : haze bottom pressure

ω : haze single scattering albedo

τ : haze optical depth

H : haze scale height (relative to gas)

Advantages:

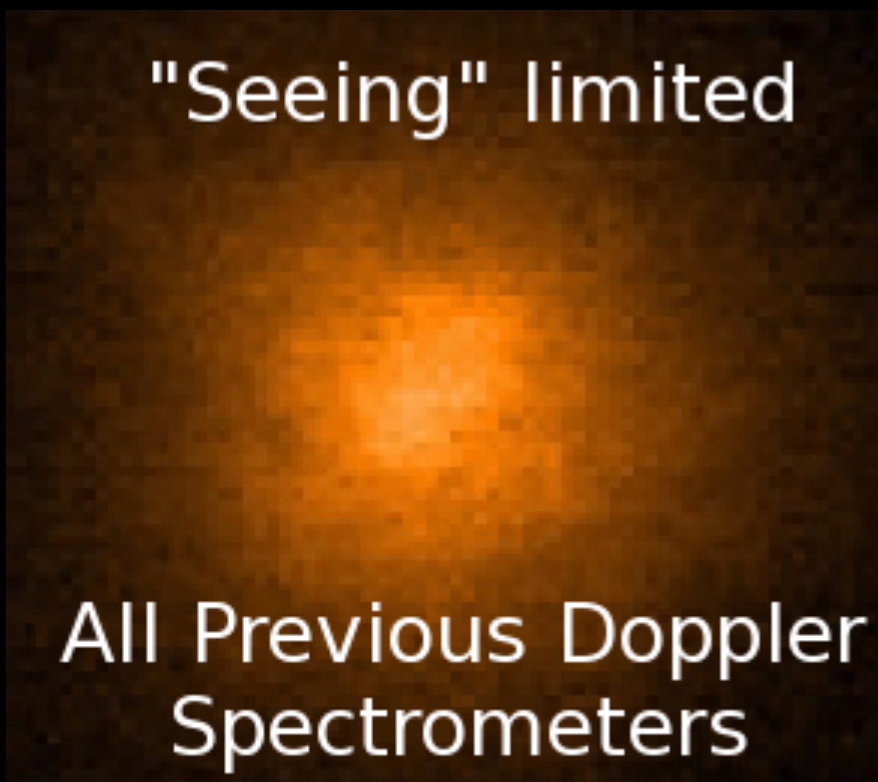
- Ability to explore a broad parameter space (e.g. of cloud properties, carbon/oxygen ratio, …)
- Flexibility

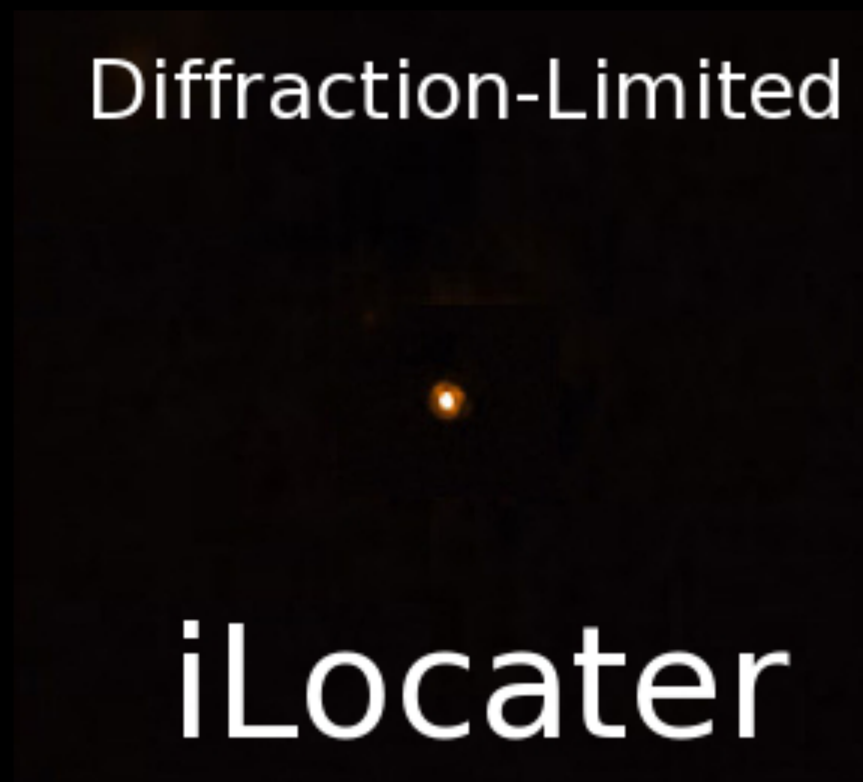
Current work: extension to exoplanets

- Greater range of temperatures, pressures, compositions
- Fewer constraints; fewer data points

contact me: shcook@amnh.org

The World's First Diffraction-Limited Doppler Spectrometer



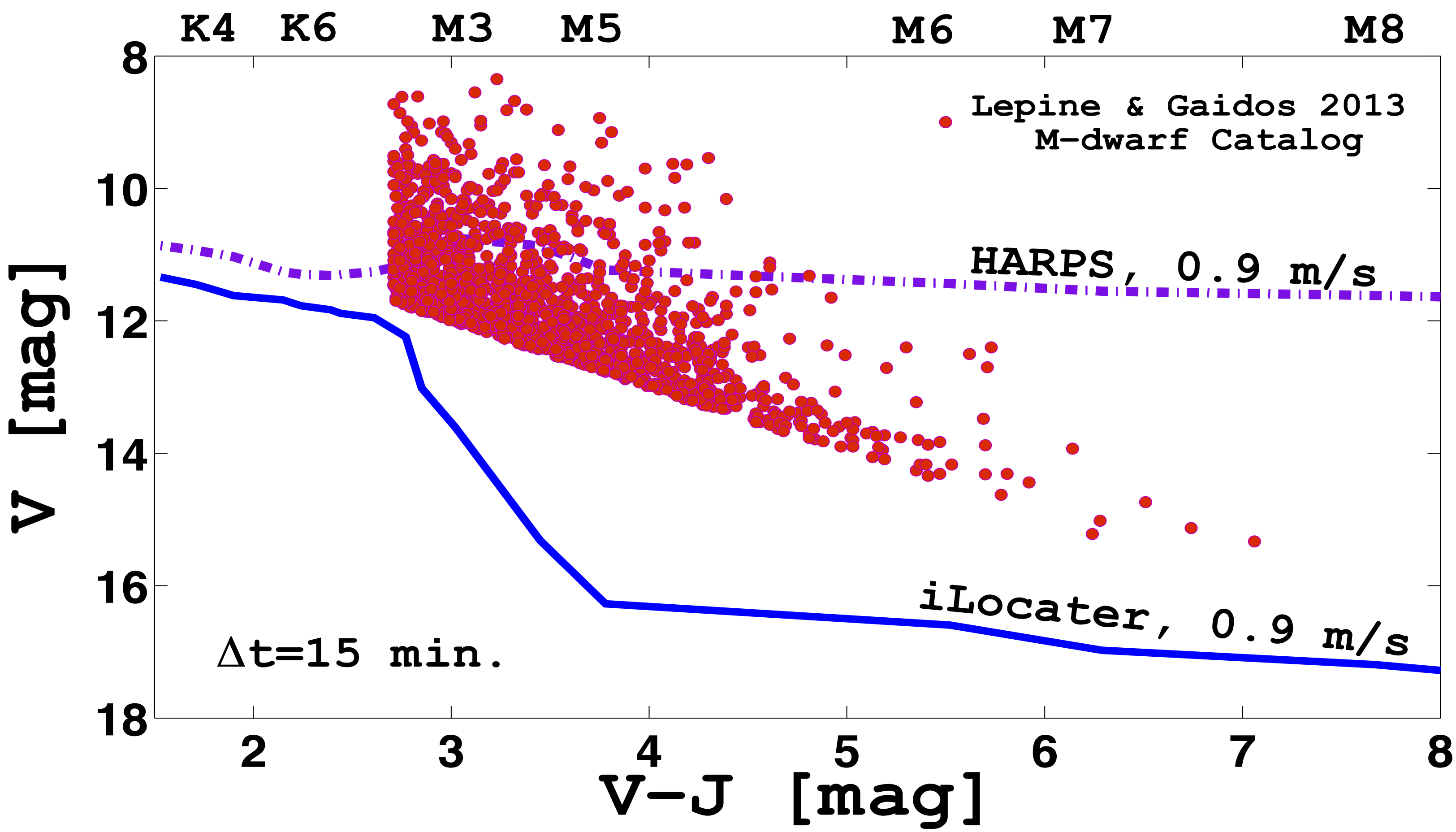


Revolutionizing the Doppler RV method using Extreme AO

Eric Bechter

University of Notre Dame

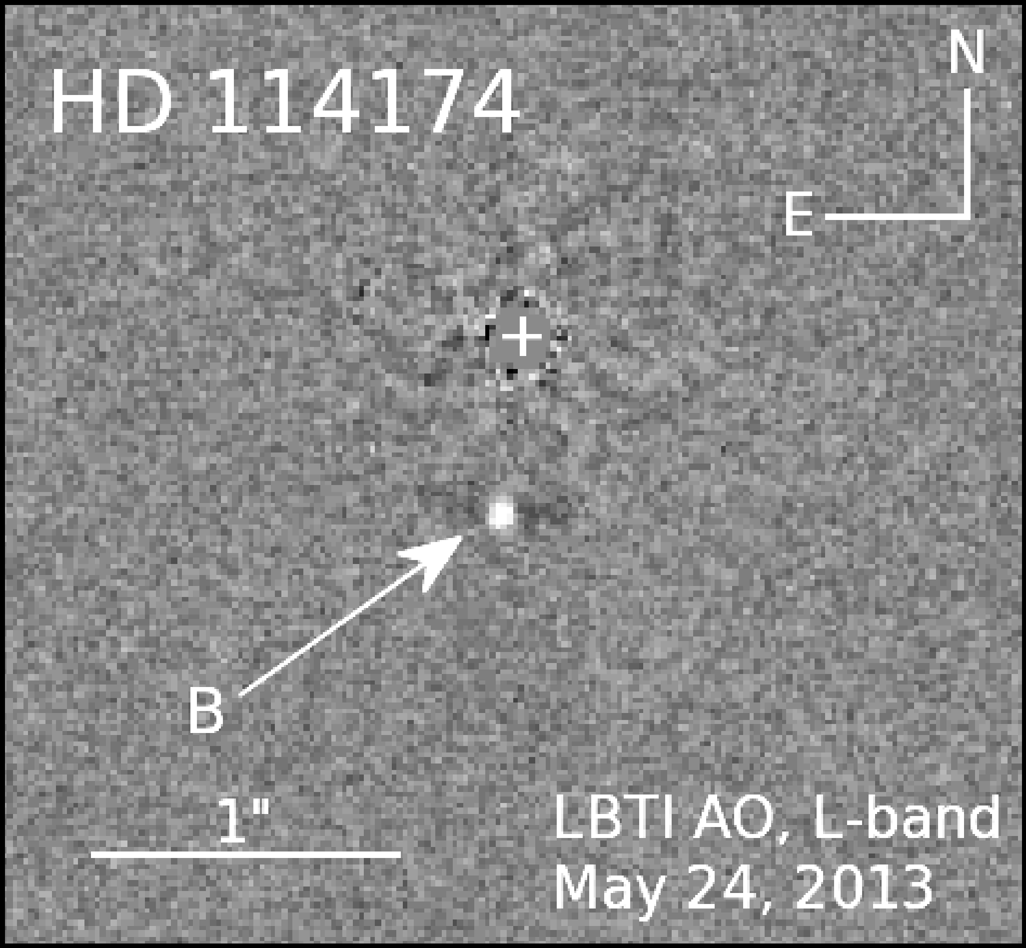
iLocater



K4
K6
M3
M5
M6
M7
M8
Lepine & Gaidos 2013
M-dwarf Catalog
HARPS, 0.9 m/s
iLocater, 0.9 m/s
Δt=15 min.
V [mag]
V−J [mag]
8
10
12
14
16
18
2
3
4
5
6
7
8

MID-INFRARED HIGH-CONTRAST IMAGING OF HD 114174 B: AN APPARENT AGE DISCREPANCY IN A "SIRIUS-LIKE" BINARY SYSTEM

Christopher T. Matthews, Justin R. Crepp, Andrew Skemer, Philip M. Hinz, Alexandros Gianninas, Mukremin Kilic, Michael Skrutskie, Vanessa P. Bailey, Denis Defrere, Jarron Leisenring, Simone Esposito, Alfio Puglisi



Object	Method	Age (Gyr)
HD 114174 A	Isochronology	$4.7^{+2.3}_{-2.6}$
HD 114174 A	Gyrochronology	$4.0^{+0.96}_{-1.09}$
HD 114174 B	Hydrogen model	7.77 ± 0.24
HD 114174 B	Helium model	6.17 ± 0.03

Deepest mid-infrared high-contrast image to date (including extrasolar planets):

$\Delta L' = 10.15 \pm 0.15$

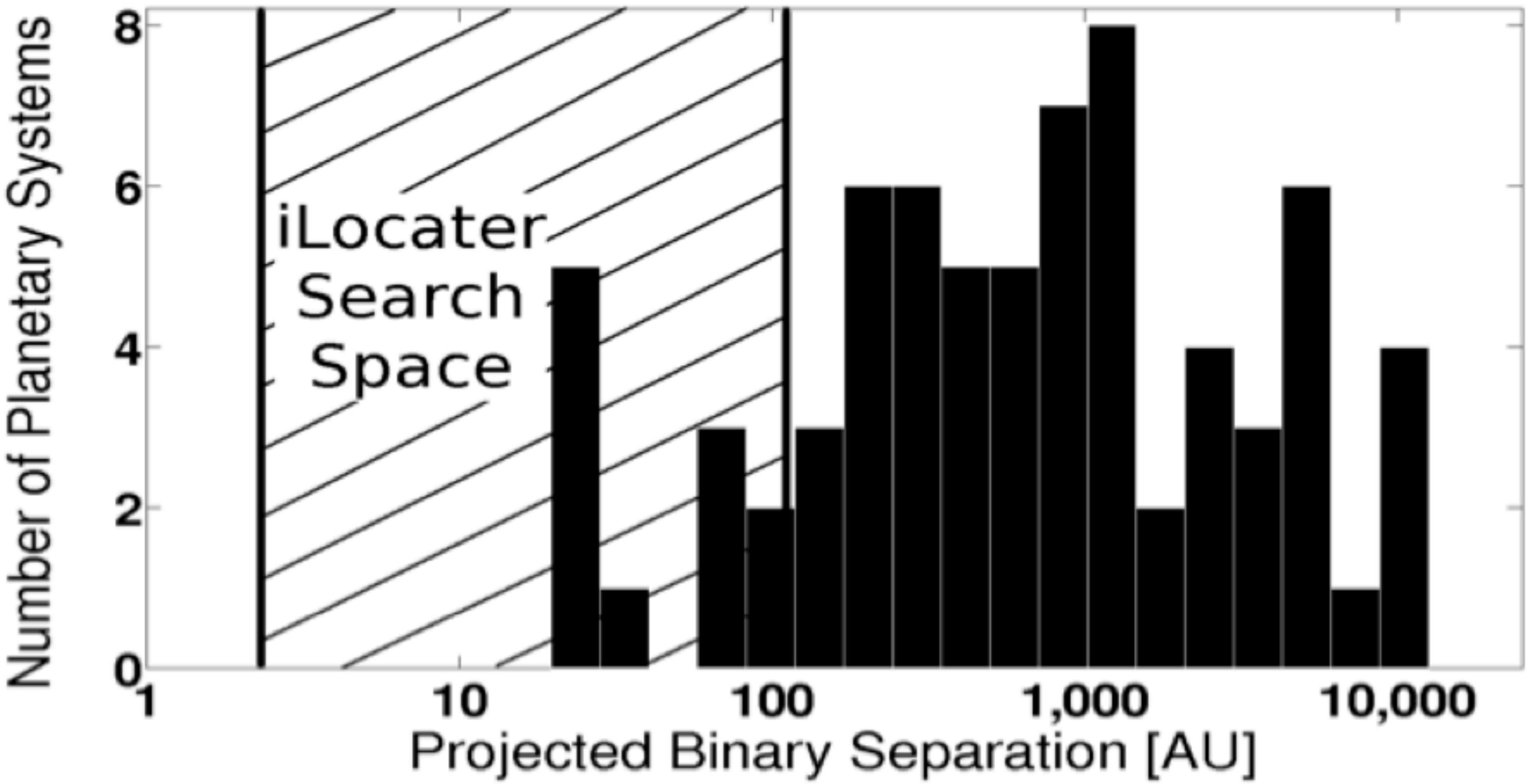
$\rho = 0.68''$

Matthews et al. 2014, ApJ Letters, 783, L25

A Diffraction Limited Doppler Spectrometer for the LBT

Andrew Bechter
University of Notre Dame
Sagan Workshop

iLocater



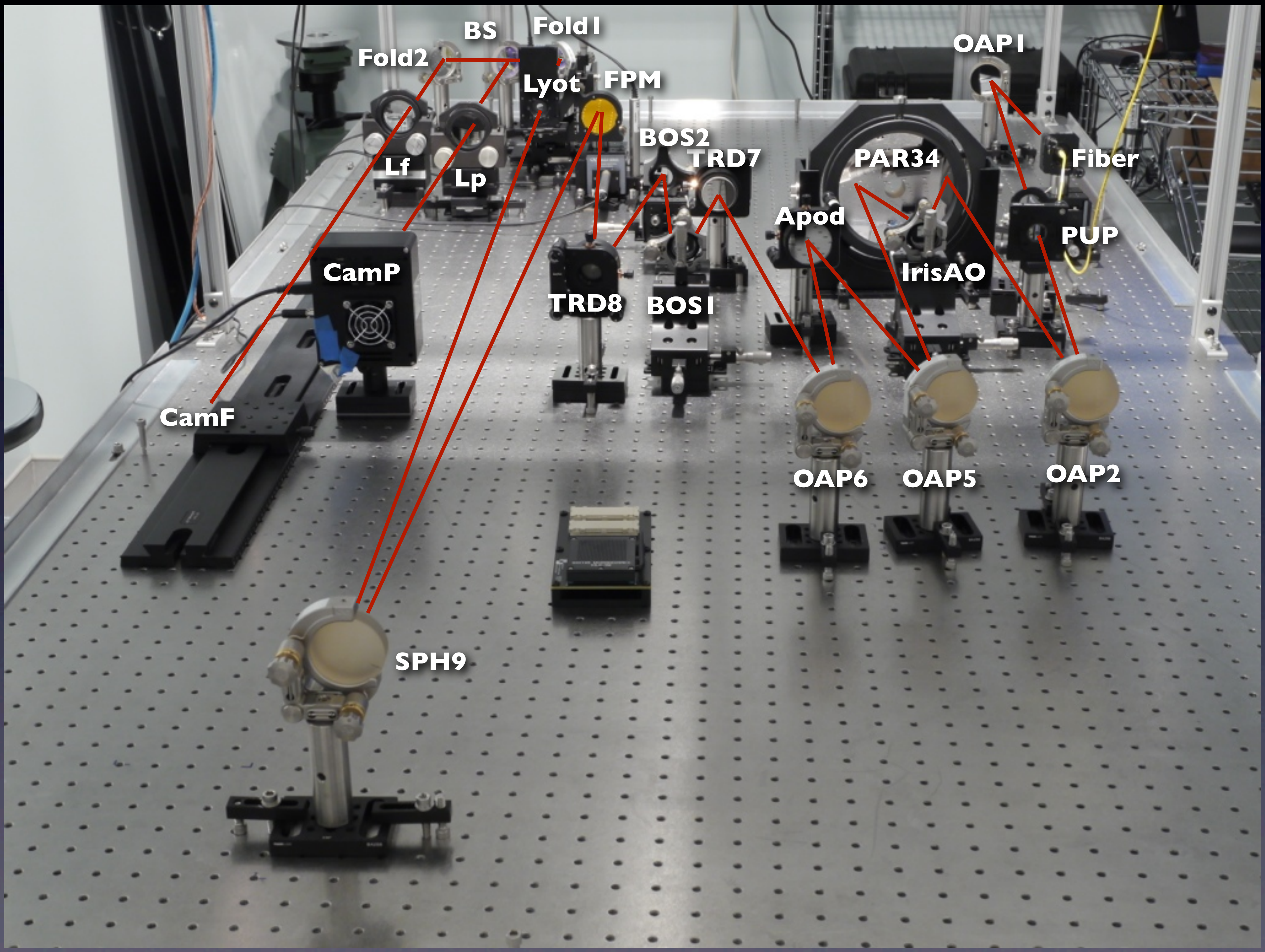
iLocater
Search
Space
Number of Planetary Systems
0
2
4
6
8
1
10
100
1,000
10,000
Projected Binary Separation [AU]

HiCAT

High-contrast Imager for Complex Aperture Telescopes

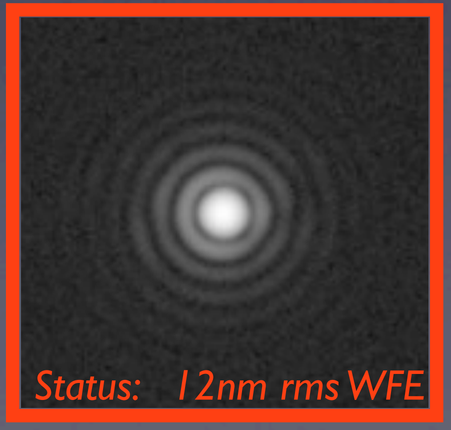
SPACE TELESCOPE SCIENCE INSTITUTE

Russell B. Makidon Optics lab



N'Diaye et al. 2013, 2014

***HICAT team*:**
Mamadou N'Diaye
Elodie Choquet
Sylvain Egron
Laurent Pueyo
Lucie Leboulleux
Olivier Levecq
Marshall D. Perrin
Erin Elliot
J. Kent Wallace
Emmanuel Hugot
Michel Marcos
Marc Ferrari
Chris A. Long
Rachel Anderson
Audrey DiFelice
Rémi Soummer



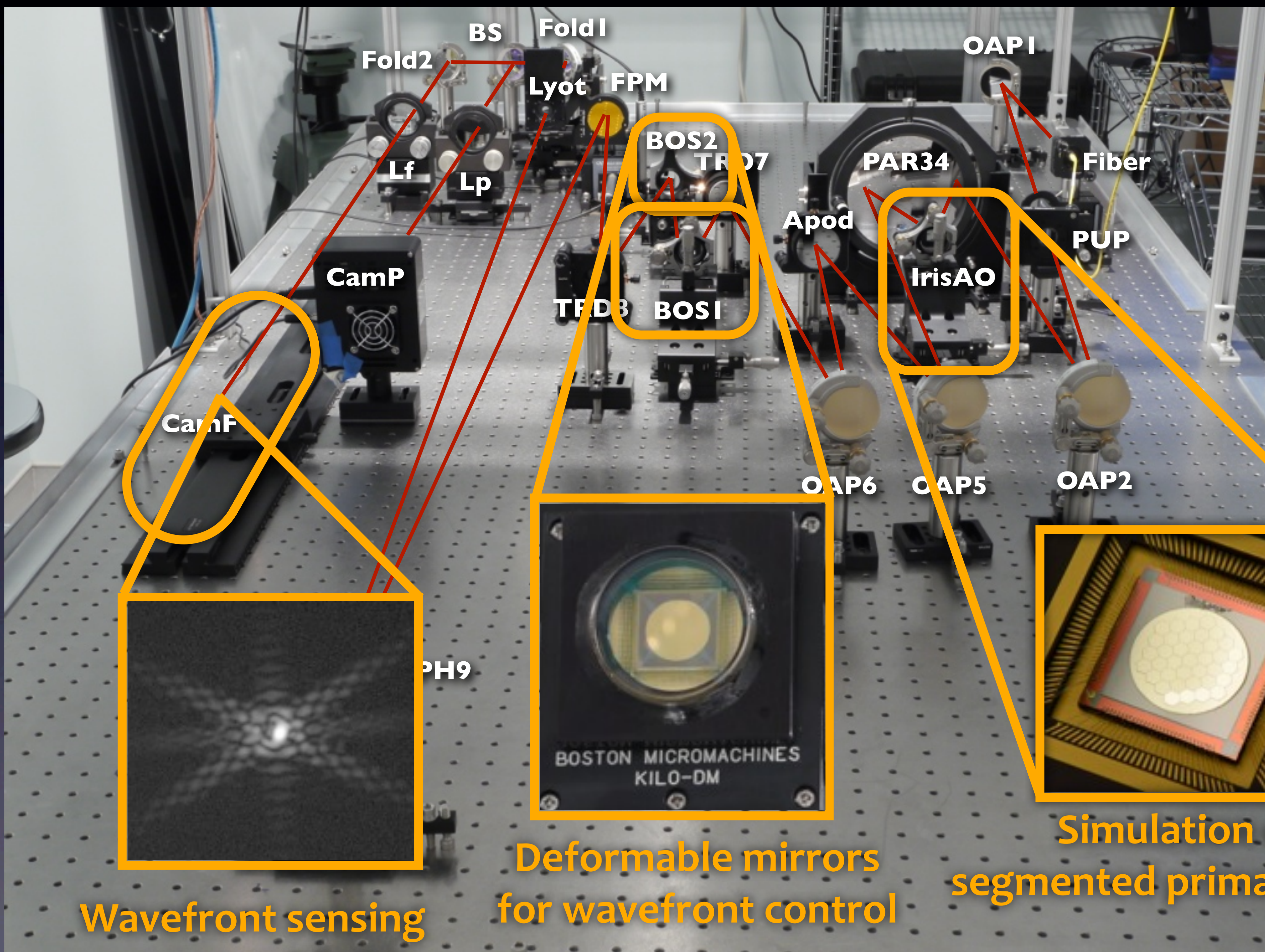
Elodie Choquet (STScI)

HiCAT

High-contrast Imager for Complex Aperture Telescopes

SPACE TELESCOPE SCIENCE INSTITUTE

Russell B. Makidon Optics lab



N'Diaye et al. 2013, 2014

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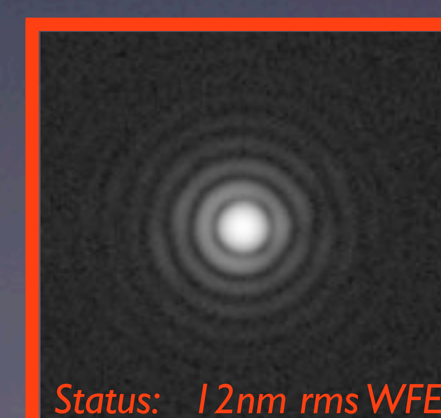
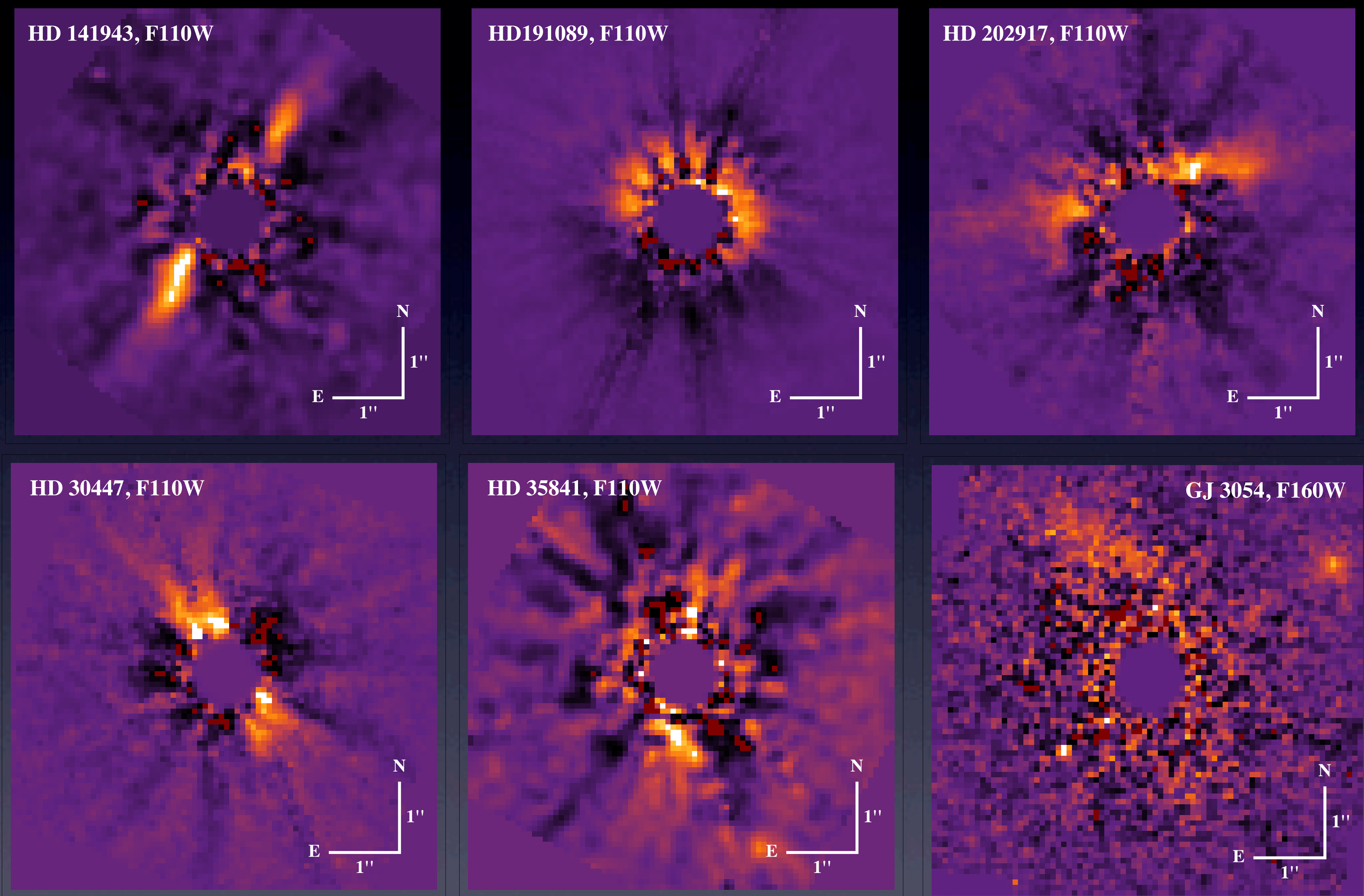


ALICE

Archival Legacy Investigations of Circumstellar Environments

SPACE TELESCOPE SCIENCE INSTITUTE

Extrasolar Planetary Systems
High Contrast Imaging Group



***ALICE team*:**
Elodie Choquet
Laurent Pueyo
J. Brendan Hagan
Elena Gofas-Salas
Abhijith Rajan
Christine Chen
Marshall D. Perrin
John Debes
David Golimovski
Dean C. Hines
Mamadou N'Diaye
Glenn Schneider
Dimitri Mawet
Christian Marois
Rémi Soummer

Soummer et al. 2014
Choquet et al. 2014

HST cycle 21: *PI L. Pueyo (WFC3), PI M. Perrin (STIS)*
HST cycle 22: *PI E. Choquet (STIS)*

Consistent reprocessing of NICMOS archive:
~ 400 targets, 5600 images, mostly in J and H bands

- **Large PSF libraries for PCA reprocessing**
- **New disks & companion candidates**

Image processing for exoplanet detection and characterization

<u>Method:</u> Bayesian inverse problem solving

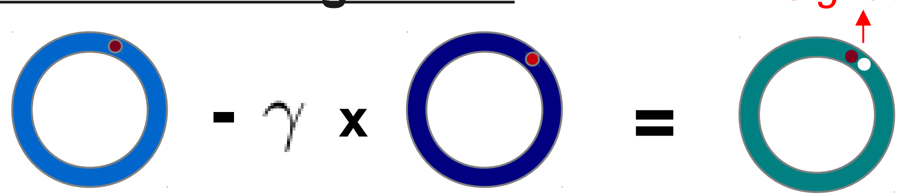
ANDROMEDA

<u>Ingredients:</u>

- Coronagraphic / saturated images
- Pupil tracking mode
-1 PSF (unsaturrated exposure)

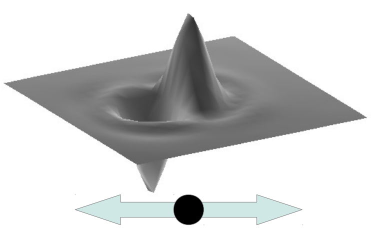
<u>1- ADI based algorithm:</u>

Signature



Annulus(t1) *Annulus(t2)* *Pseudo-annulus*

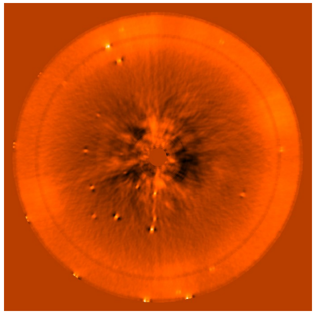
<u>2- Model for the pseudo-image:</u>



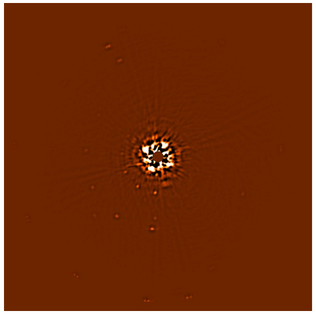
x **Flux** (unknown) + **noise**

Position (unknown)

<u>3- Maximum likelihood:</u>



&

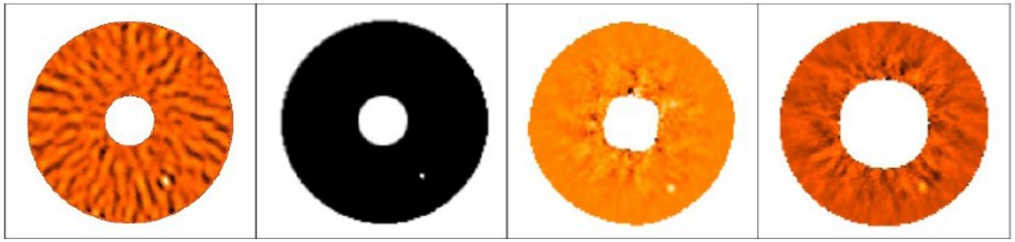


Likelihood map
→ Detection + position

Flux map
→ Flux

<u>4-Comparison to other algorithms</u>

Beta-Pictoris b



ANDROMEDA ***LOCI*** ***PCA***

<u>Main interest:</u>

-Thresholding for detection
-Direct flux retrieval
-Speed and accuracy

See my poster for more nice results!

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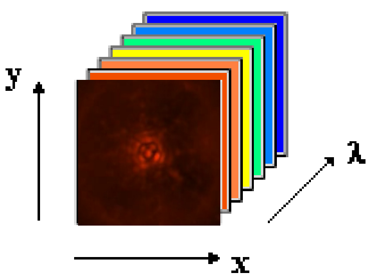
Institut de Planétologie et d'Astrophysique de Grenoble

ONERA
THE FRENCH AEROSPACE LAB

Image processing for exoplanet detection and characterization

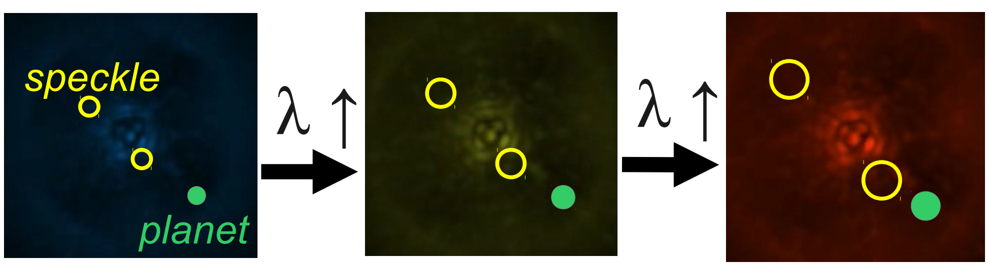
<u>Method:</u> Bayesian inverse problem solving

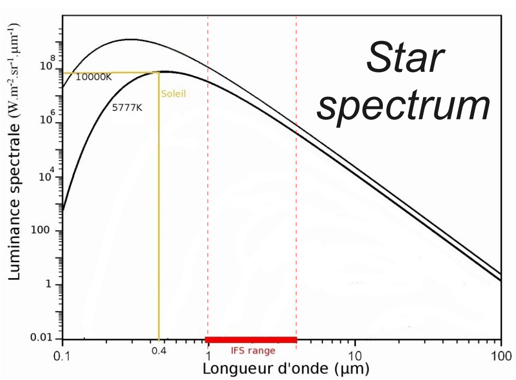
Multispectral data

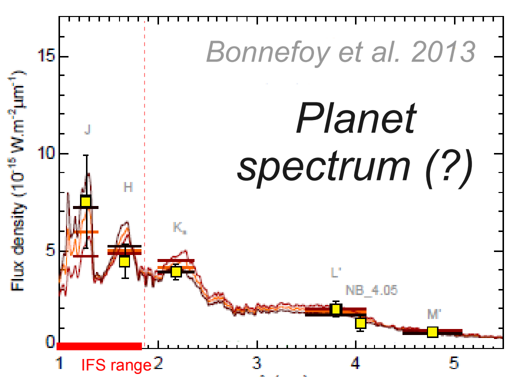


What we know...

-Spectrum star ≠ planet
-Planet's position is still
-Spreading of the speckles







What we want to distinguish...

-**Planets:** position and spectrum
-**Speckle distribution:** Aberrations

How I will do that...

- **Joint estimation of object and aberrations**
  Start from Marie Ygouf PhD results

- **Preparation** for real data application:
  - Refined **model** of coronagraphic image
  - Introduce **field rotation**
  - Introduce **prior knowledge** on planets

- **Application** to real data (SPHERE):
  - Improvements, optimization ...
  - Performances assessment
  - Comparison to other algorithms

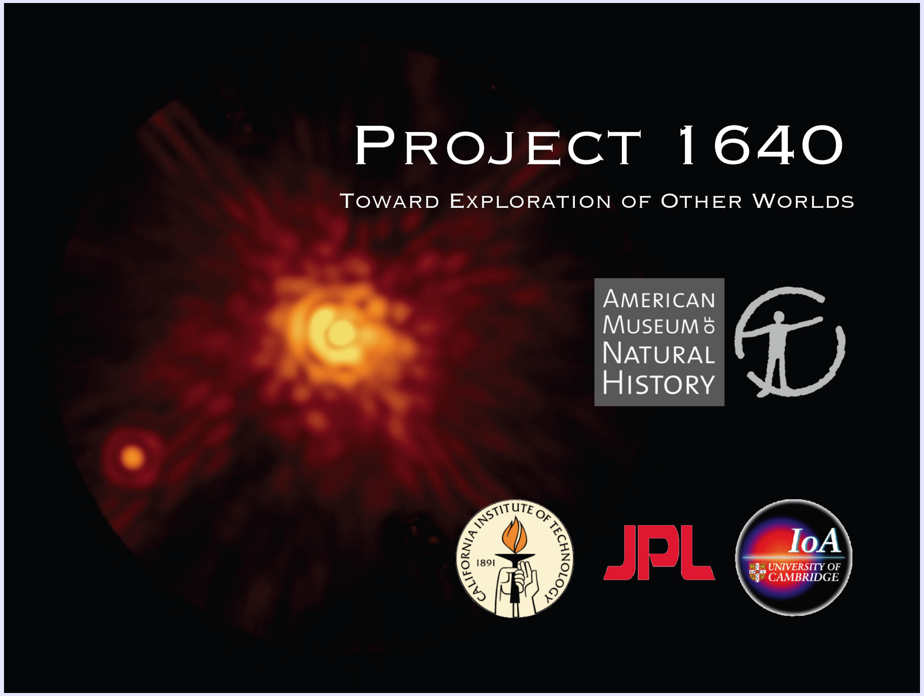
See Marie Ygouf's poster for more info about the inner method

Stability of Spectral Extractions Utilizing Project 1640 Data and the S4 Pipeline

AAron Veicht

American Museum of Natural History

Columbia University



Ricky Nilsson[1,2], AAron Veicht[1], B. R. Oppenheimer[1], Douglas Brenner[1], Neil Zimmerman[1,3], Rob Fergus[4], Ian R. Parry[5], Eleanor Bacchus[5]

[1]Department of Astrophysics, American Museum of Natural History, New York, USA
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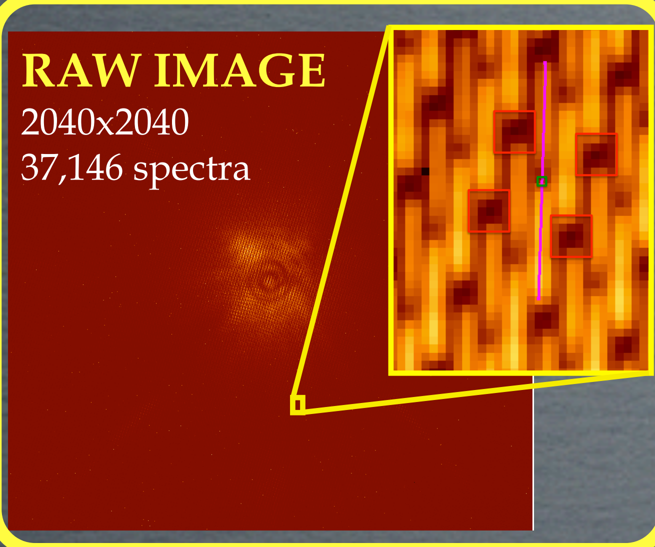
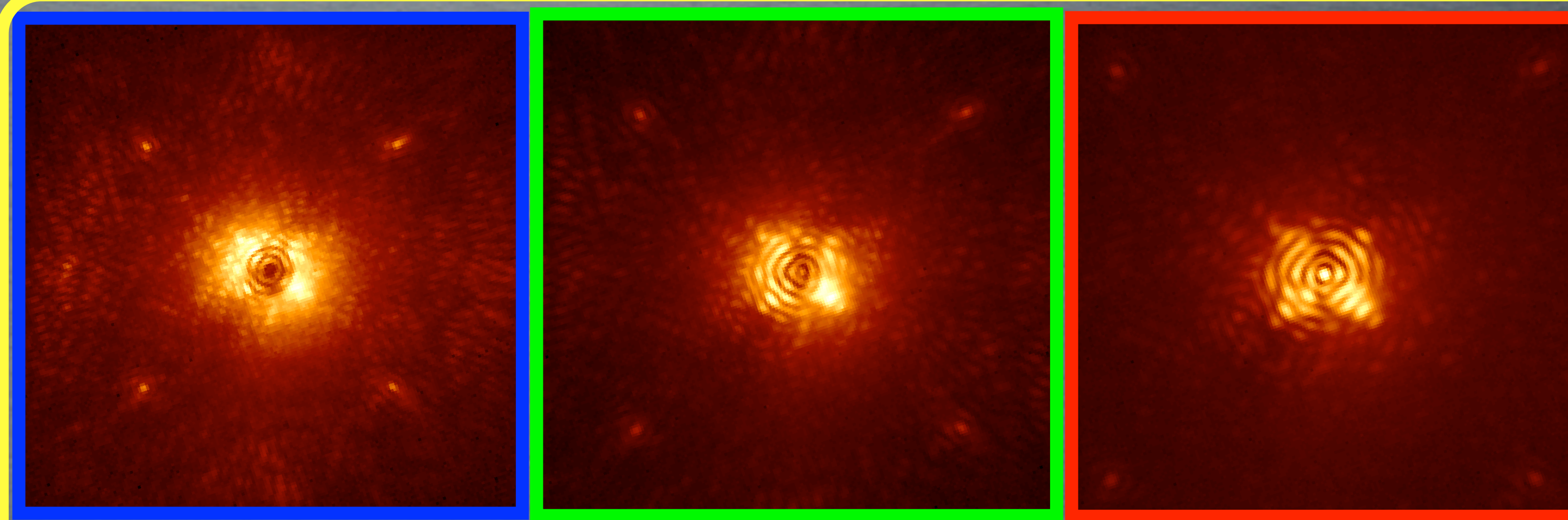
[3]Now at Max Planck Institute for Astronomy, Heidelberg, Germany
[4]Department of Computer Science, Courant Institute of Mathematical Sciences, New York University, New York, USA
[5]Institute of Astronomy, Cambridge University, Cambridge, UK

High-Contrast Imaging and Planet Detection with Project 1640

RAW IMAGE
2040x2040
37,146 spectra



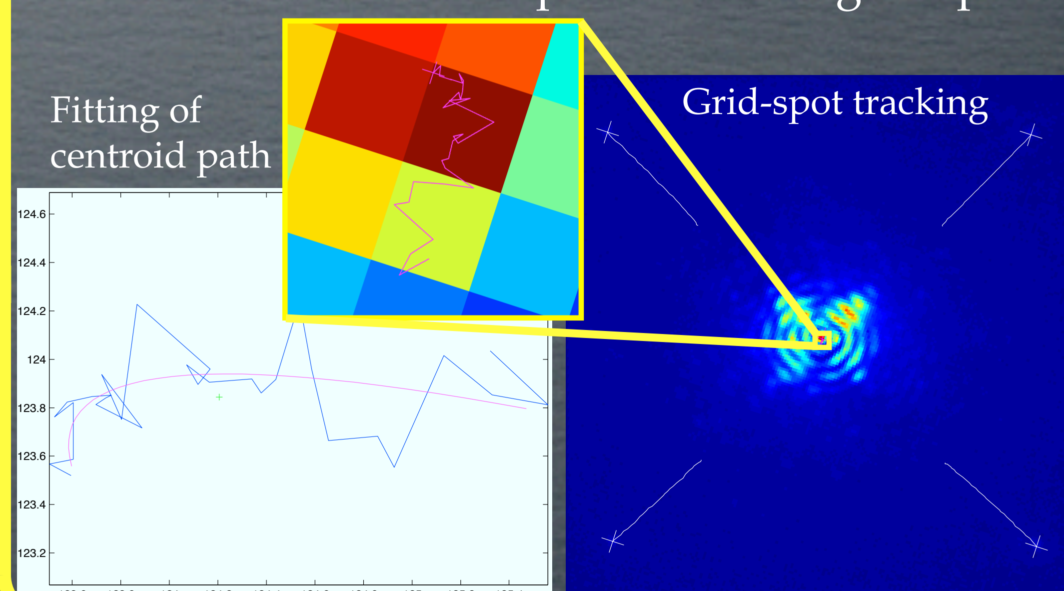
PCXP
90 s/cube



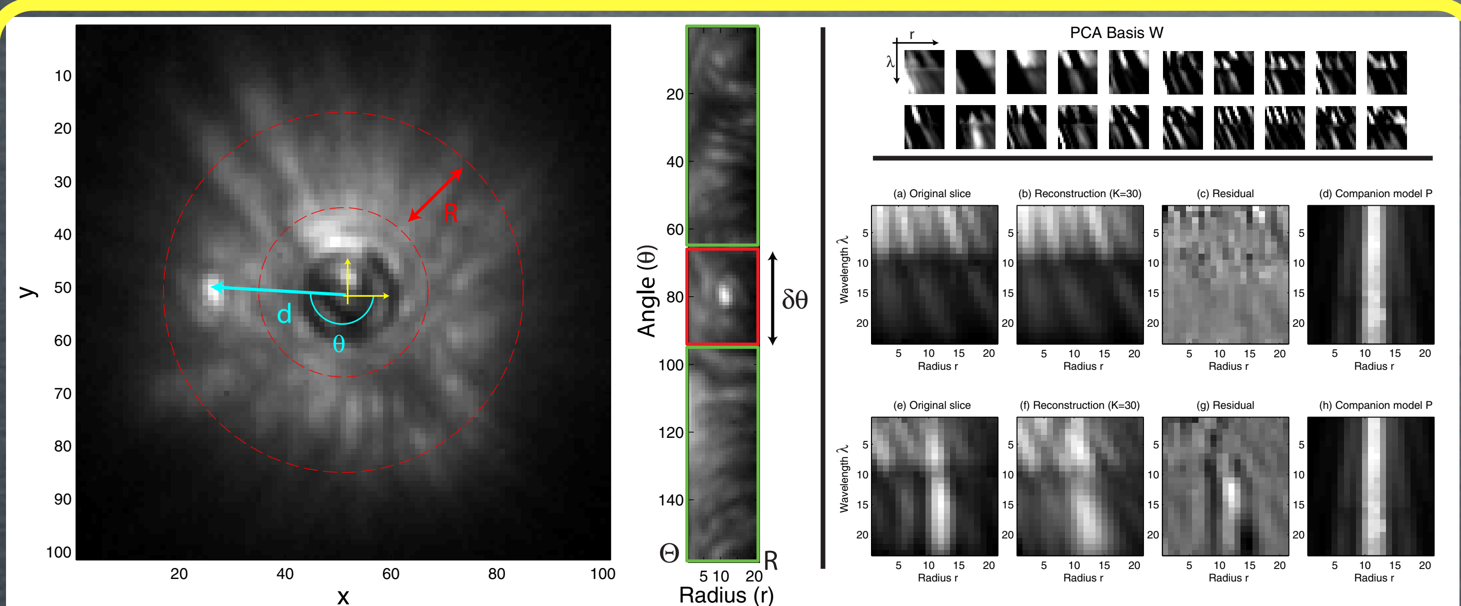
EXTRACTED CUBES (x, y, λ) with size 250 × 250 × 32 (3.8″ × 3.8″, 995-1769 nm)

CACS 60 s/cube

DISPERSION CORRECTION Sub-pixel determination of stellar position from grid spots.

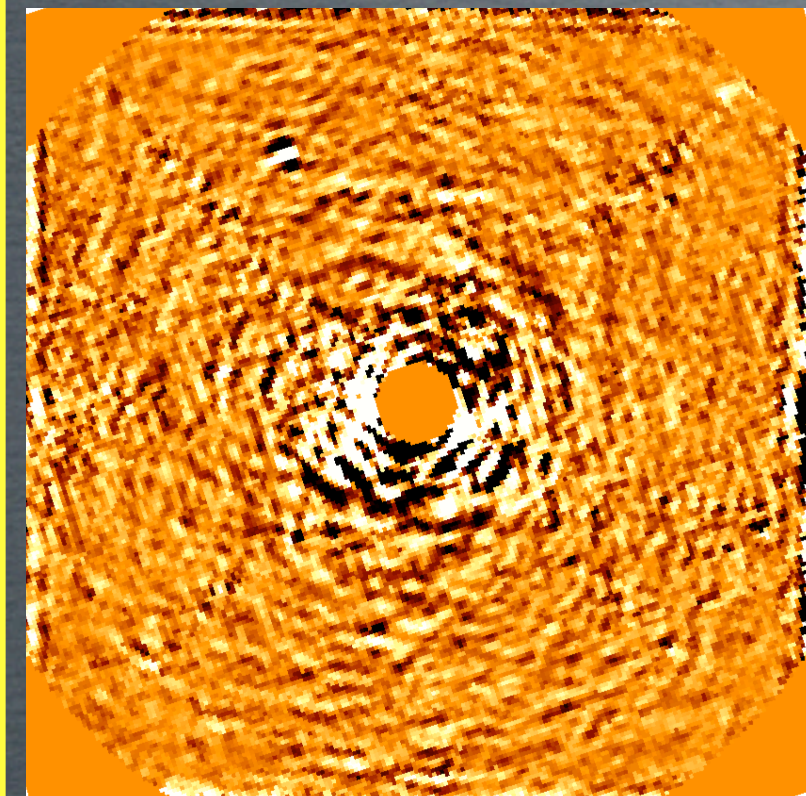


S4d ~10 hrs

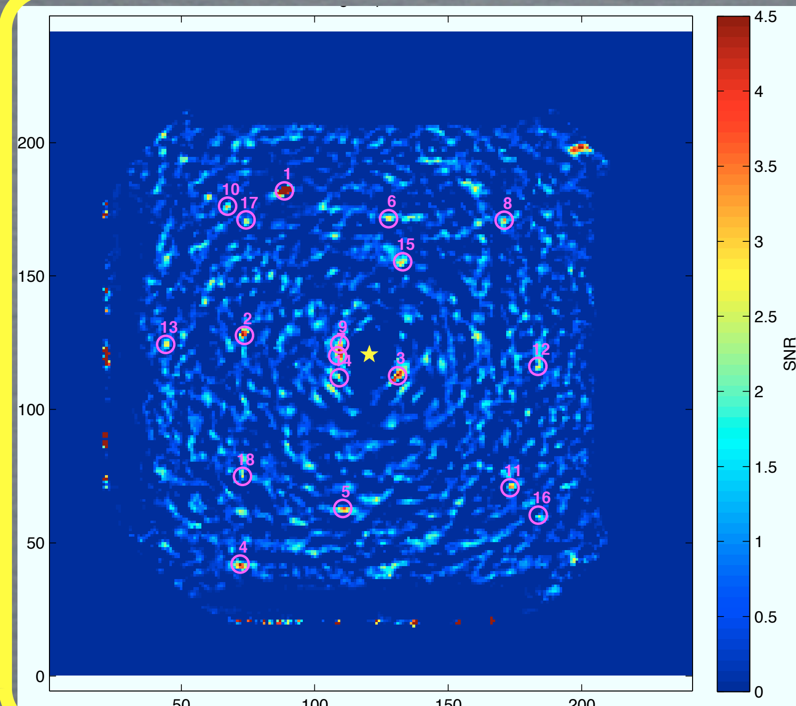


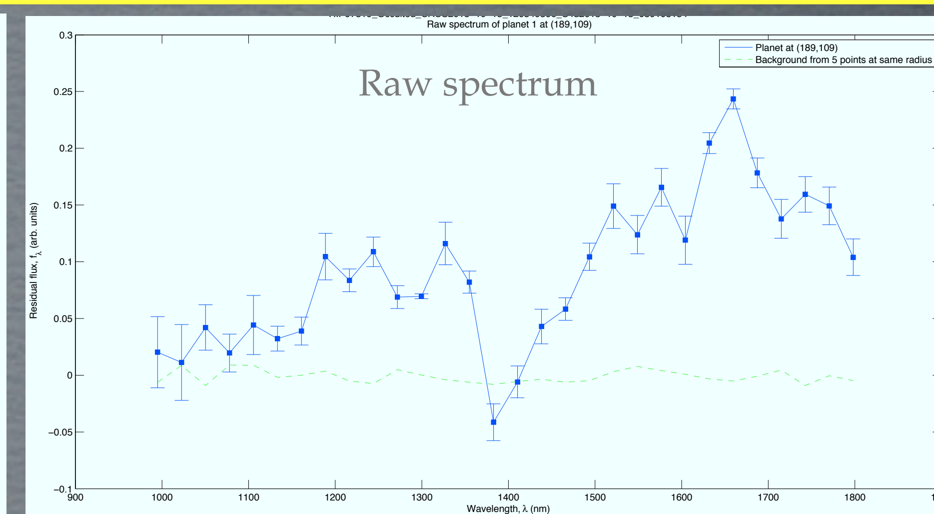
SPECKLE SUPPRESSION Modeling of speckles using Principal Component Analysis (PCA).

DETECTION MAP
Residuals cross correlated with PSF model



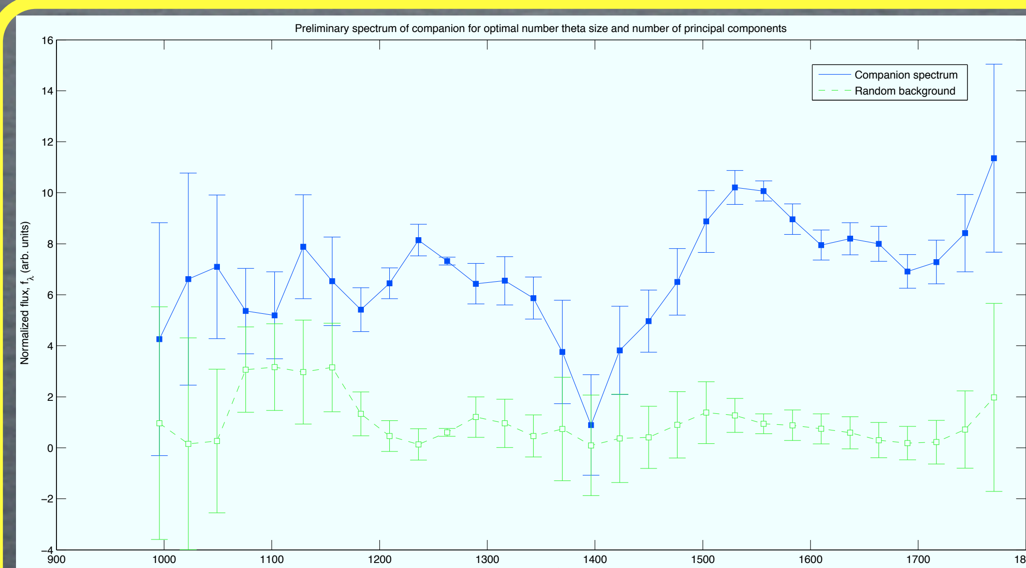
PlanetFinder
20 min/cube

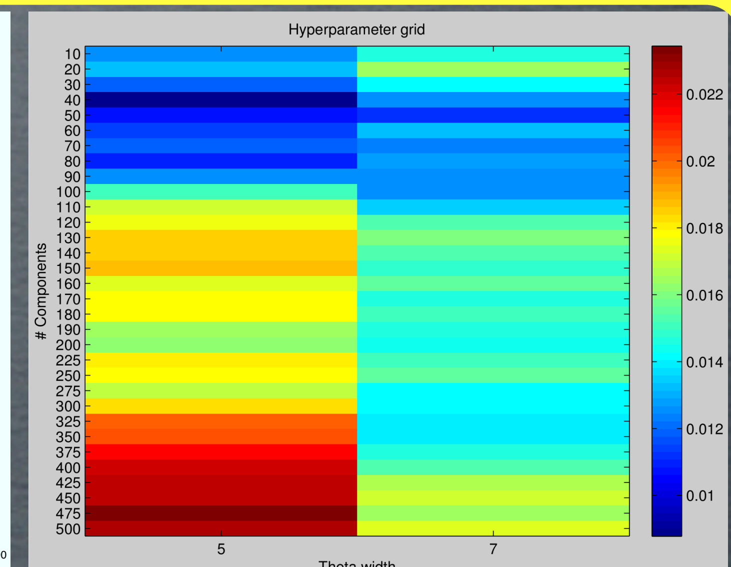




LOCAL S/N MAP
Automated search for significant peaks and extraction of raw spectrum.

S4s
~ 5 hrs



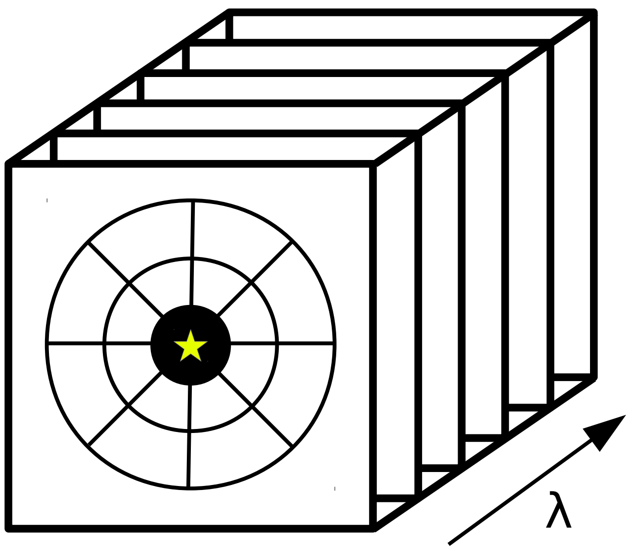


SPECTRUM OF PLANET CANDIDATE
PCA modeling and extraction of calibrated spectrum, including noise and stability analysis (see POP by Veicht).

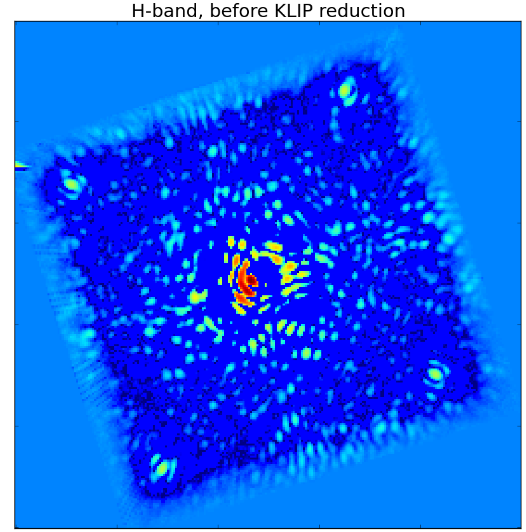
References
Nilsson et al. (in prep.)
Fergus et al. (2014, submitted)
Pueyo et al. (2014, submitted)
Oppenheimer et al. (2014, 2013, 2012)
Zimmerman et al. (2011)

KLIP speckle suppression and spectrum extraction at Project 1640

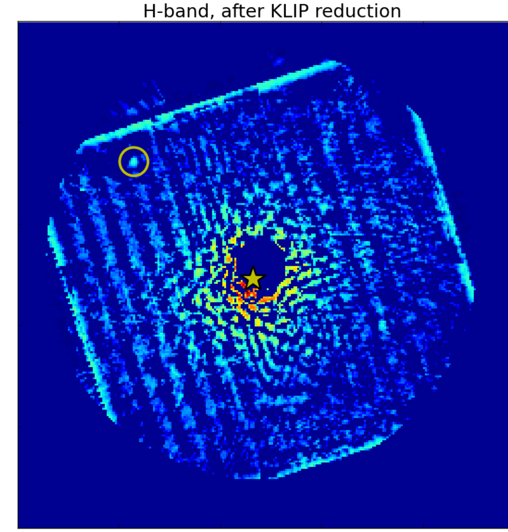
Jonathan Aguilar (Johns Hopkins University)
Laurent Pueyo (Space Telescope Science Institute)



H-band, before KLIP reduction

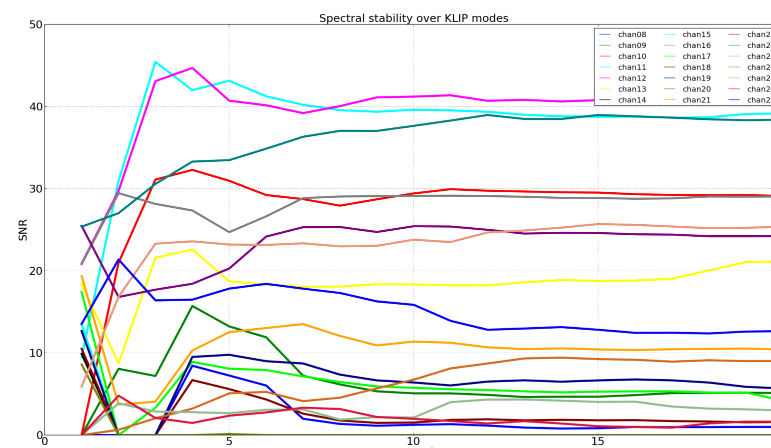


H-band, after KLIP reduction



KLIP: Karhunen-Loeve Image Projection

1)Scale and align slices (1/λ)
2)Partition the image into search zones
3)Remove adjacent wavelengths from PSF lib
4)Compute the K-L transform of each zone
5)Reconstruct the zones based on top *n* modes
6)Subtract reconstructed zones from the true image to remove speckles



Direct Imaging of HD 19467

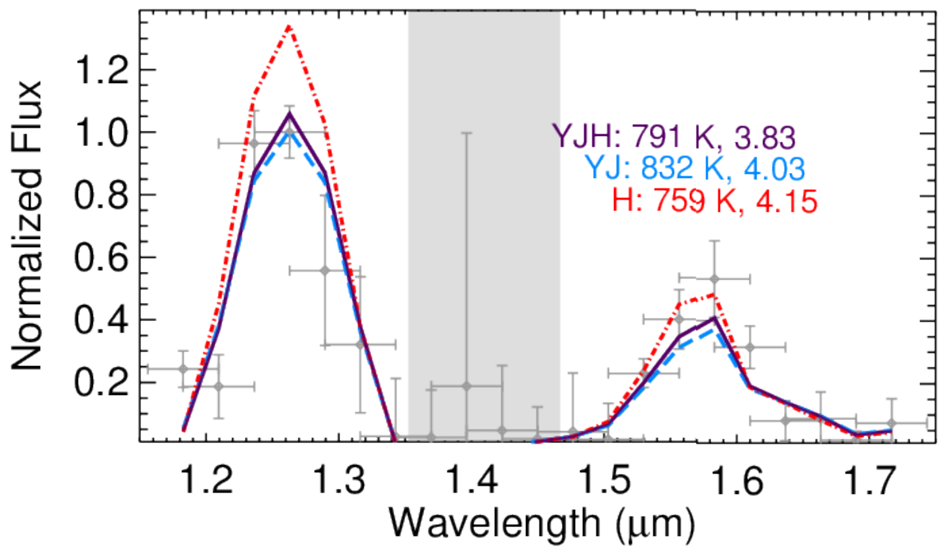
with Justin Crepp (Notre Dame) and Emily Rice (CUNY) and the P1640 team

Crepp et al., 2013

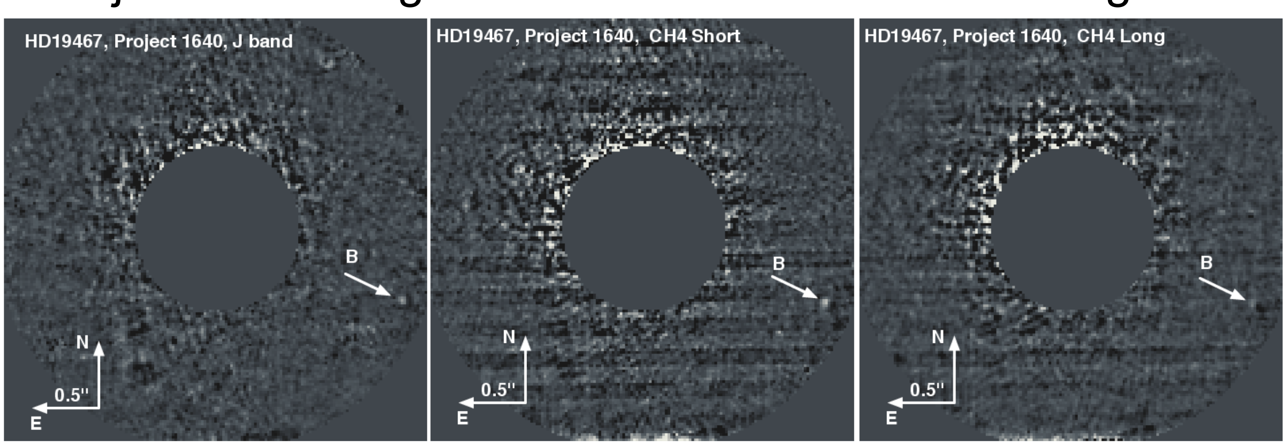
Brown dwarf in a high mass-ratio system with both RV trend and NIR colors (Keck)

Proj.sep. [AU]	51.1 +/- 1.0
M_J	15.16 +/- 0.12
T_{eff} [K]	1050 +/- 40
Dynamical mass [M_J]	>51.9 +3.6/-4.6
Model mass [M_J]	56.7 +4.6/-7.2

Fitting atmospheric models to the P1640 spectrum



Project 1640 imaged HD 19467 B with 32 wavelengths



- NIR spec of prob. a T6 dwarf
- If it's 10 Gy old, evolutionary models give m~52 M_J, right at the dynamical mass limit
- If it's younger... the models are way off

JA is funded by the National Physical Science Consortium