Direct imaging of extrasolar planets

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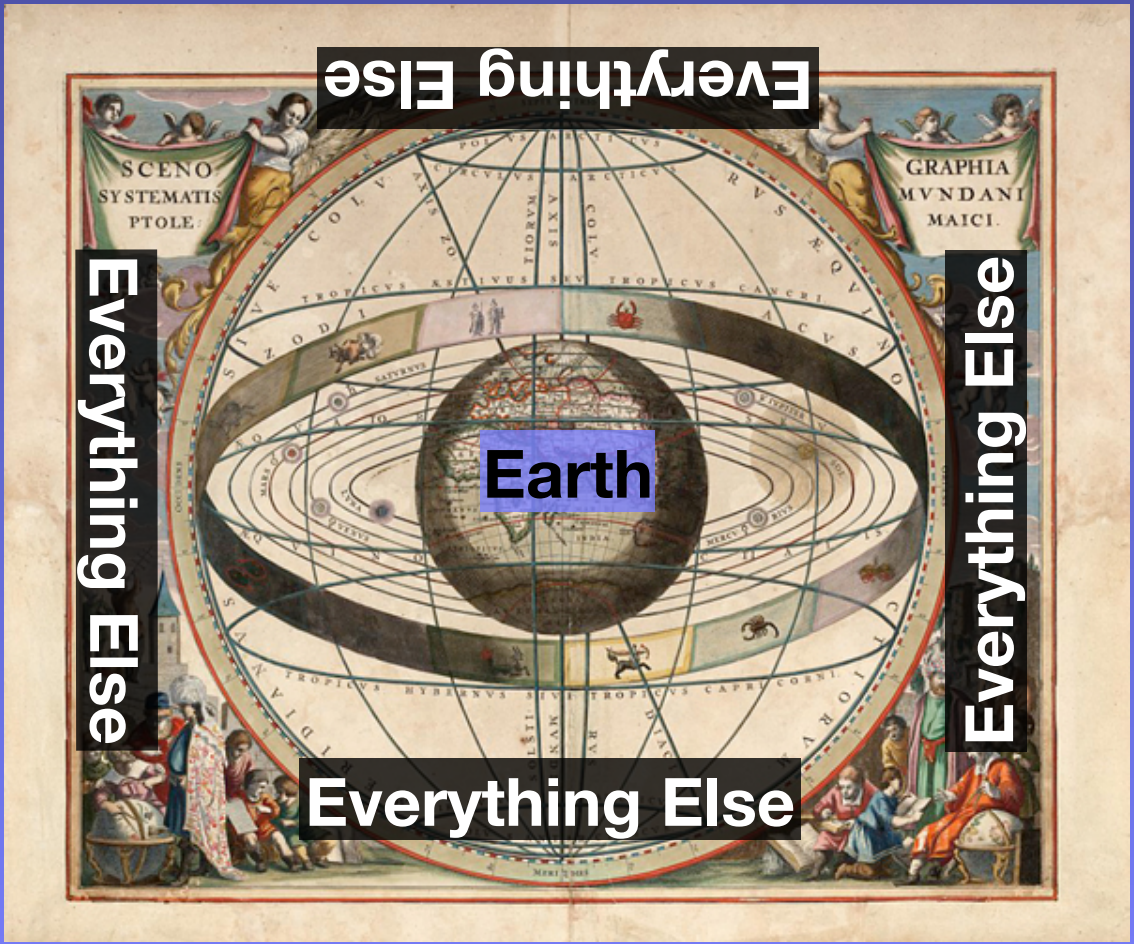
UC Berkeley: James Graham, Jason Wang, Paul Kalas
Toronto: Quinn Konopacky, Jerome Marie, Max Millar-Blanchaer
UC Santa Cruz: Don Gavel, Daren Dillon, Jim Ward, Sloane Wiktorowicz
JPL: Kent Wallace, John Angione, Bijan Nemati, Chris Shelton, Fred Vescelus
UCLA: James Larkin, Jeff Chilcote, Jason Weiss, Mike Fizgerald, Evan Kress
Gemini: Stephen Goodsell, Markus Hartung, Kayla Harding, Brian Wolf, Carlos Quiroz, Fredrik Rantakyro, Pascale Hibon, Andrew Cardwell, Markus Hartung
HIA: Les Saddlmyer, Jennifer Dunn, Dan Kerley, Kris Kaputa, Andre Anthony, Christian Marois, Zach Draper, Darren Erikson, Malcolm Smith, Alexis Hill, Vlad Reshitov, John Pazder
AMNH/STScI/JHU: R. Oppenheimer, Remi Soummer, Anand Sivaramakrishnan, Lauret Puyeo Marshall Perrin, Schuyler Wolfe, Alex Greenbaum Stanford: Patrick Ingraham
Other: Dmitry Savransky, Sandrine Thomas, Mark Marley, Franck Marchis, Katie Morzinski, Rene Doyon, Simon Thibaut Arizona: Abi Rajan, Joanna Bulger, Jennifer Patience, Rob deRosa, Travis Barman

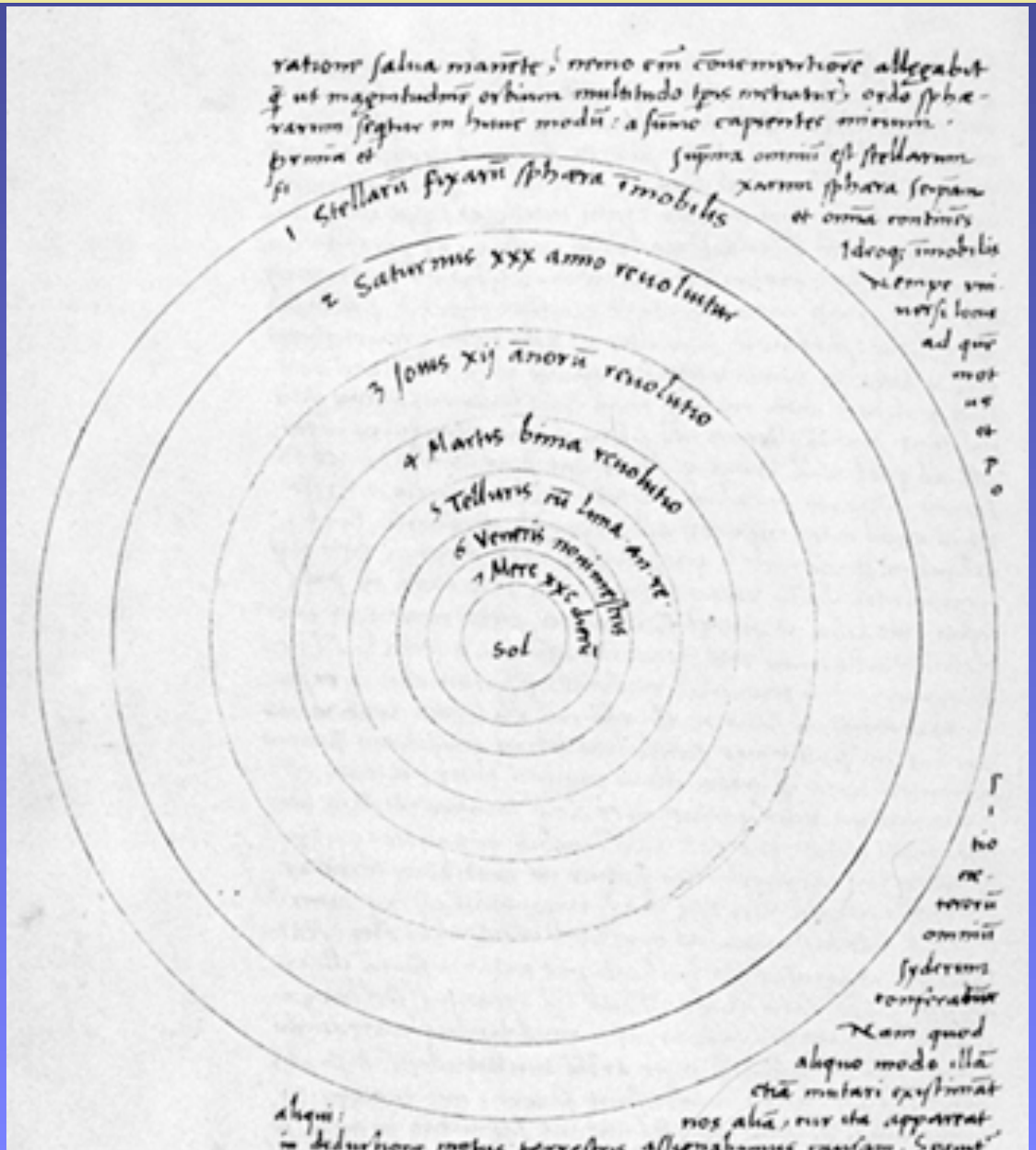
Dunlap Institute for Astronomy & Astrophysics UNIVERSITY OF TORONTO

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Ptolemy's view of the universe

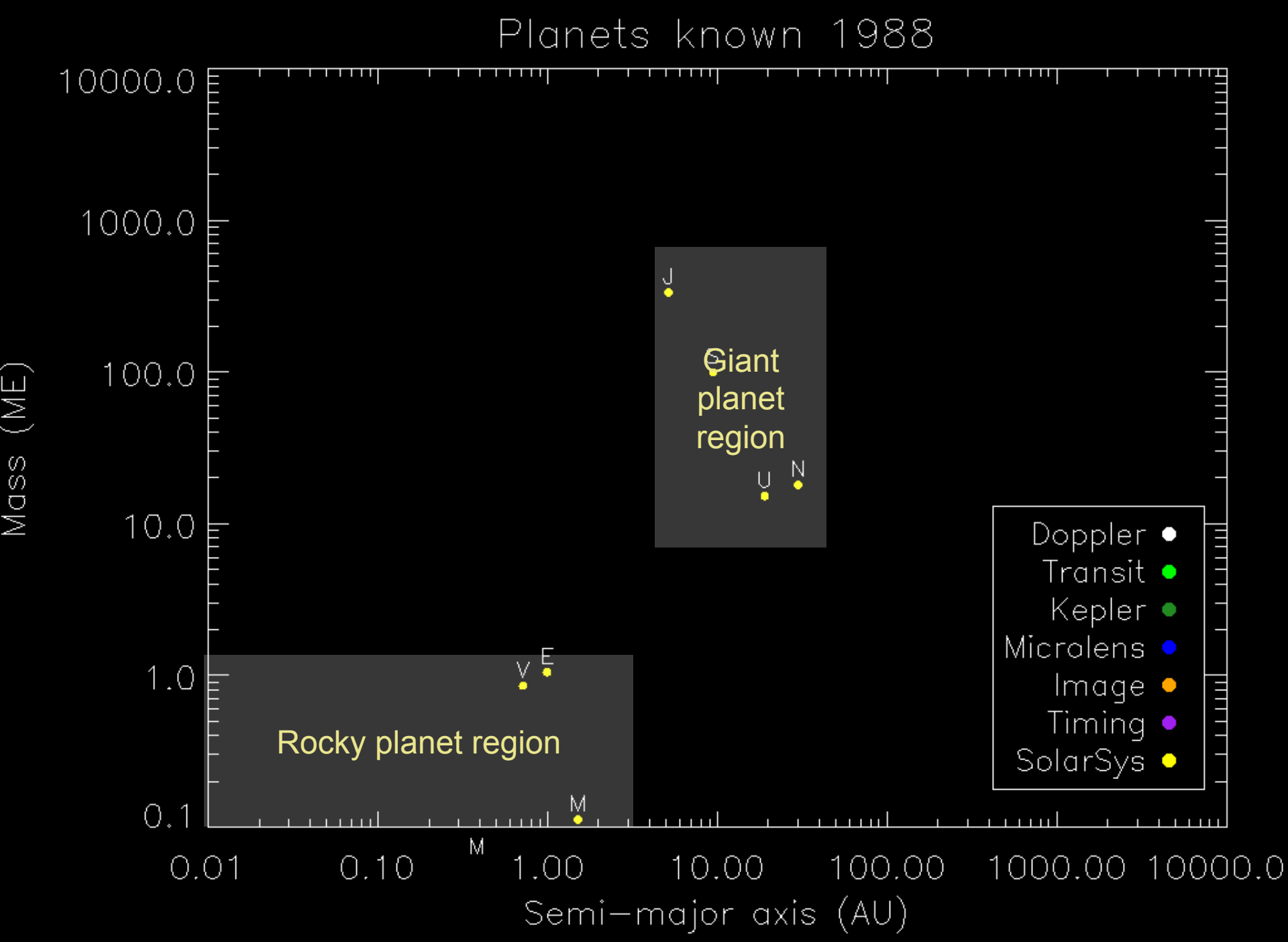


Copernicus to Kepler

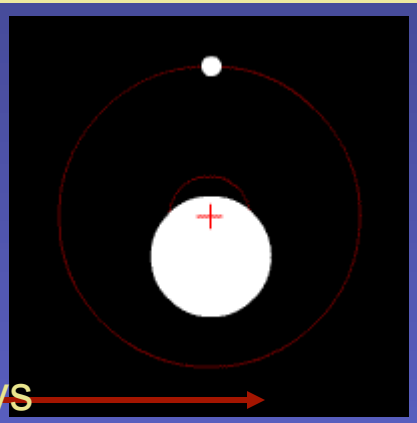


Galileo’s view of Jupiter

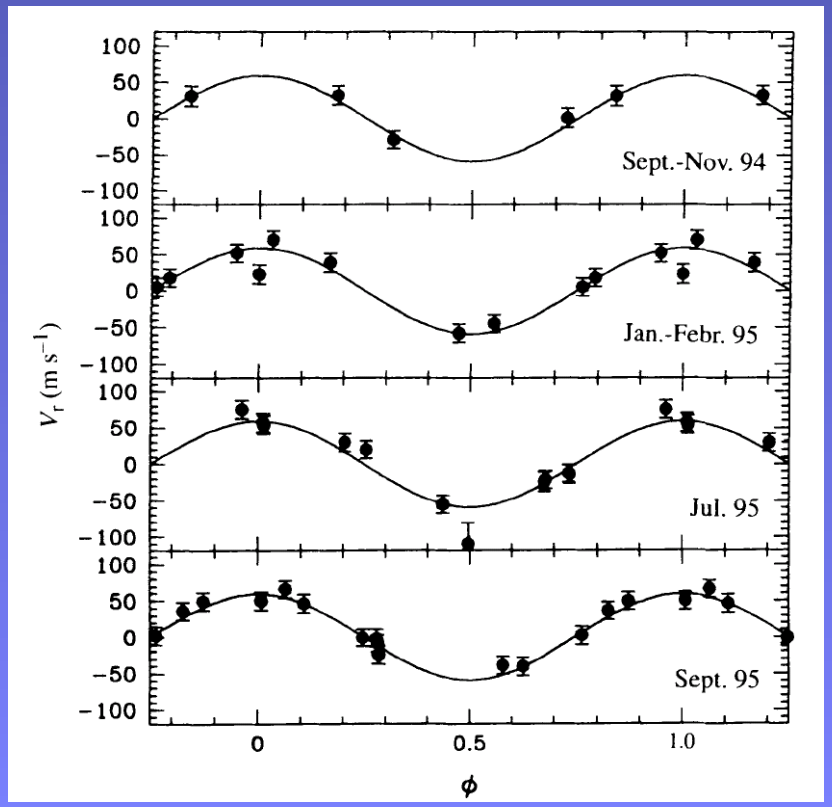
Movie was created by Massimo Mogi Vicentini for public education use, originally at the Civico Planetario di Milano.


Planets known 1988
Mass (ME)
10000.0
1000.0
100.0
10.0
1.0
0.1
0.01
0.10
1.00
10.00
100.00
1000.00
10000.0
Semi-major axis (AU)
J
S
U
N
V
E
M
M
Giant planet region
Rocky planet region
Doppler
Transit
Kepler
Microlens
Image
Timing
SolarSys

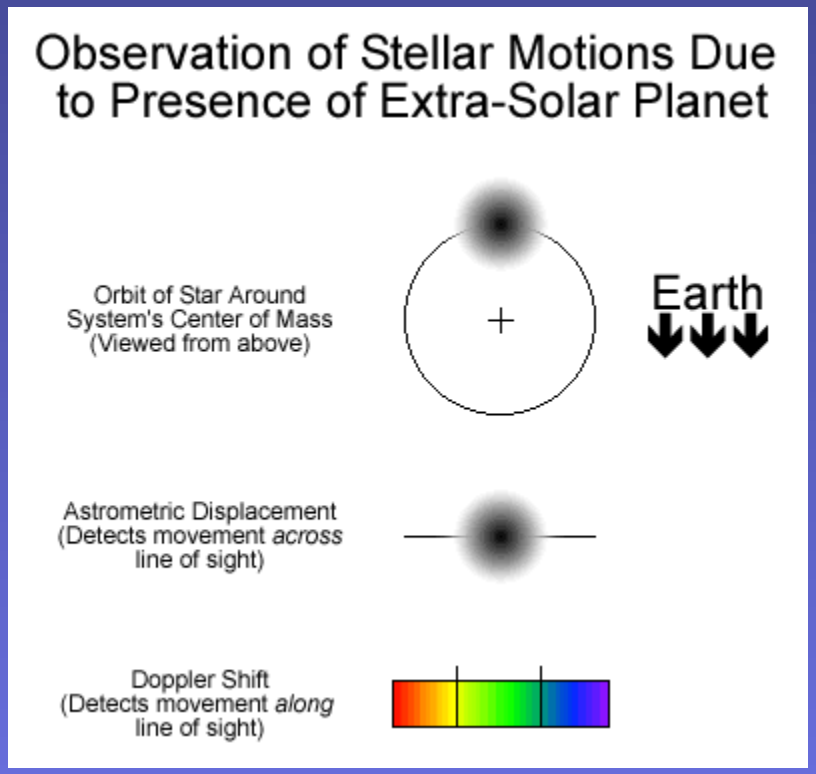
Doppler detection of exoplanets



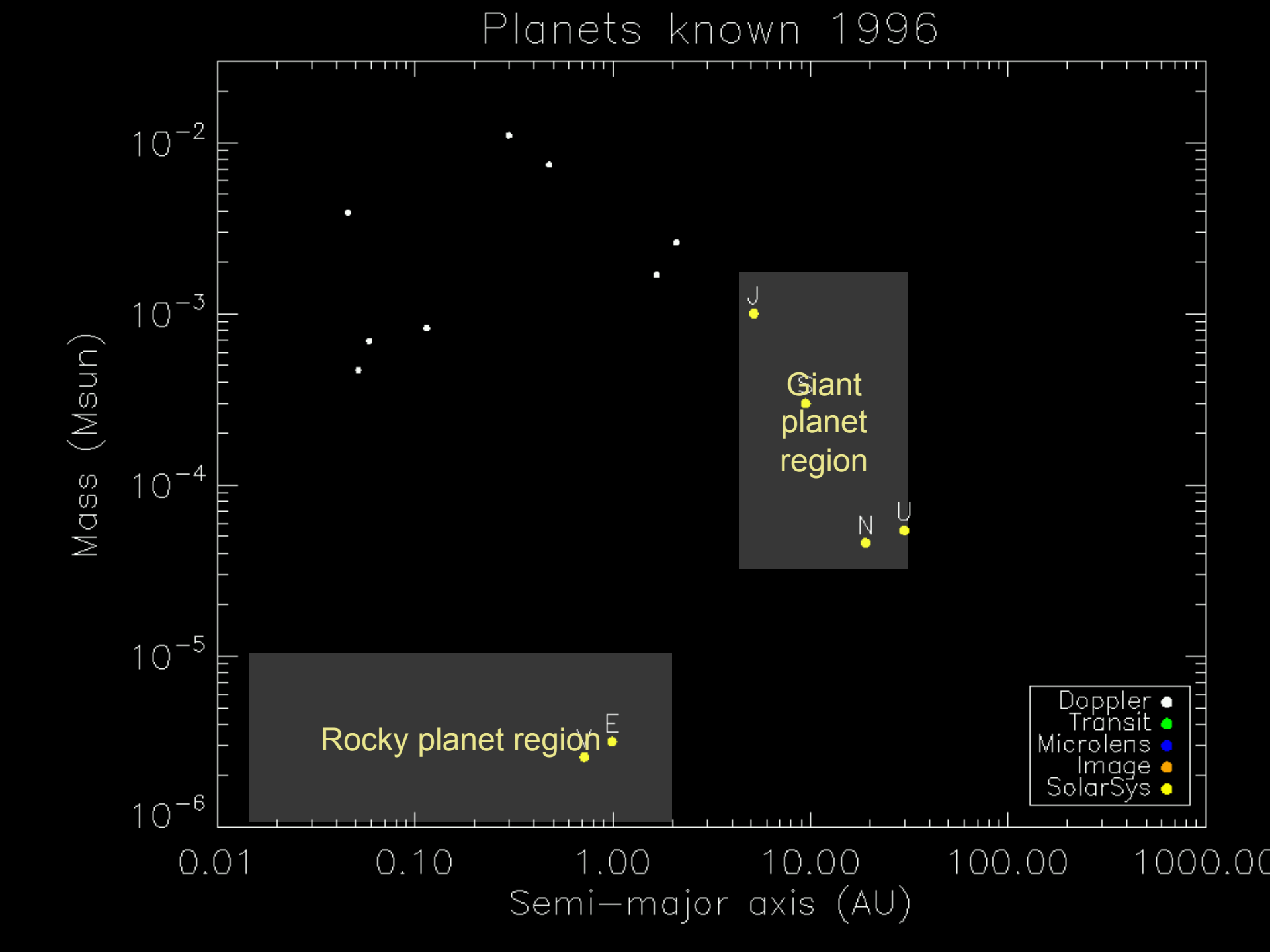
4.2 days

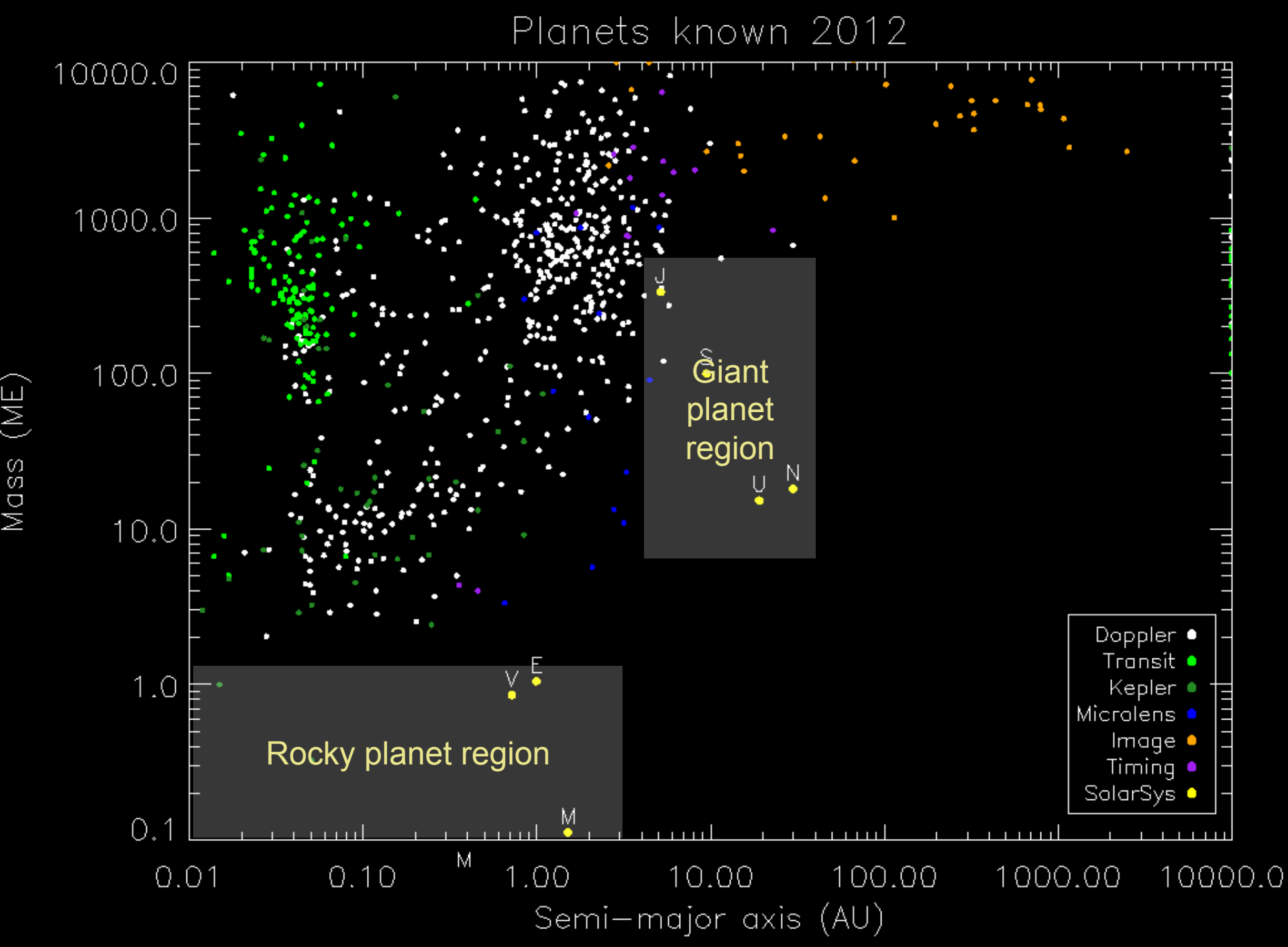


0.5 MJ

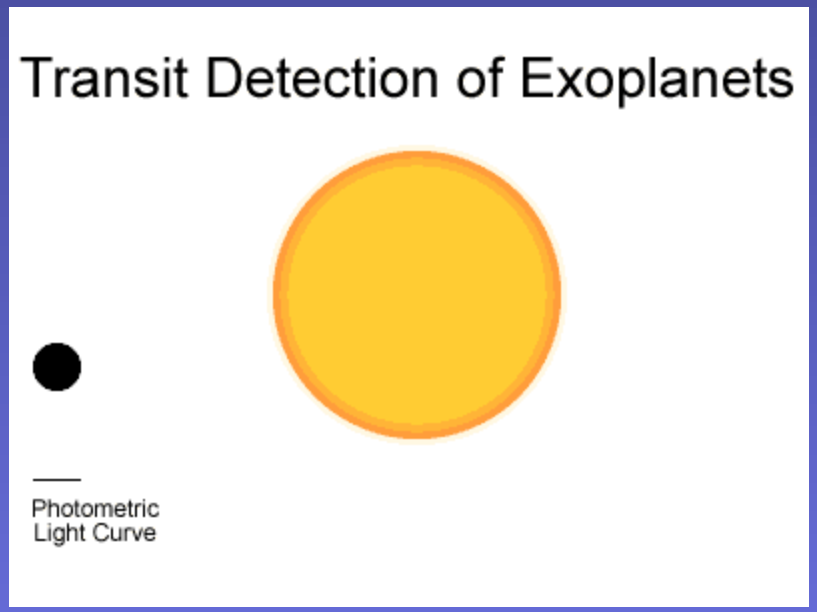


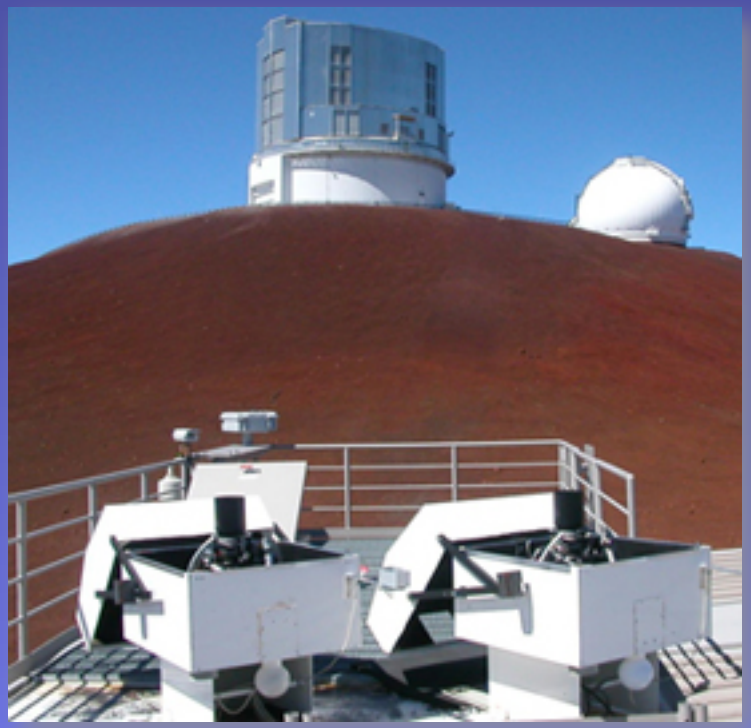
Mayor & Queloz 1995


Planets known 1996
Mass (Msun)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0.01
0.10
1.00
10.00
100.00
1000.00
Semi-major axis (AU)
J
S
N
U
E
Giant planet region
Rocky planet region
Doppler
Transit
Microlens
Image
SolarSys


Planets known 2012
Mass (ME)
10000.0
1000.0
100.0
10.0
1.0
0.1
0.01
0.10
1.00
10.00
100.00
1000.00
10000.0
Semi−major axis (AU)
J
S
U
N
V
E
M
Giant planet region
Rocky planet region
Doppler
Transit
Kepler
Microlens
Image
Timing
SolarSys

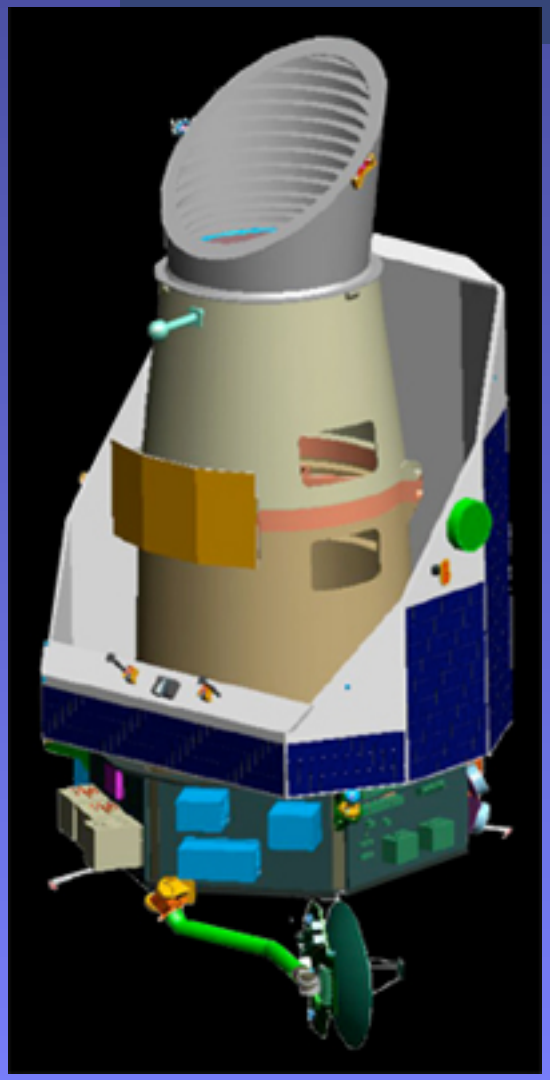
Transiting extrasolar planets

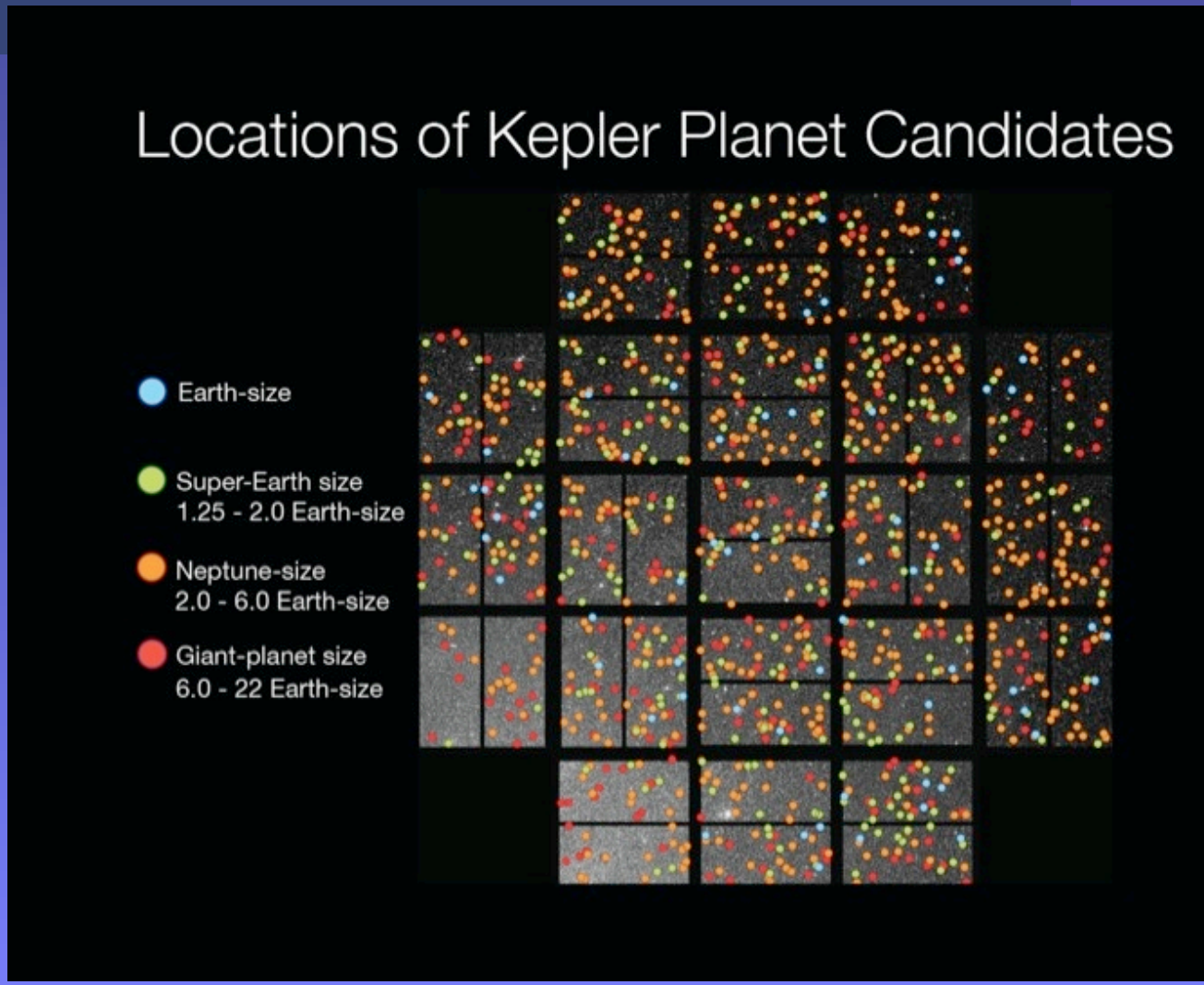




HATNET 11-cm telescopes

Kepler




Locations of Kepler Planet Candidates
Earth-size
Super-Earth size
1.25 - 2.0 Earth-size
Neptune-size
2.0 - 6.0 Earth-size
Giant-planet size
6.0 - 22 Earth-size

Kepler planet candidates

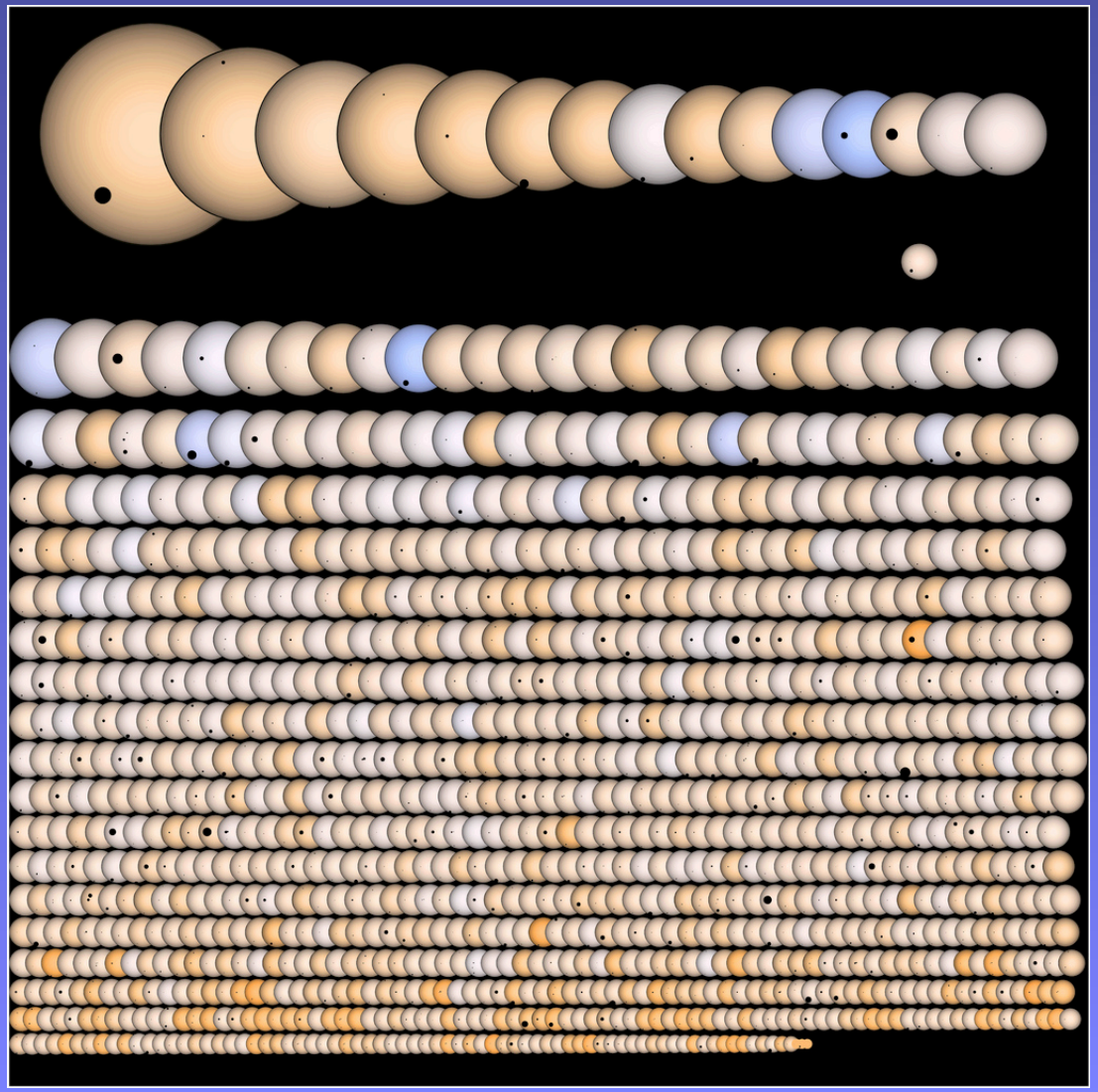
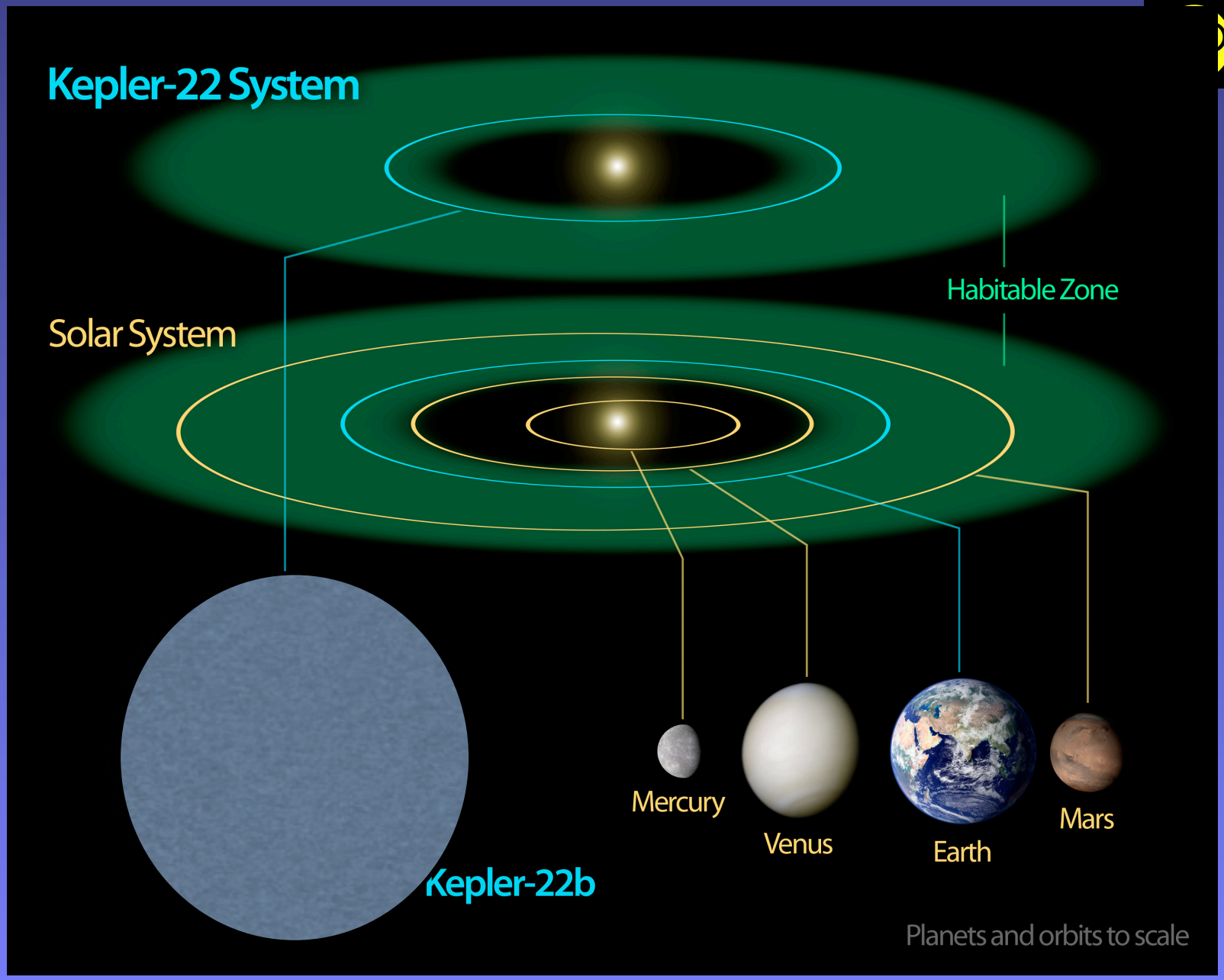
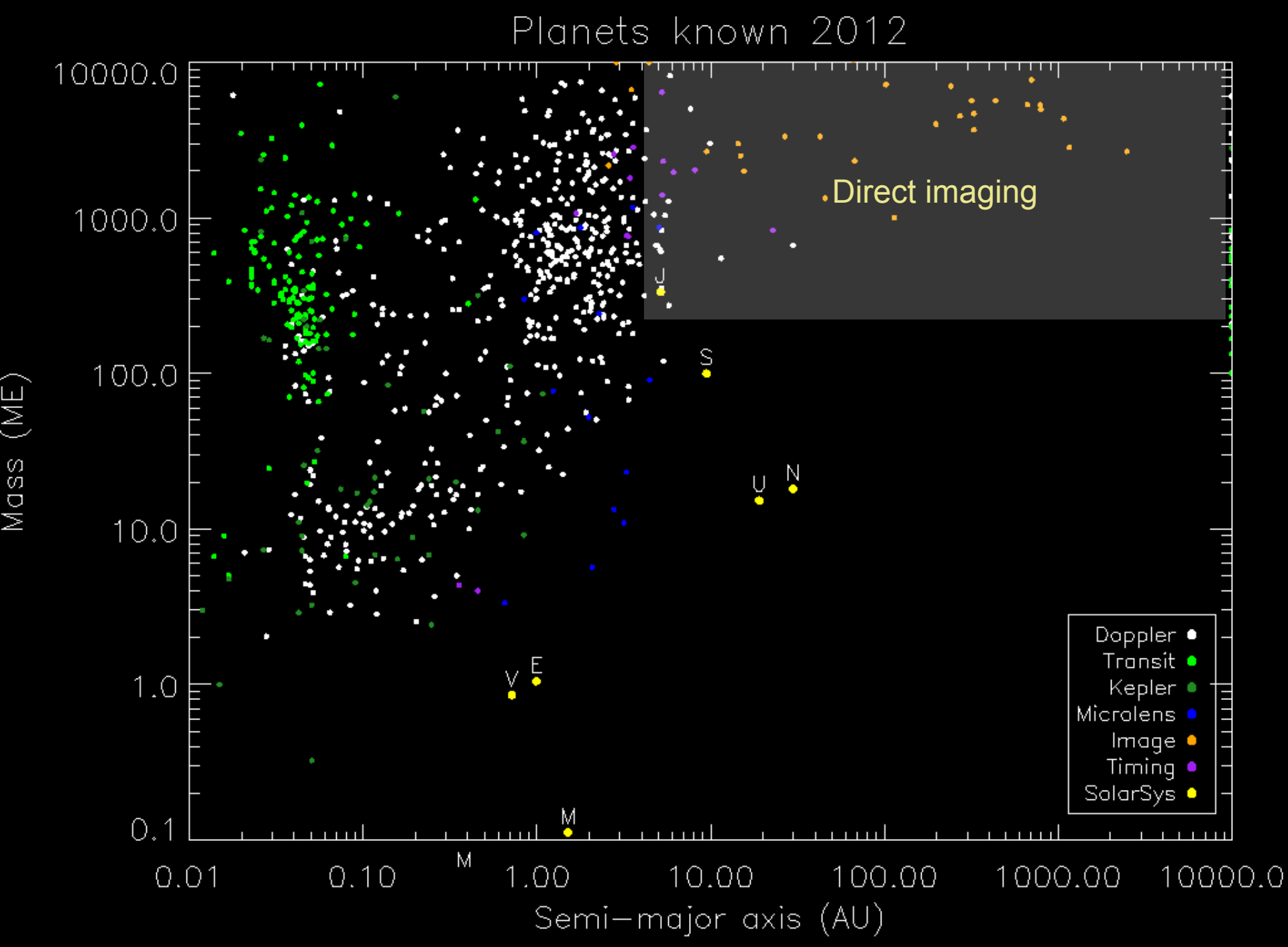


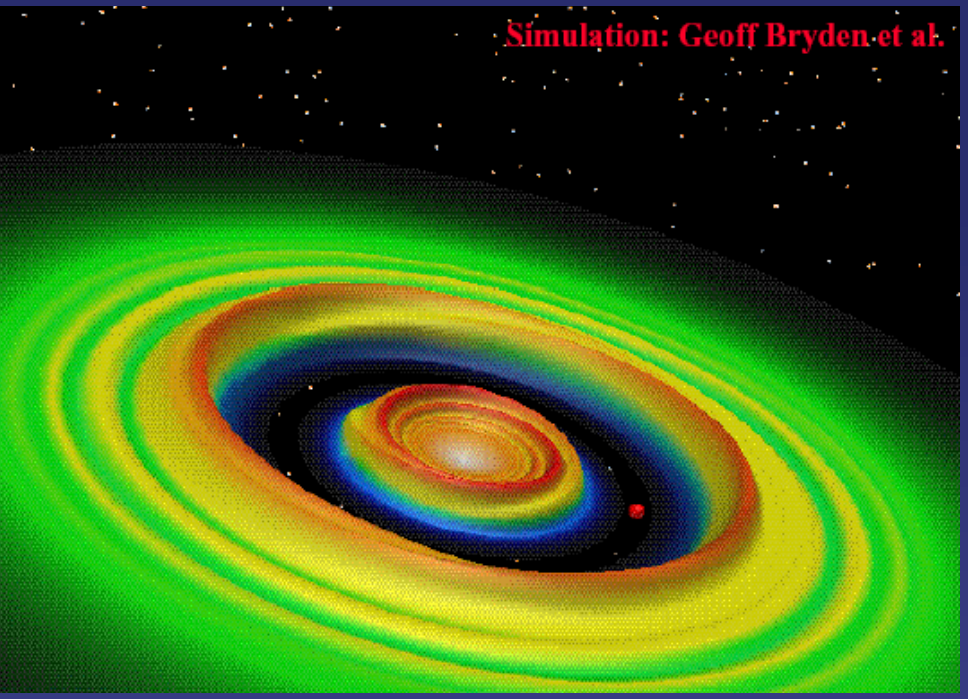
Figure by Jason Rowe

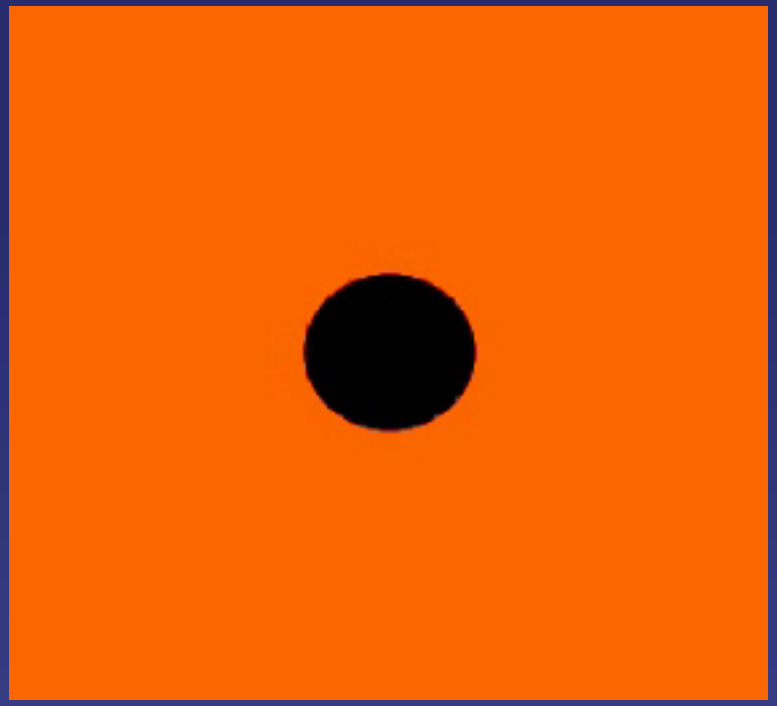


Gemini Planet Imager


Planets known 2012
Direct imaging
Mass (ME)
Semi−major axis (AU)
10000.0
1000.0
100.0
10.0
1.0
0.1
0.01
0.10
1.00
10.00
100.00
1000.00
10000.0
J
S
U
N
V
E
M
Doppler
Transit
Kepler
Microlens
Image
Timing
SolarSys

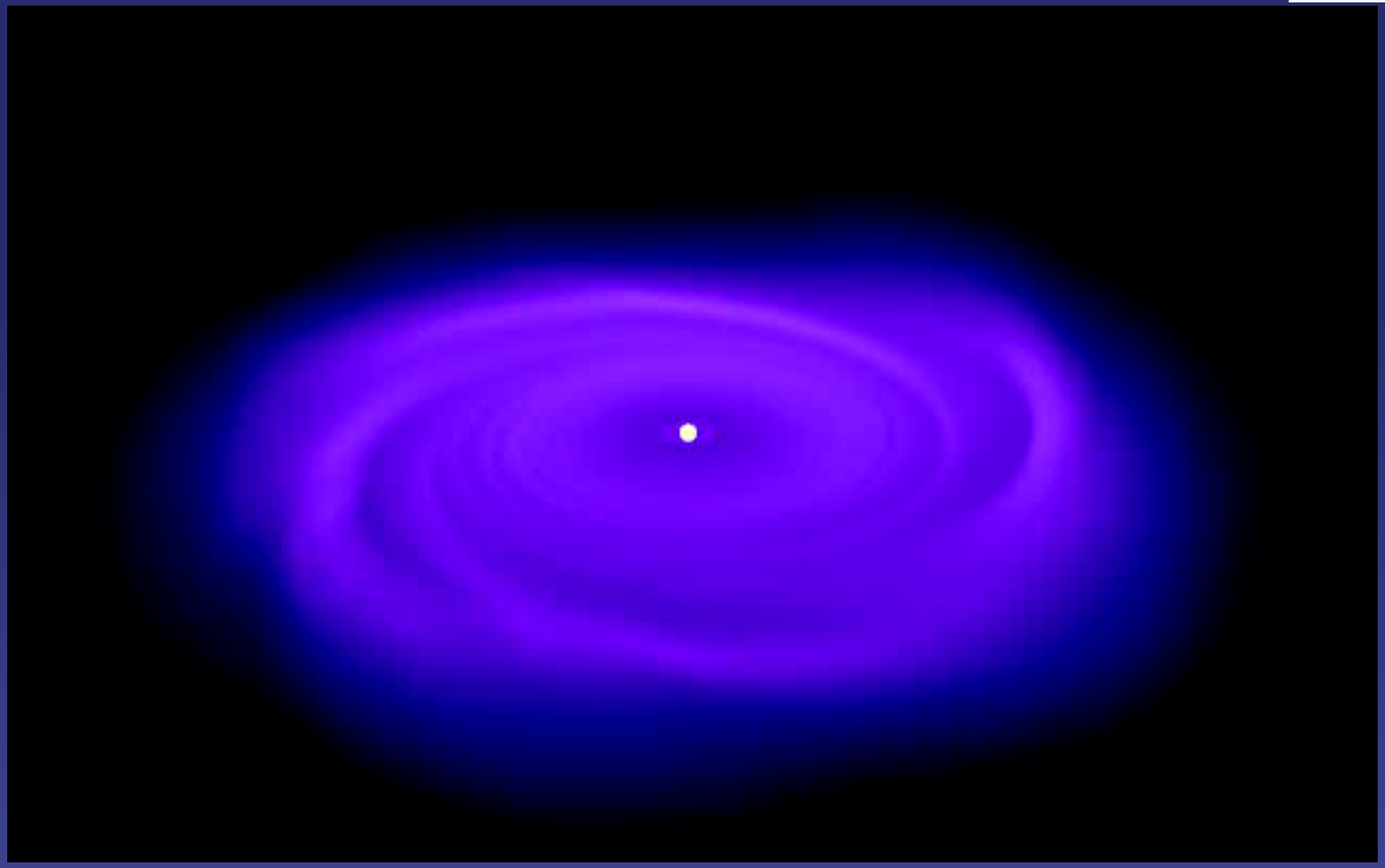
Core accretion + migration



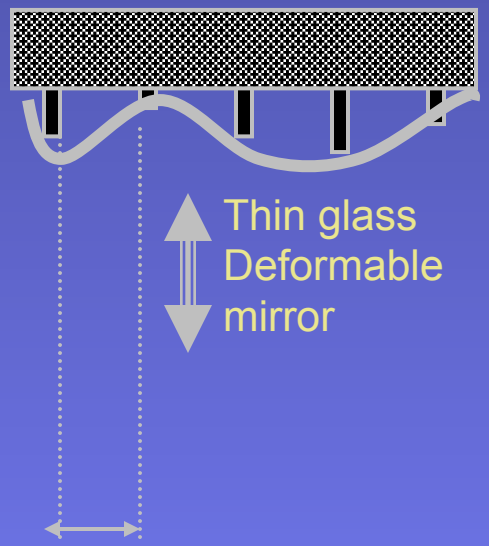


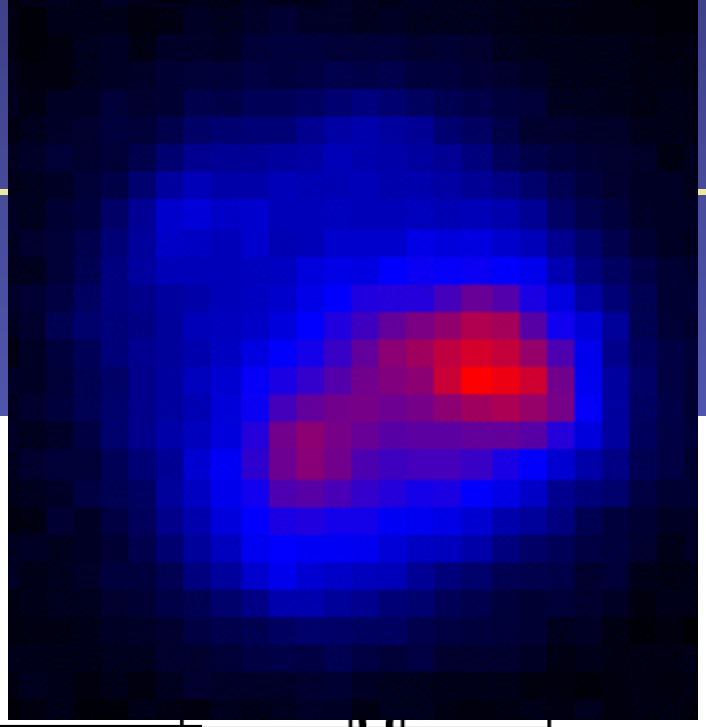
Animation by F. Masset
http://www.maths.qmul.ac.uk/~masset/moviesmpegs.html

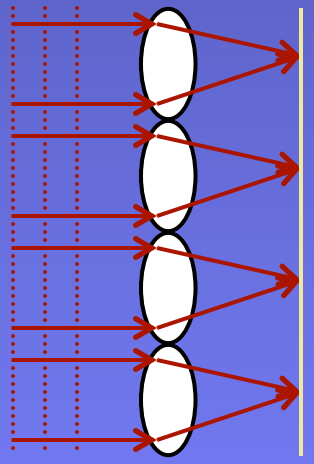
Global disk instability formation



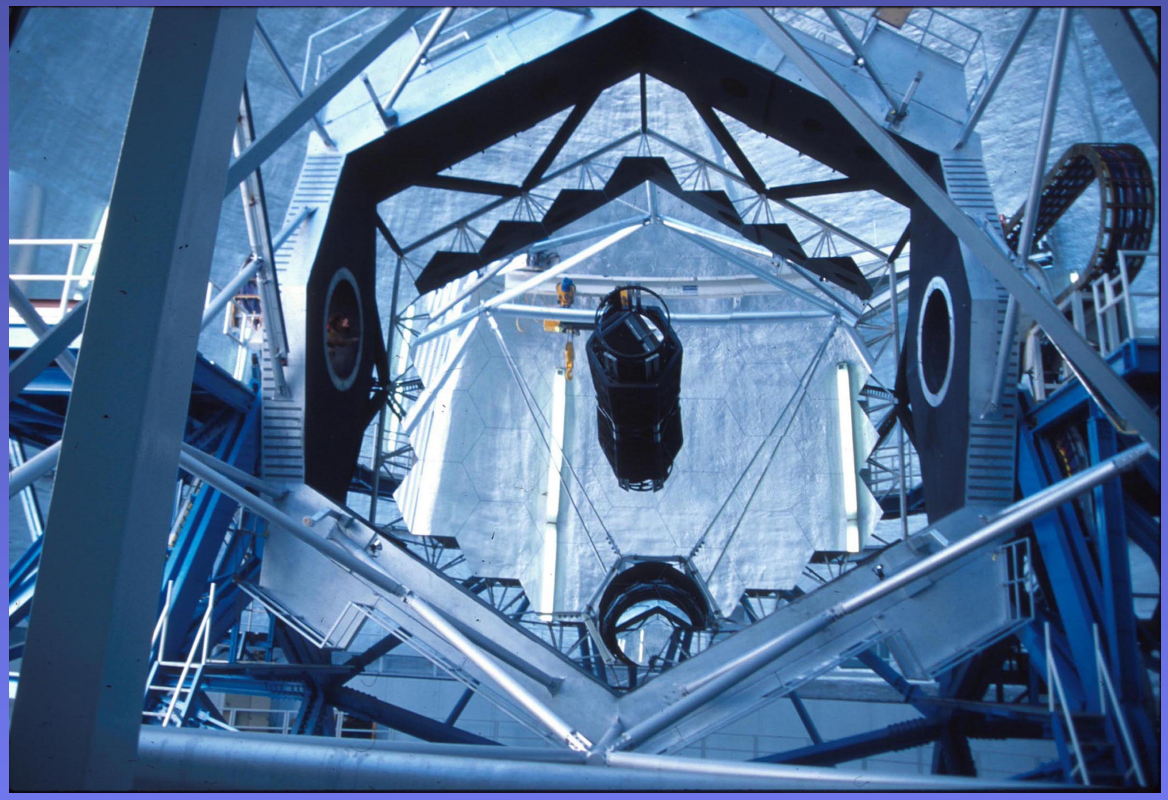
- Animation from Mayer et al


Thin glass
Deformable
mirror
d=actuator spacing

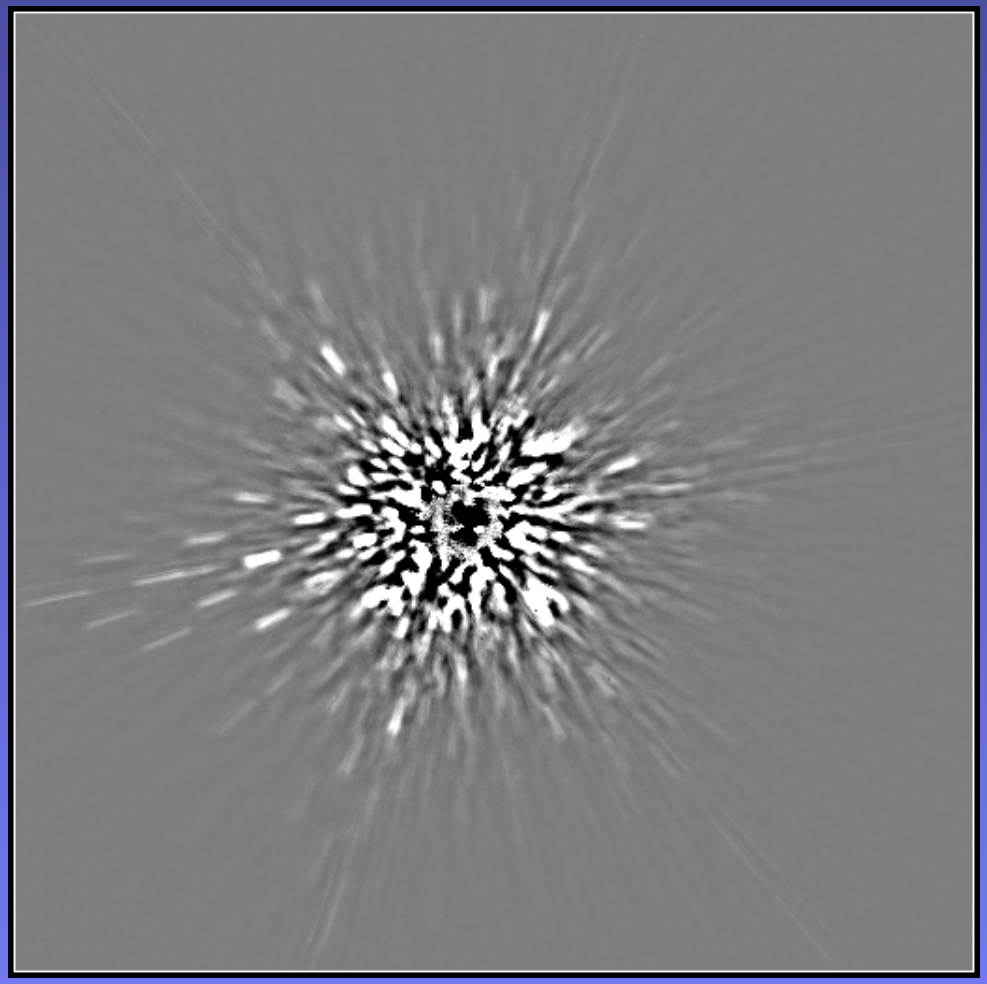



Shack-Hartmann
Wavefront sensor
d

10-m W.M. Keck II Telescope



Keck AO Image of a bright star



Fourier Optics 101

Pupil plane

$$E(x,y) = A(x,y)e^{i\Phi(x,y)}$$

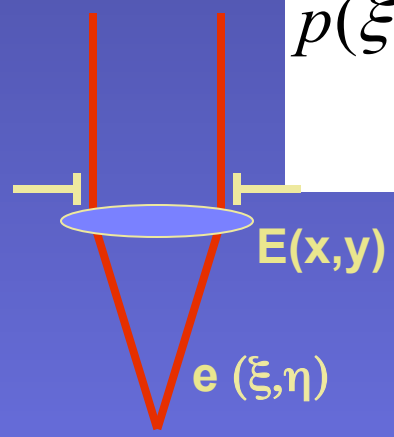
A(x,y) = Amplitude
Φ(x,y) = Phase

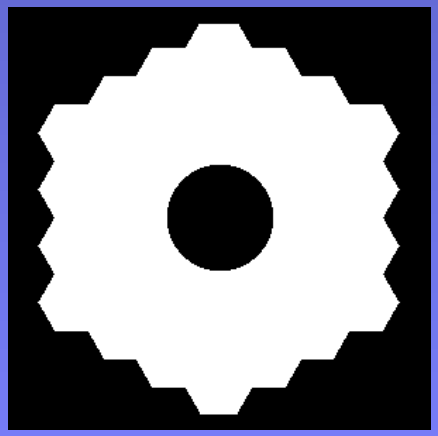
Focal plane

$$e(\xi,\eta) = FT(A(x,y)e^{i\Phi(x,y)})$$

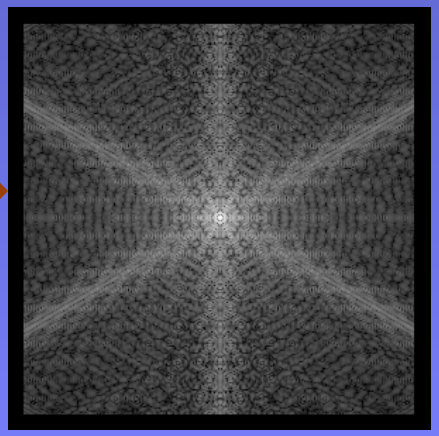
$$p(\xi,\eta) = |e(\xi,\eta)|^2$$

$$\approx |FT(A)|^2 + [\ldots] + |FT(\Phi)|^2$$



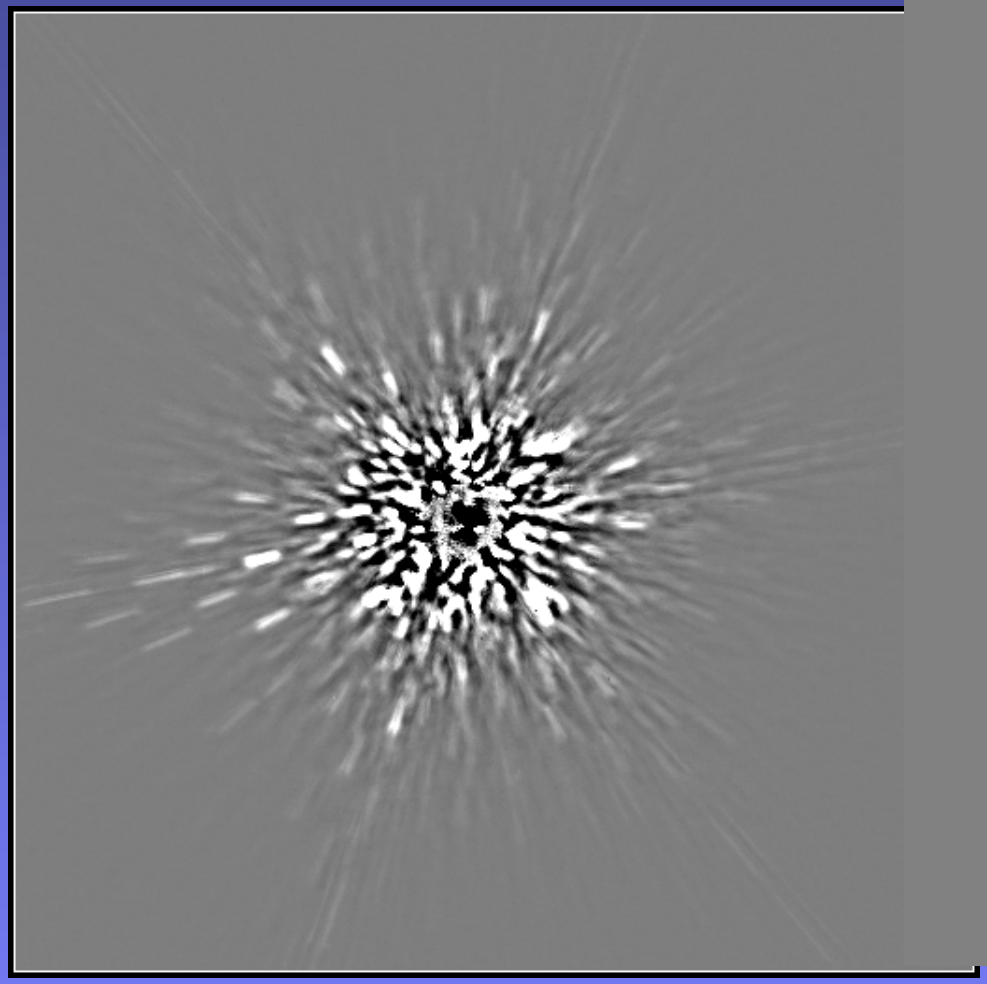


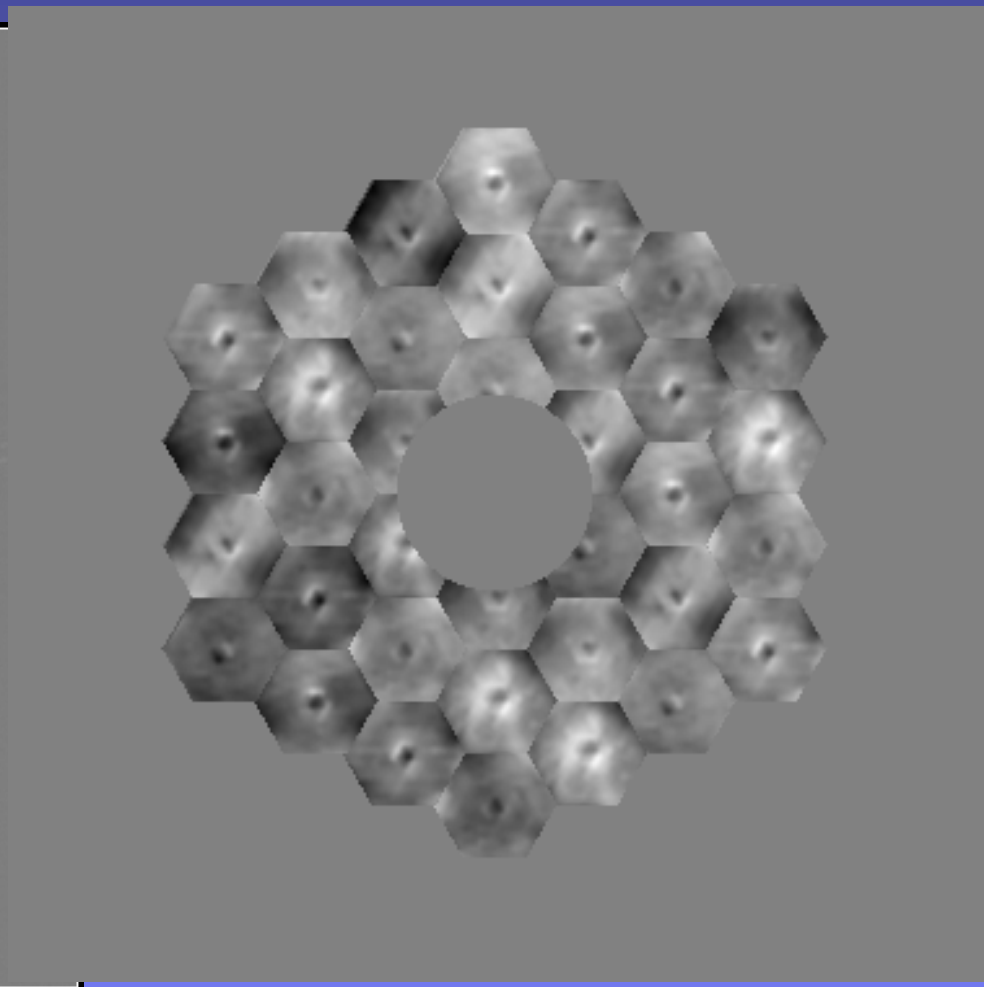
FOURIER TRANSFORM



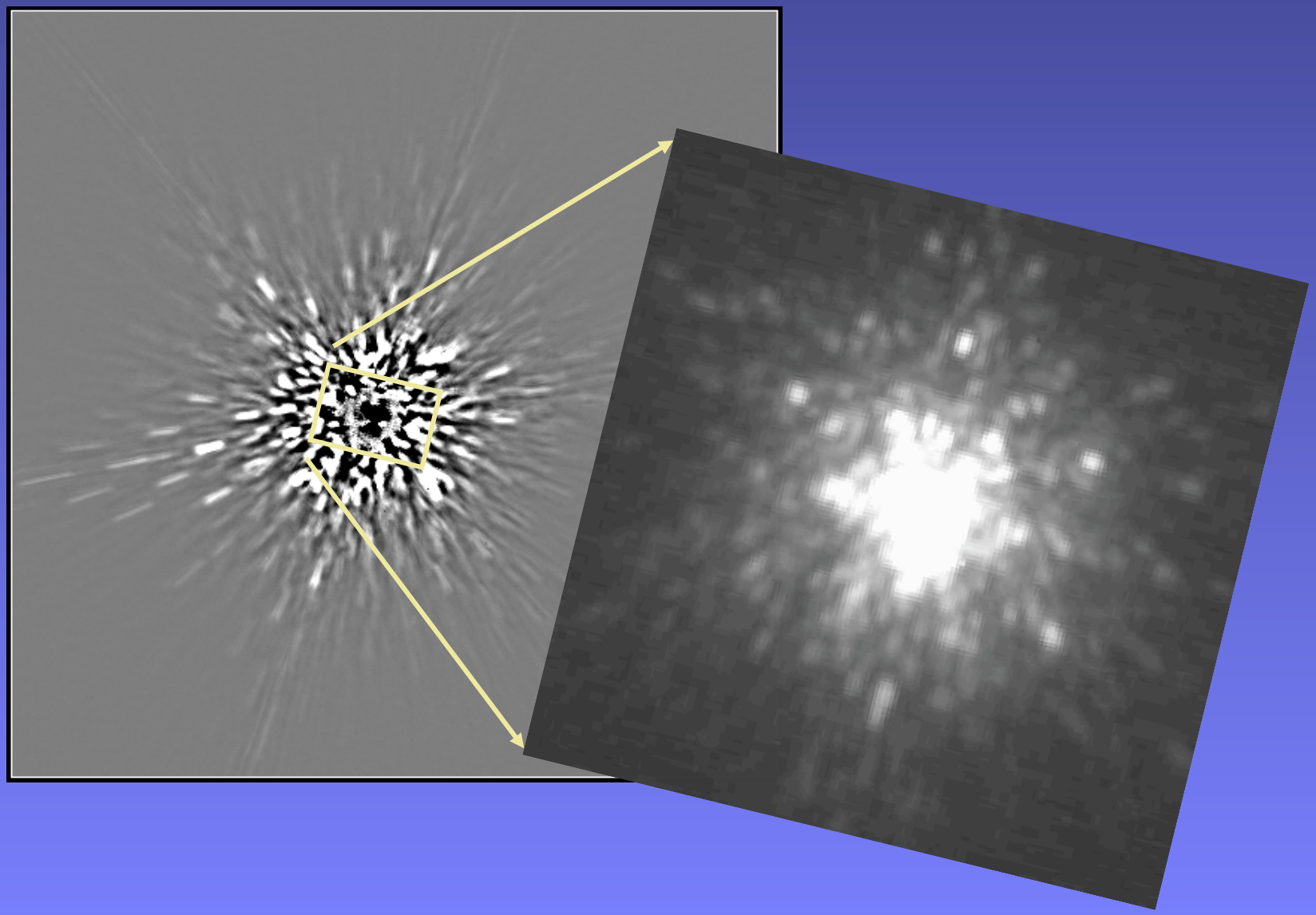
(Sivaramakrishnan et al 2002 Ap.J. 581, L59; Perrin et al 2003)

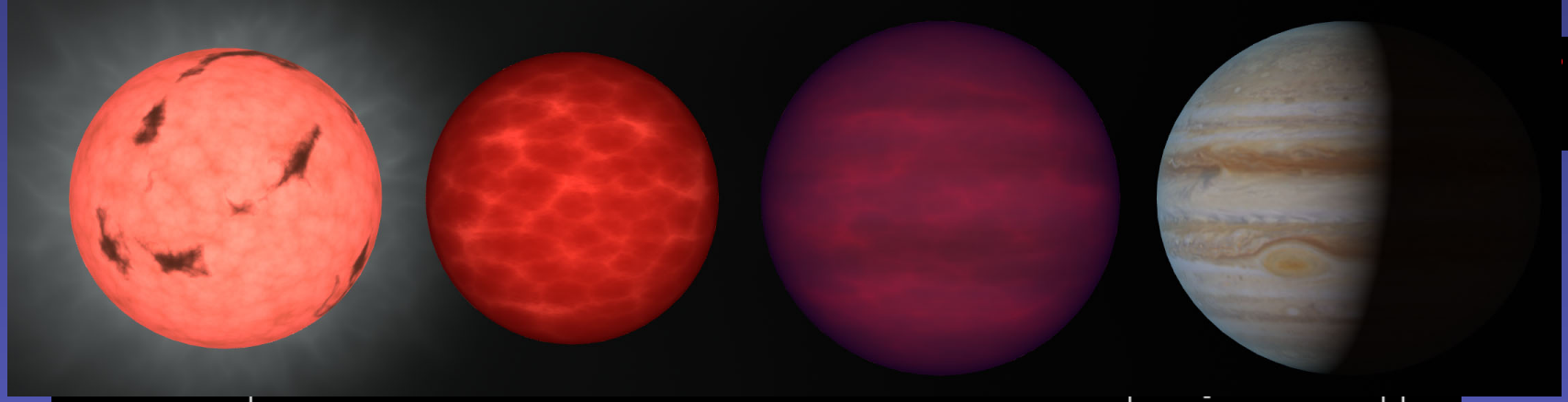
Keck AO Image of a bright star



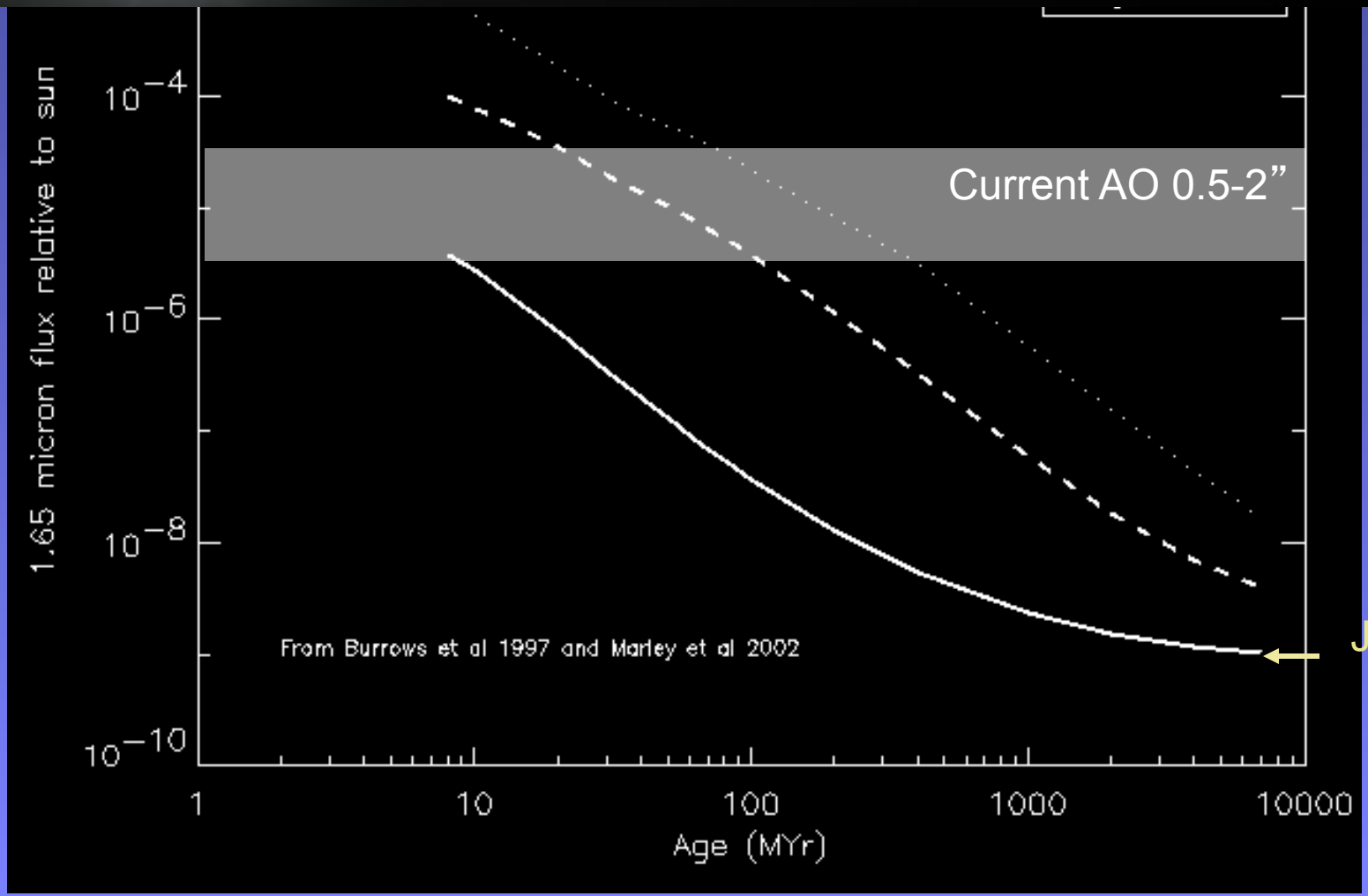


Inner part of image - artifacts due to AO optics

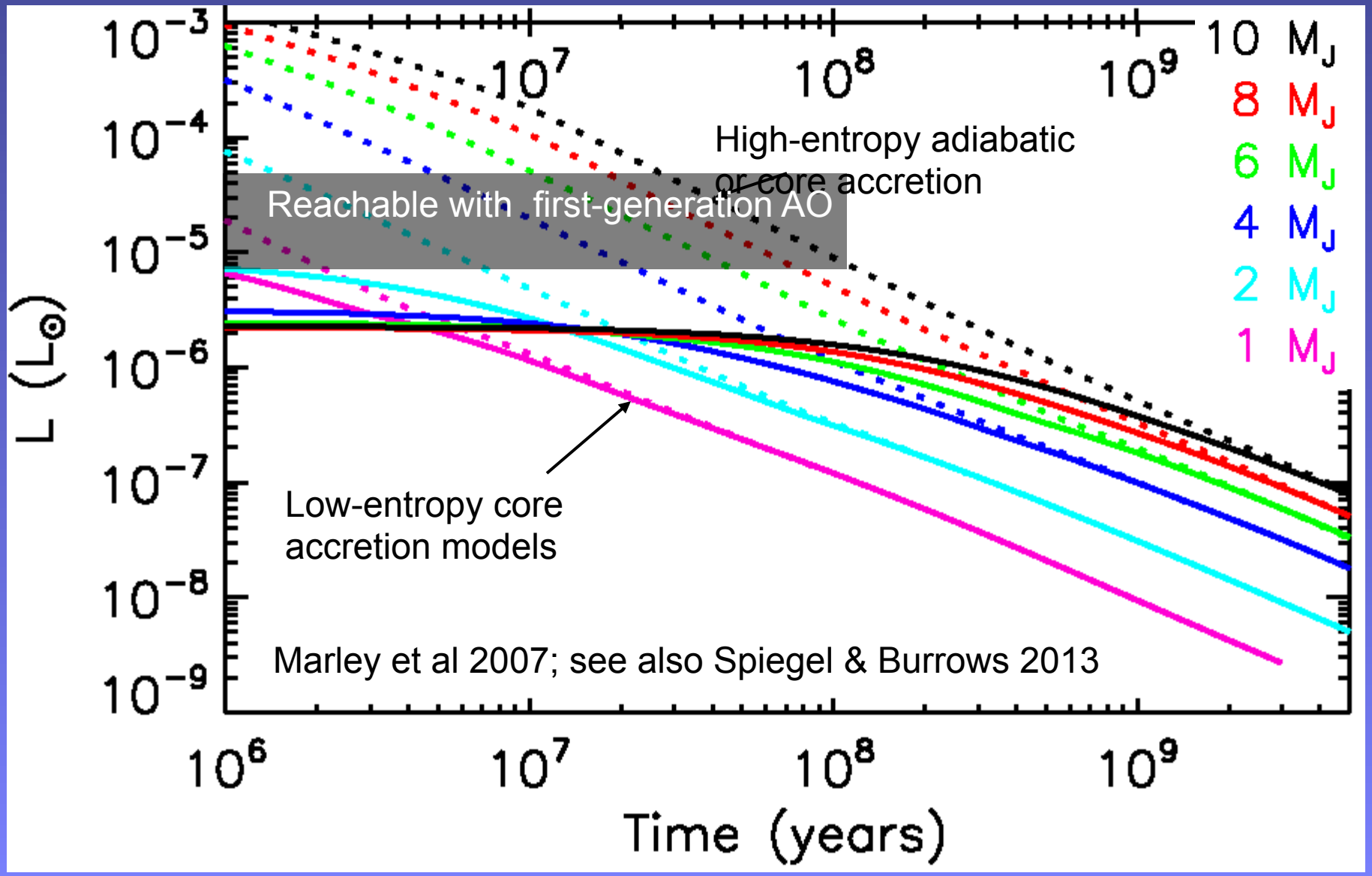




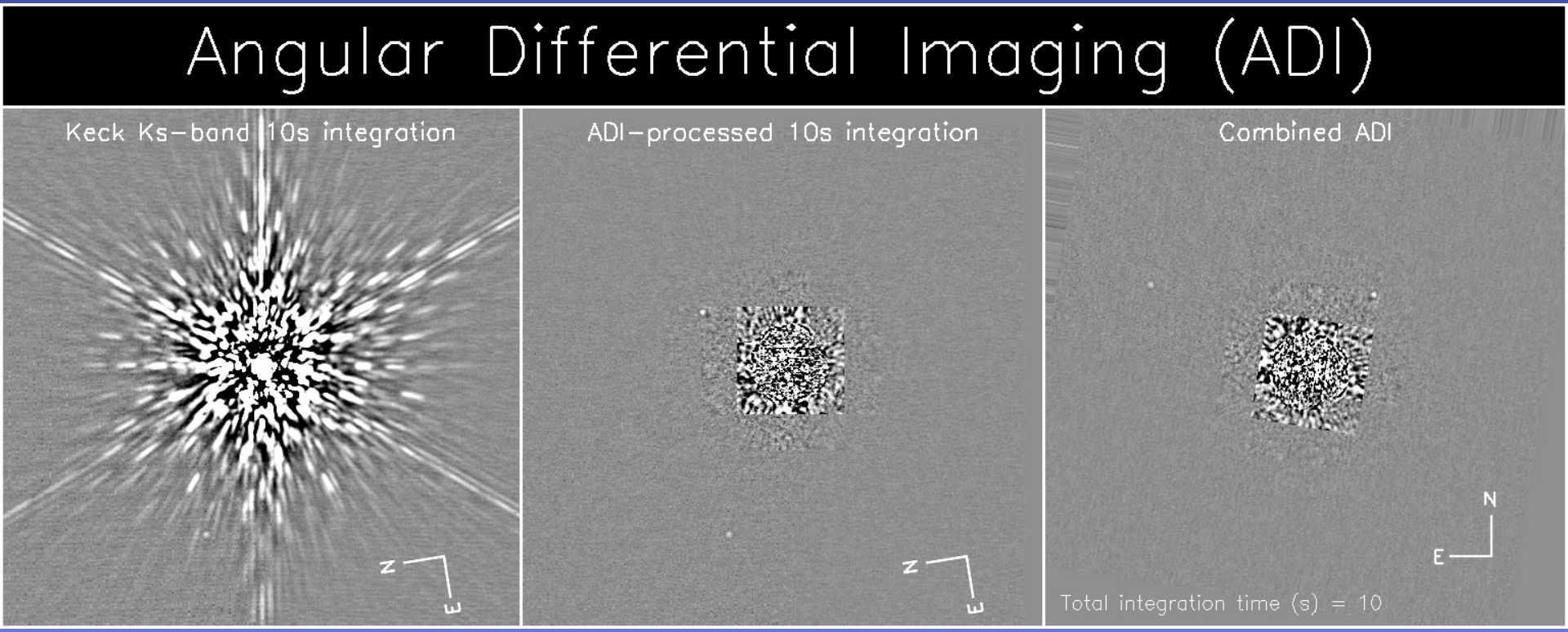
Gemini Planet Imager



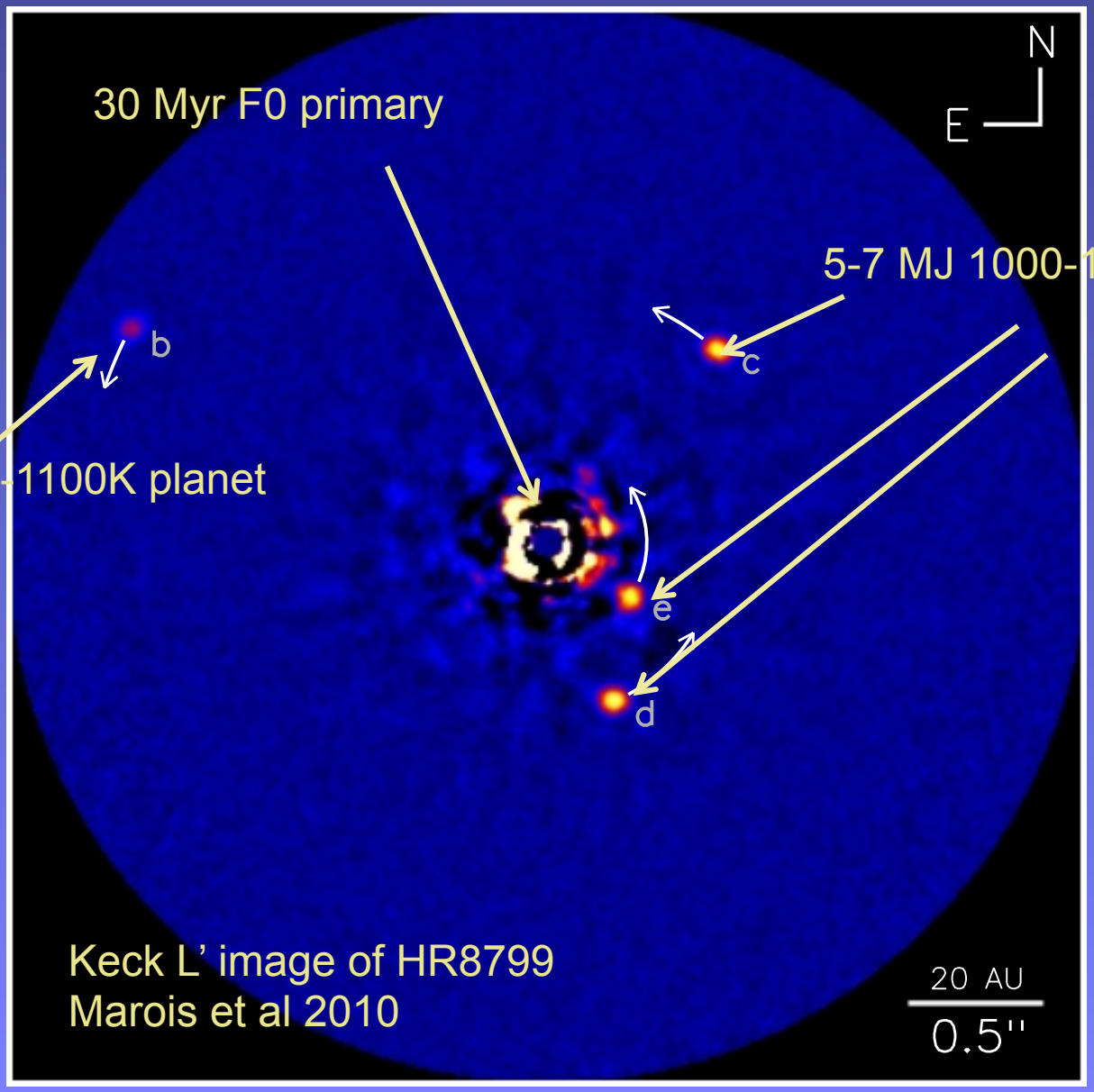
Luminosity depends on initial conditions

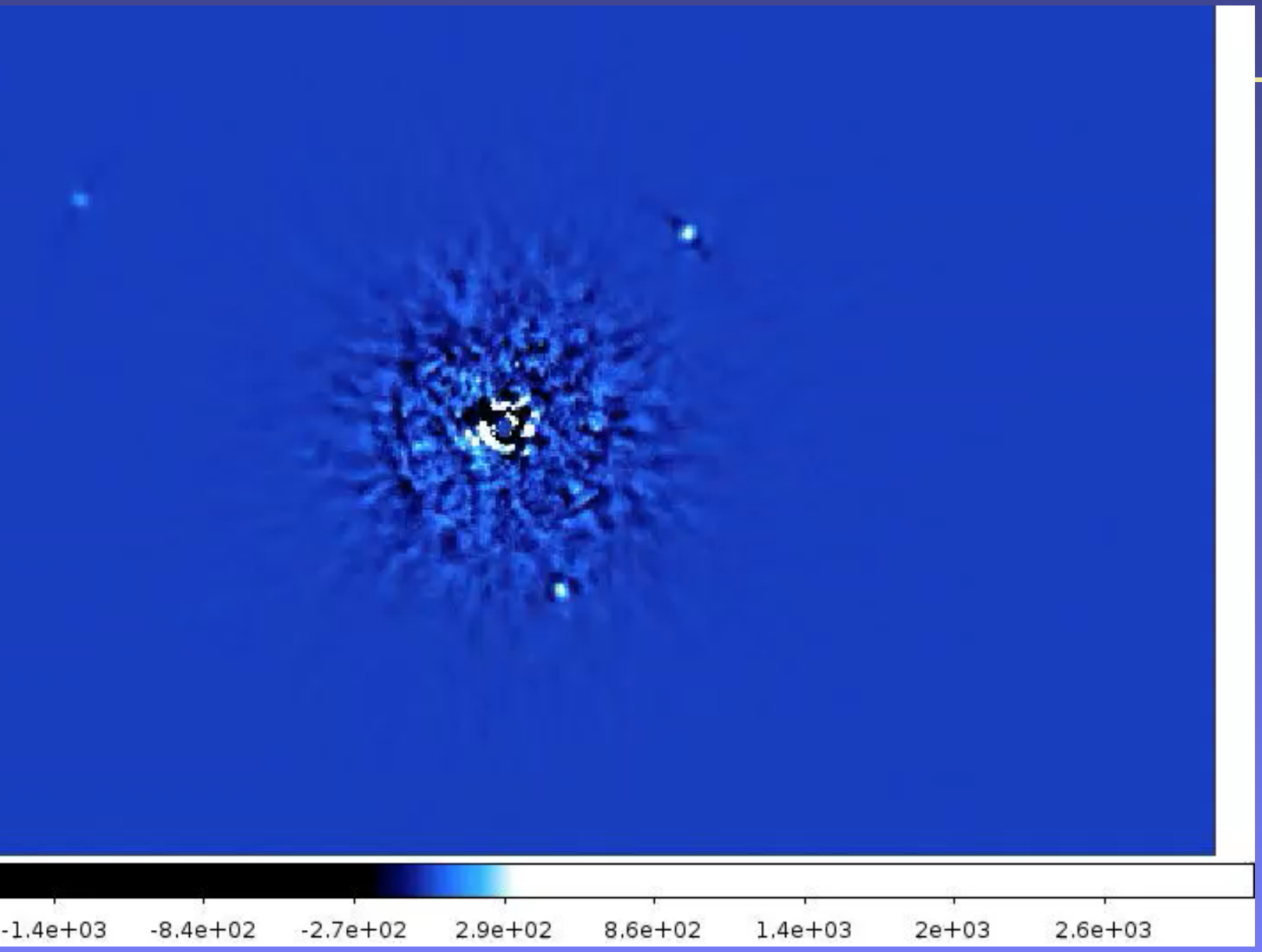


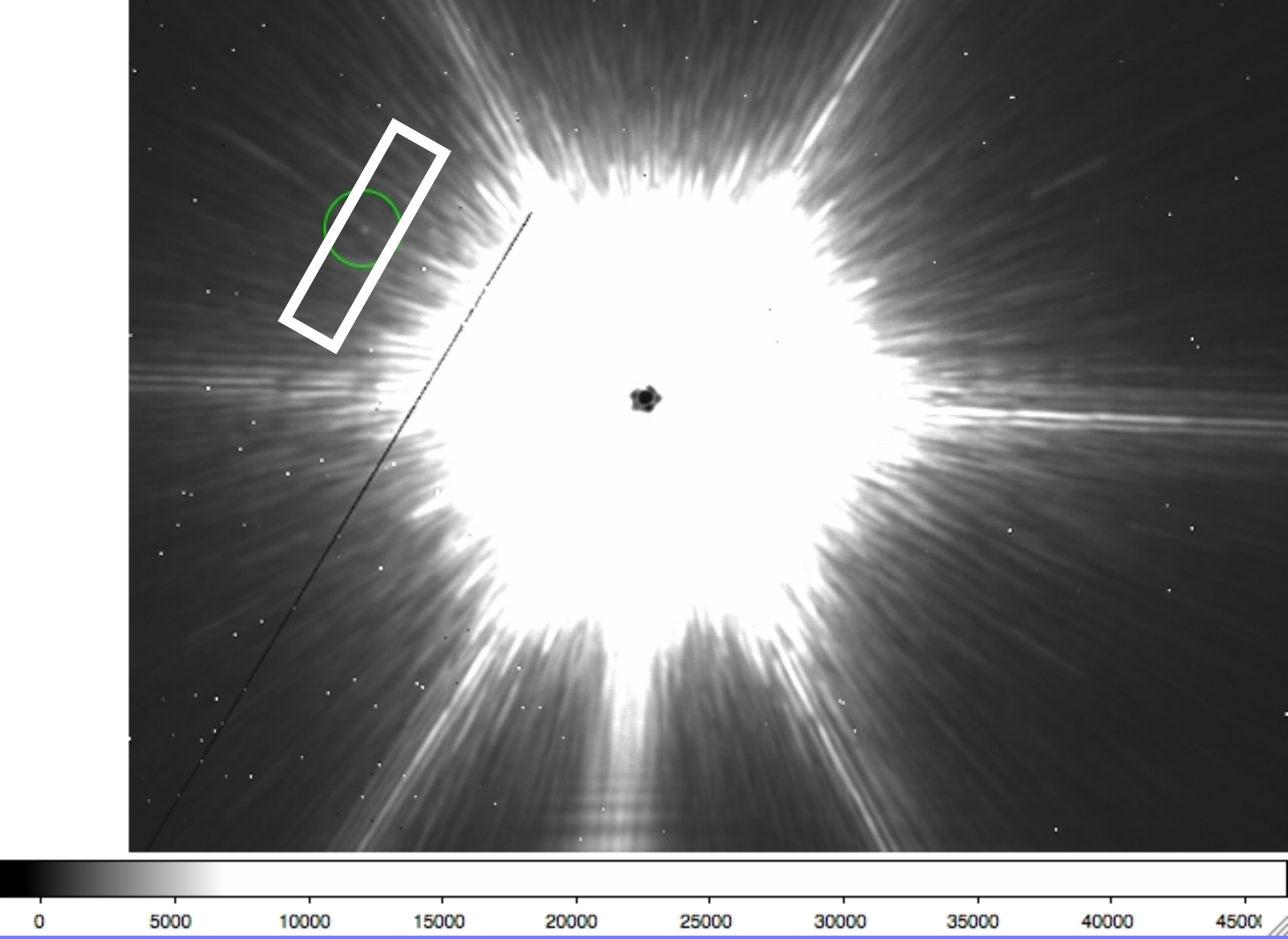
Taking advantage of the Earth's rotation



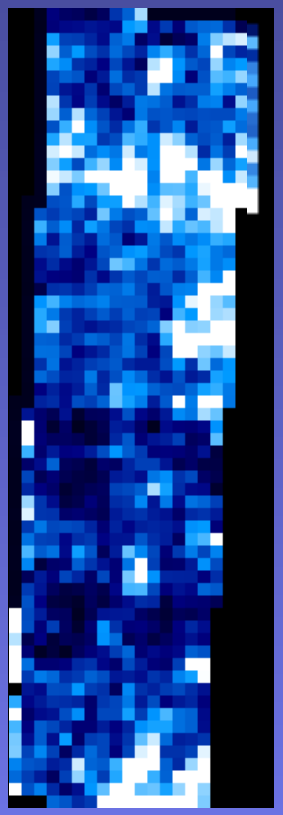
HR8799

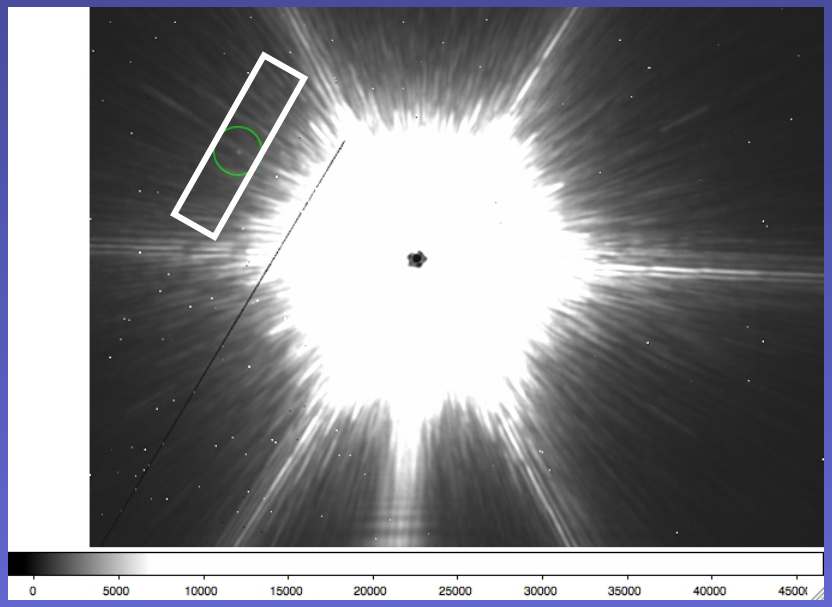

30 Myr F0 primary
N
E
5-7 MJ 1000-1300K planets
b
c
3-5 MJ 800-1100K planet
e
d
Keck L' image of HR8799
Marois et al 2010
20 AU
0.5''

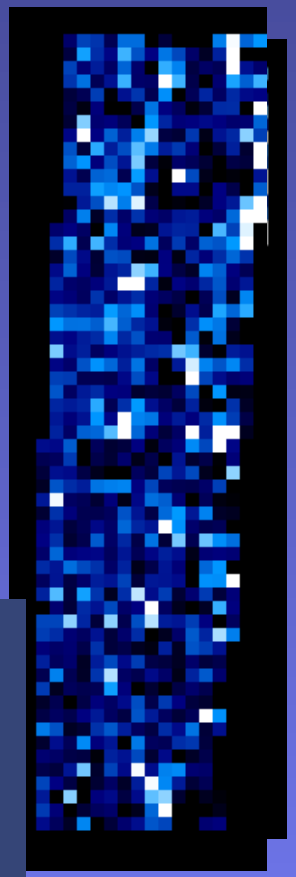

-1.4e+03
-8.4e+02
-2.7e+02
2.9e+02
8.6e+02
1.4e+03
2e+03
2.6e+03


0
5000
10000
15000
20000
25000
30000
35000
40000
4500

Integral Field Spectroscopy of the HR8799 planets

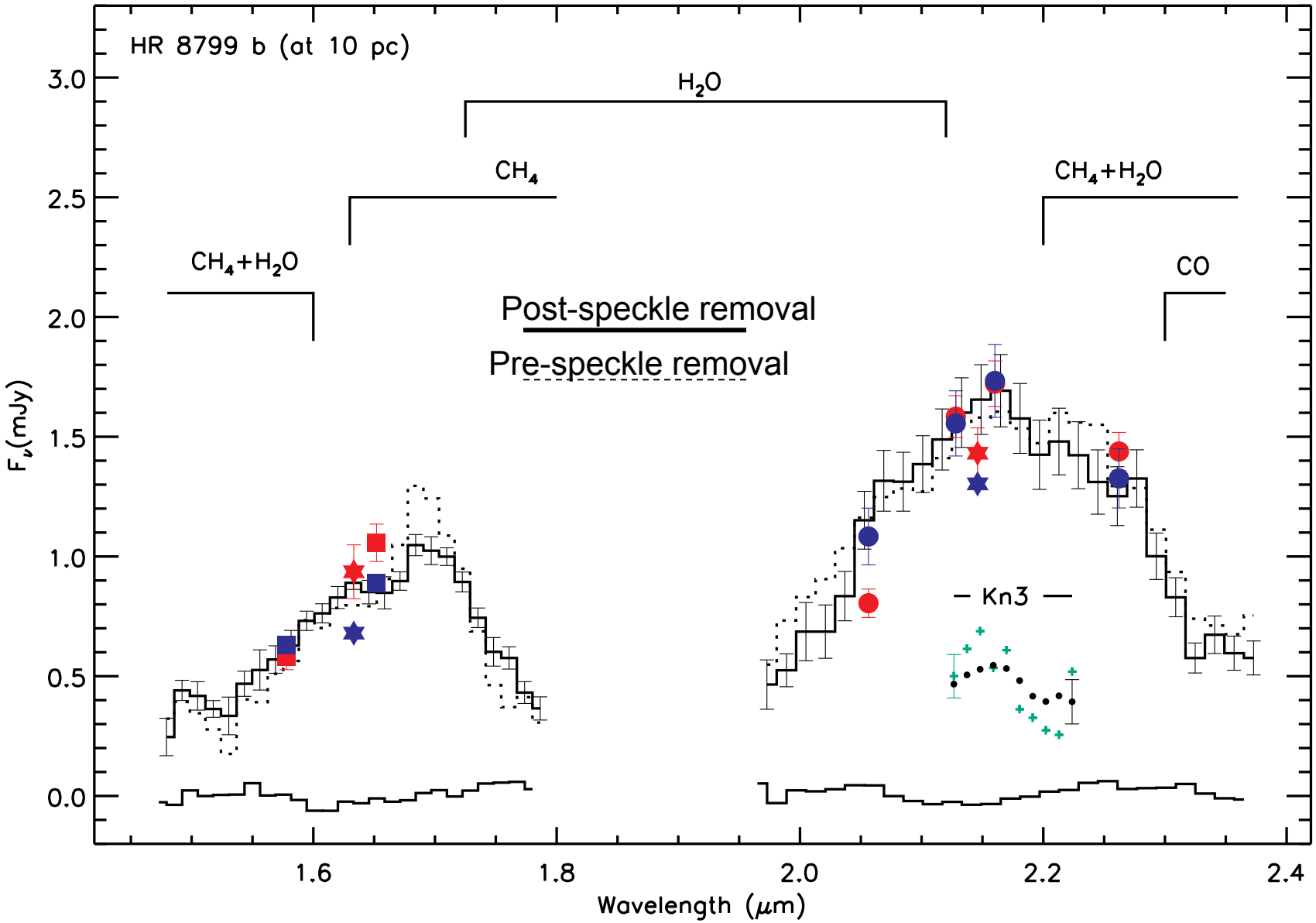




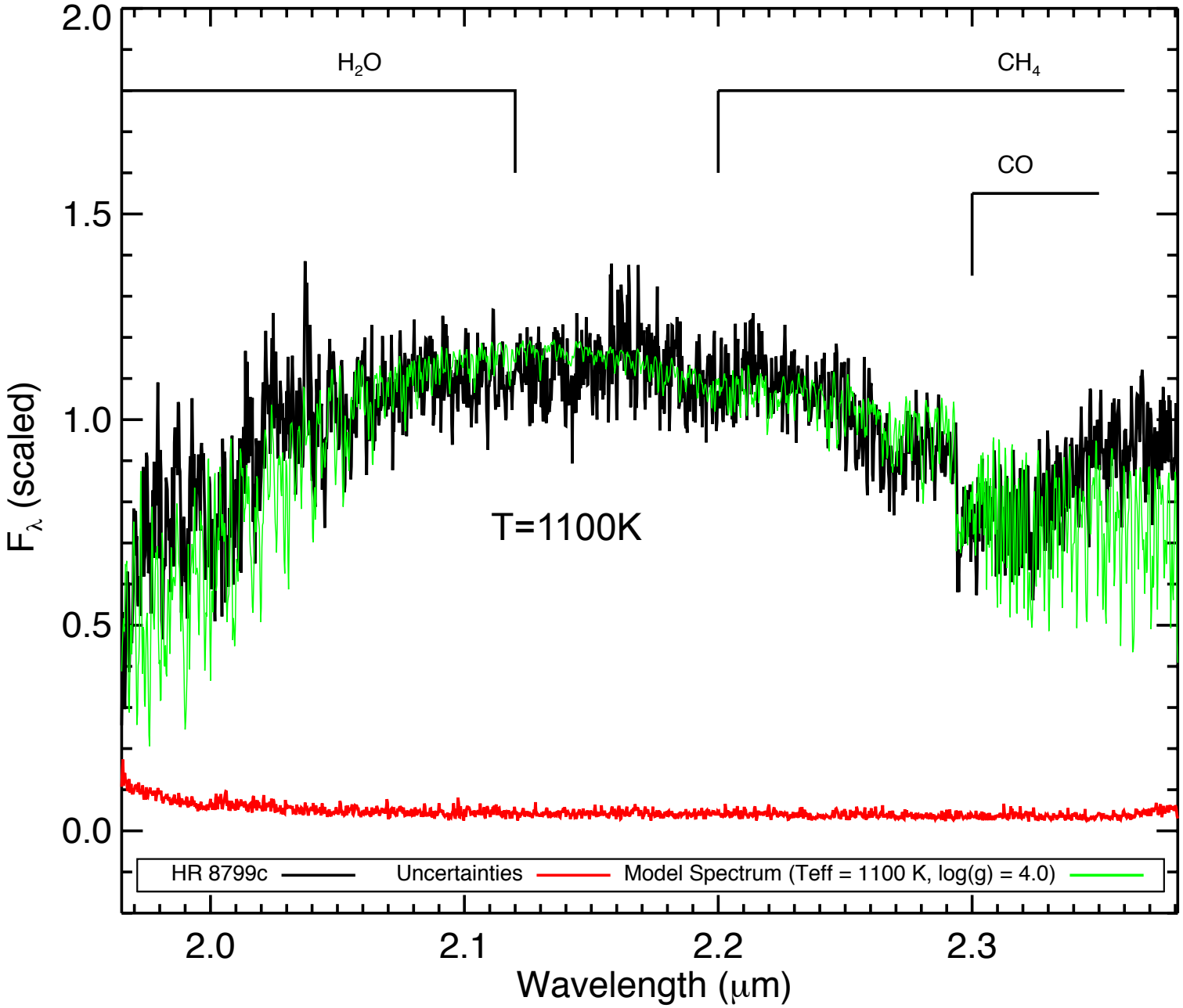


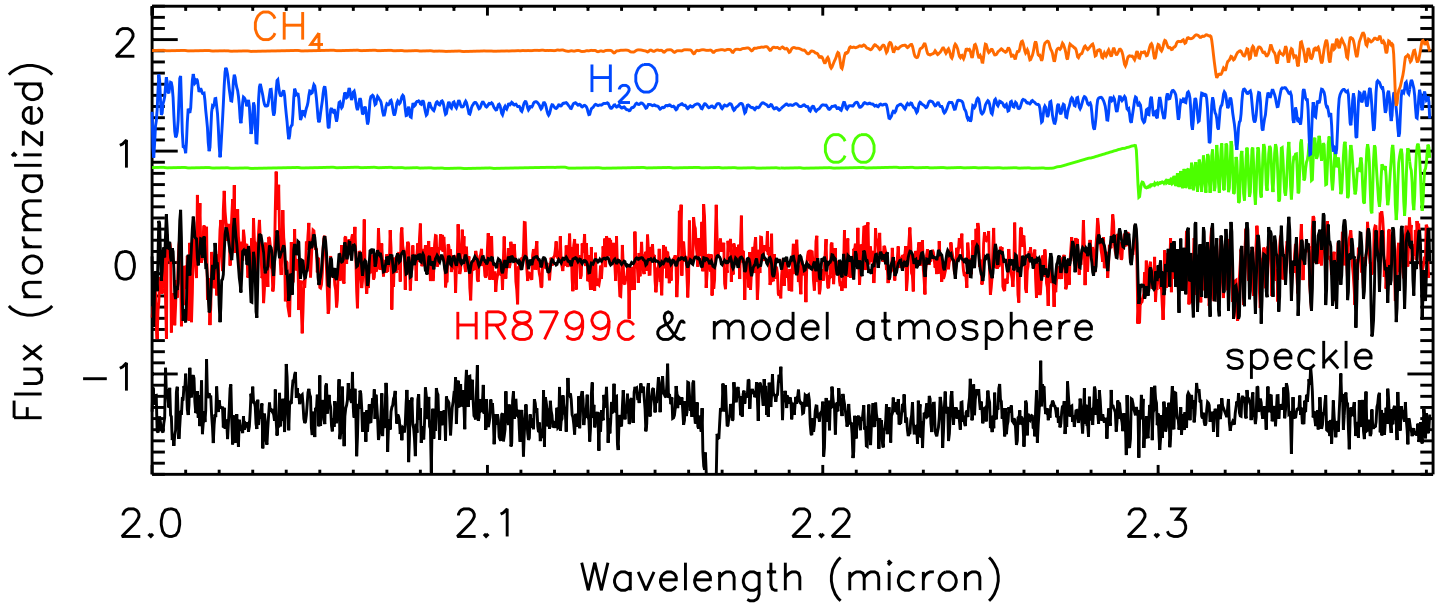
- Diffraction scaling with wavelength can partially remove artifacts

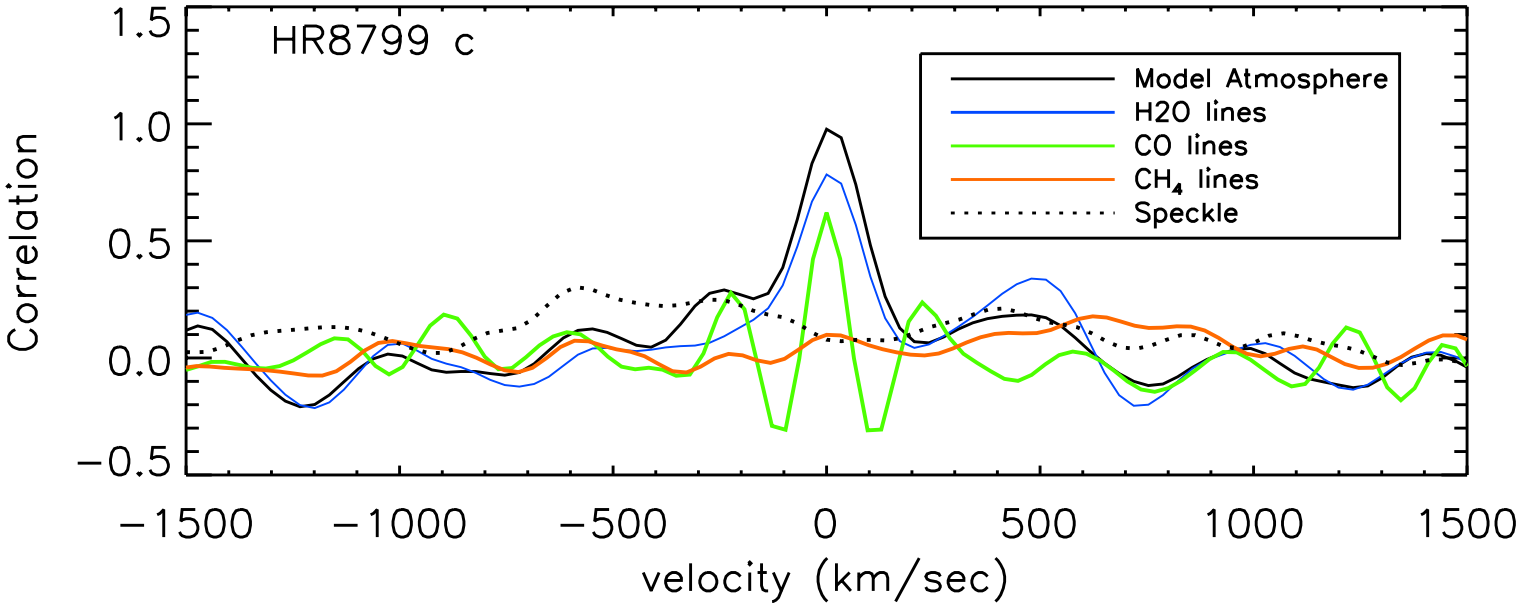
Extracted spectra of HR8799b



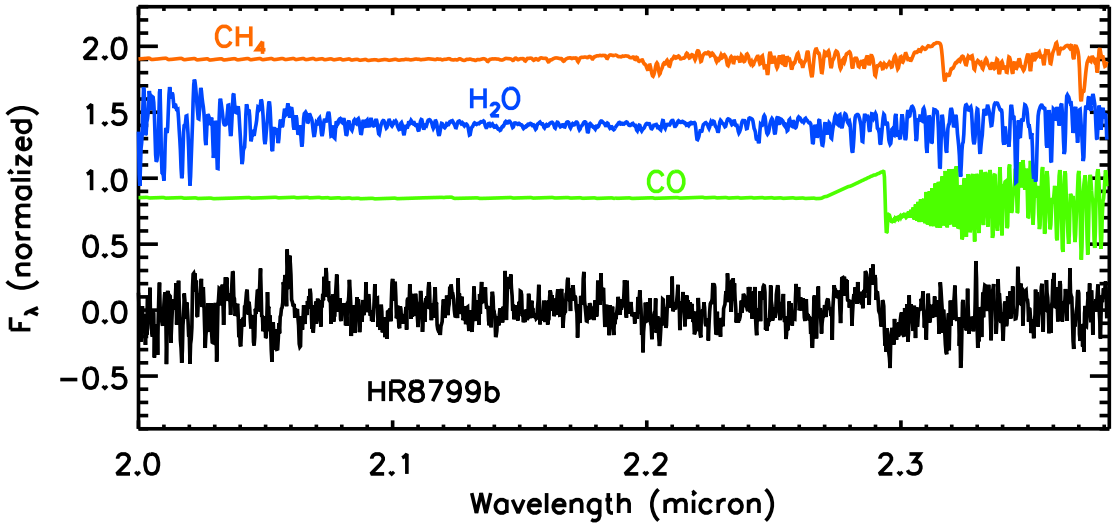
High-res spectra of HR8799c (Konpacky et al 2013)

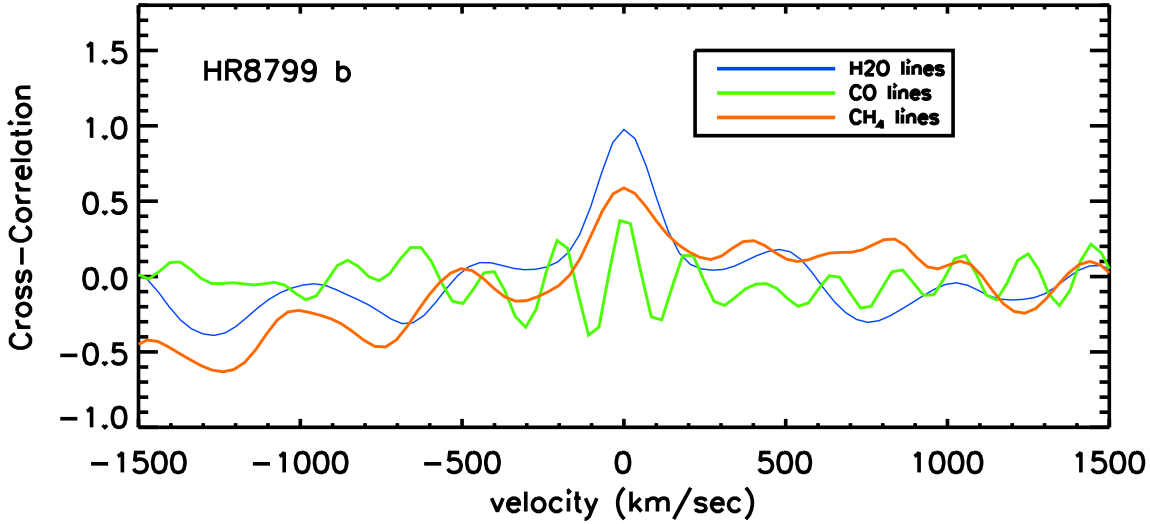



CH4
H2O
CO
HR8799c & model atmosphere
speckle
Flux (normalized)
2
1
0
−1
2.0
2.1
2.2
2.3
Wavelength (micron)


HR8799 c
Model Atmosphere
H2O lines
CO lines
CH4 lines
Speckle
Correlation
1.5
1.0
0.5
0.0
−0.5
−1500
−1000
−500
0
500
1000
1500
velocity (km/sec)

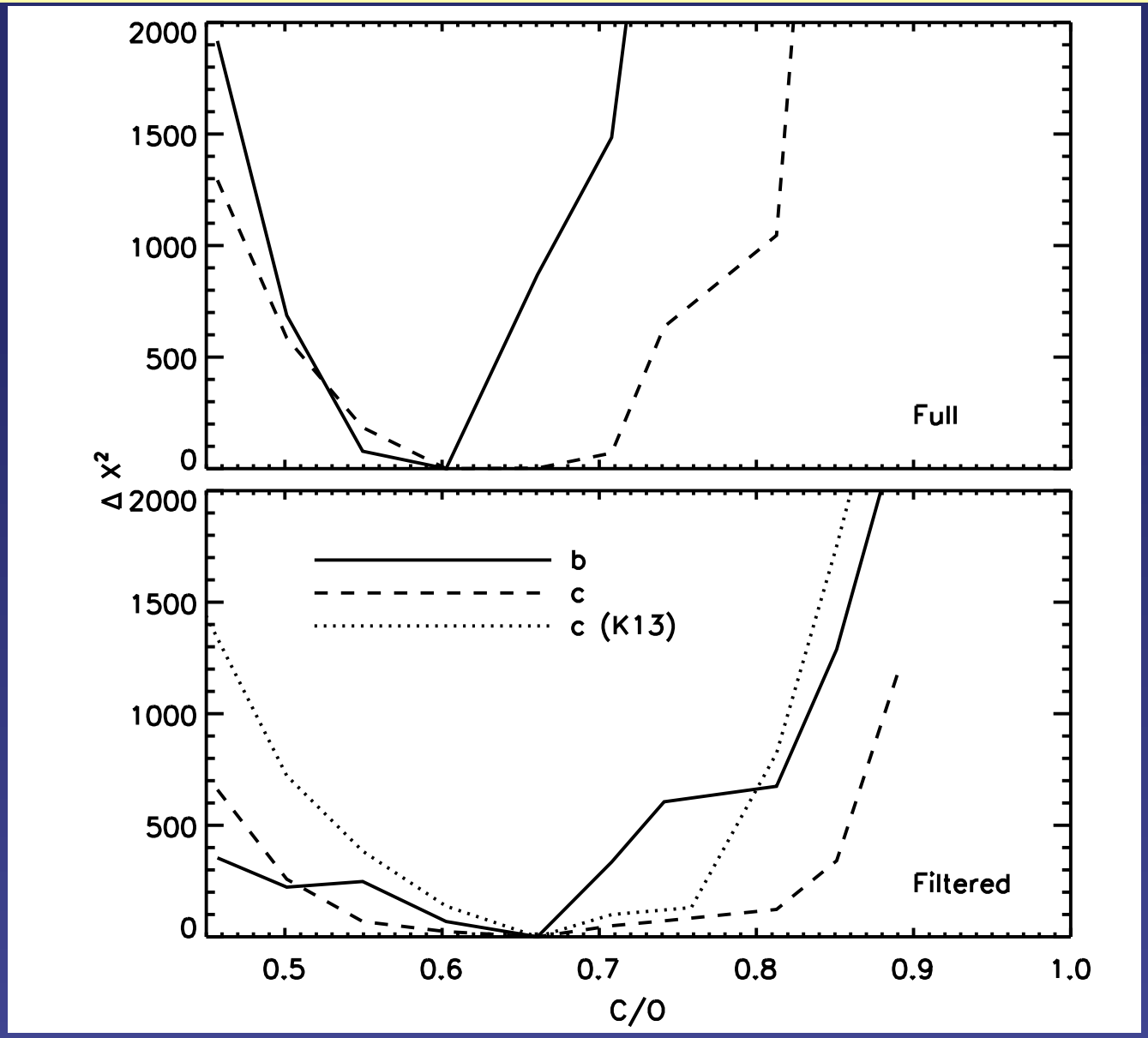
Spectra of HR8799b show weak methane





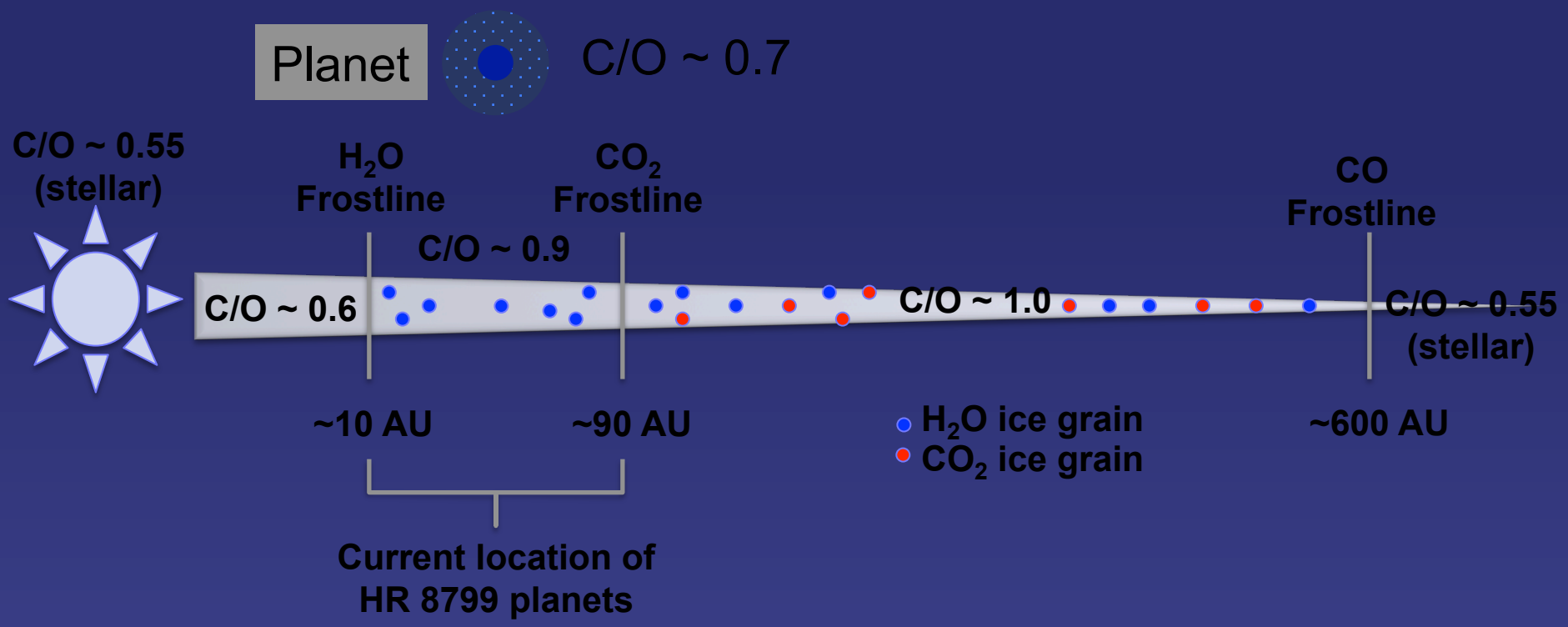
Barman et al 2015

Measured C/O ratios slightly higher than solar

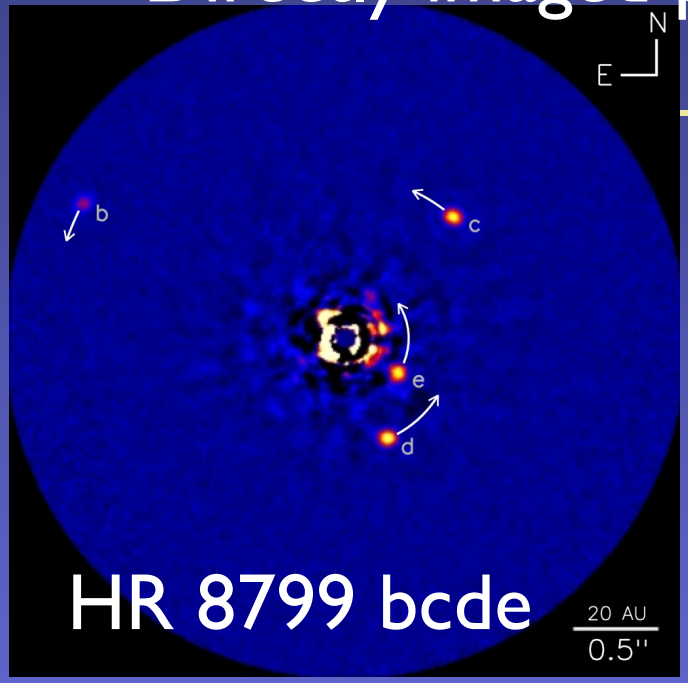


Barman et al 2015

Enhanced C/O -> Core accretion?



Directly imaged planetary systems



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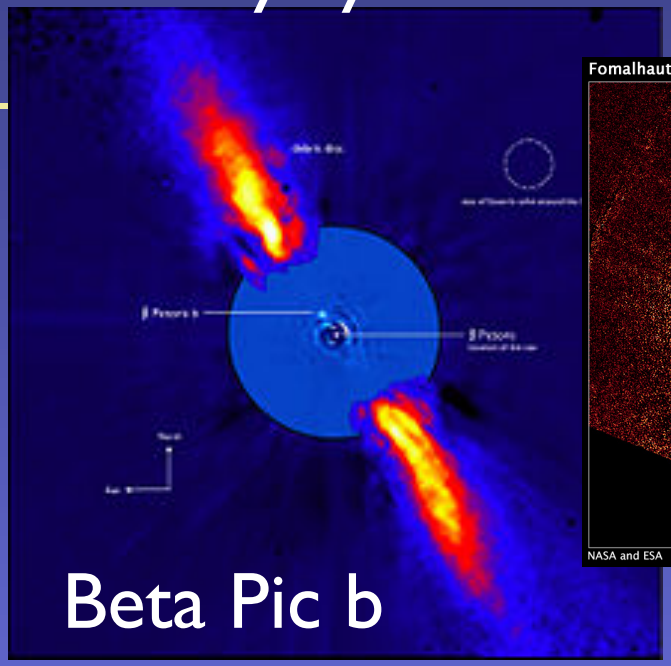
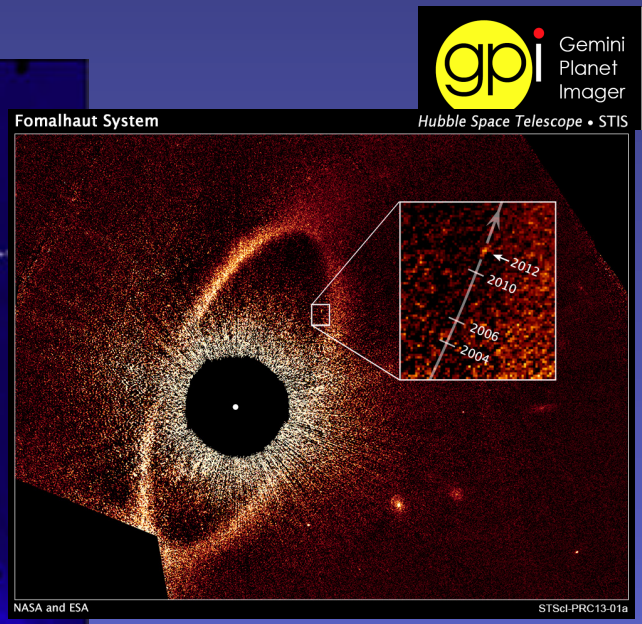
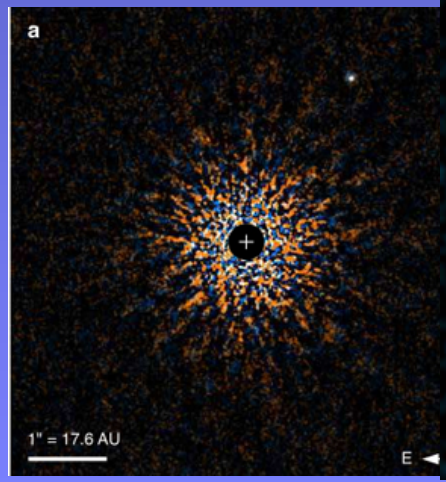


Beta Pic b

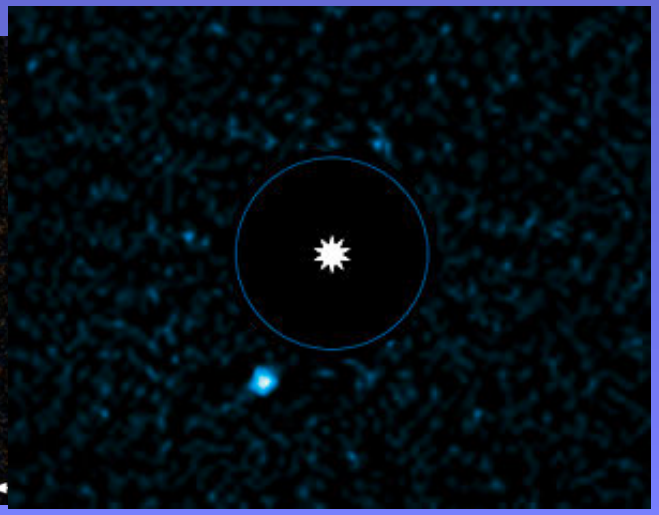


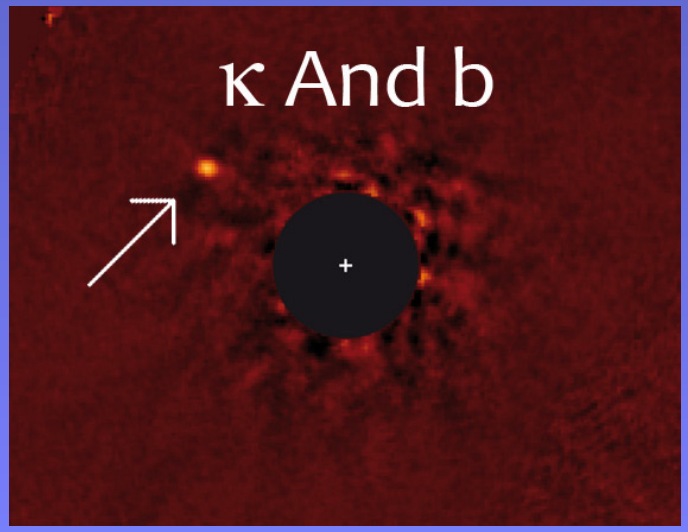
Fomalhaut b

GJ 504 b

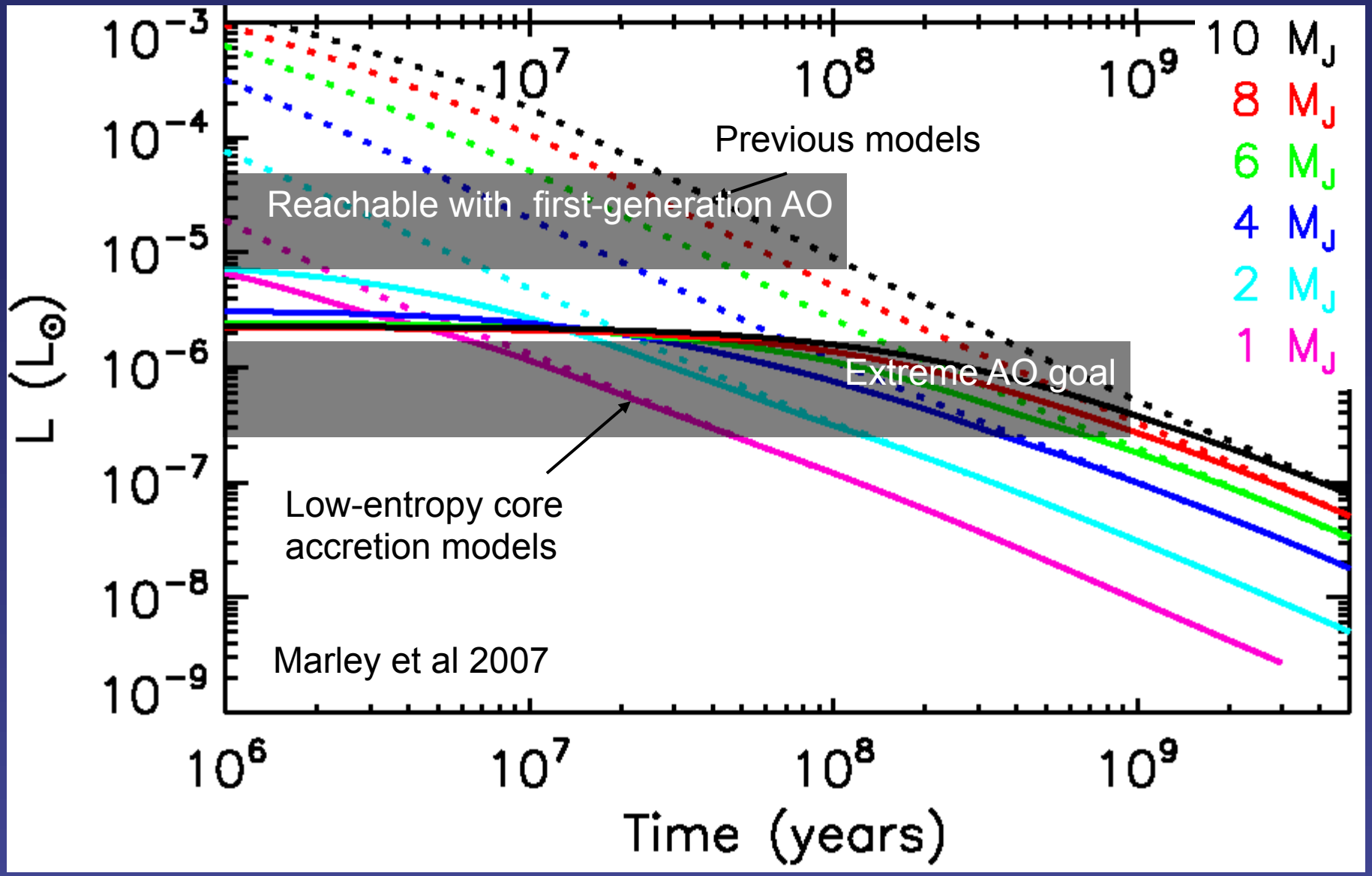


HD 95086 b

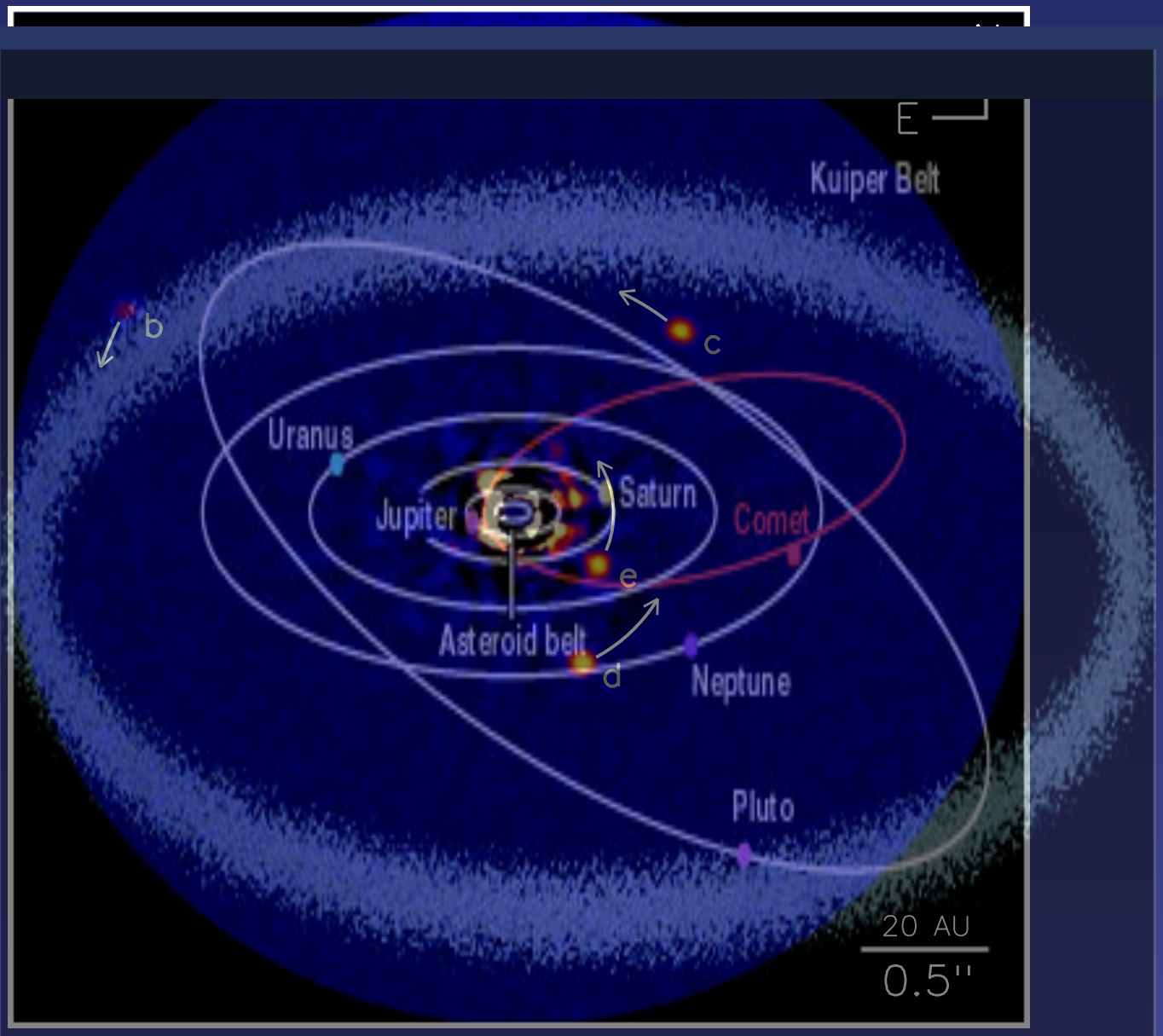




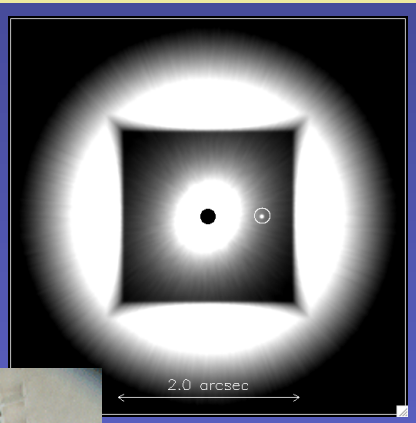
Motivation for higher contrast

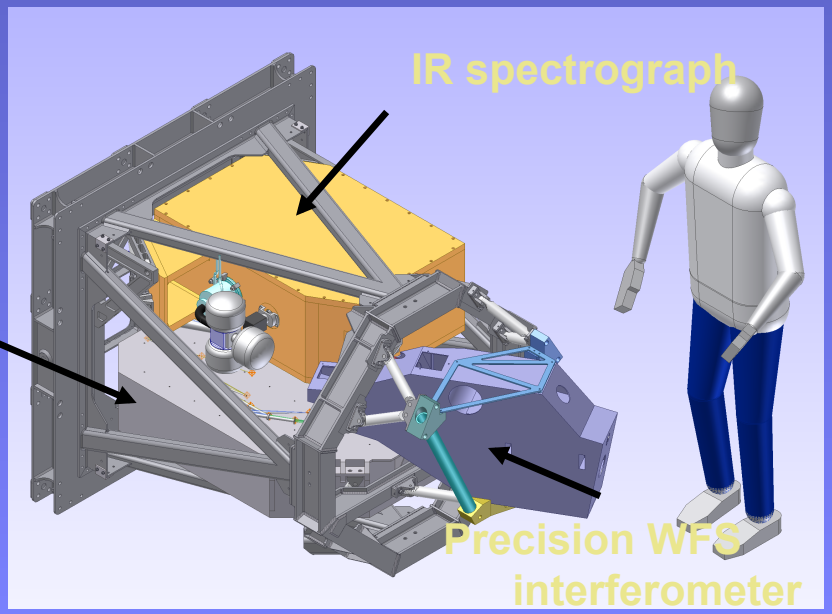


Motivation for smaller IWA



Gemini Planet Imager: 2004-2013



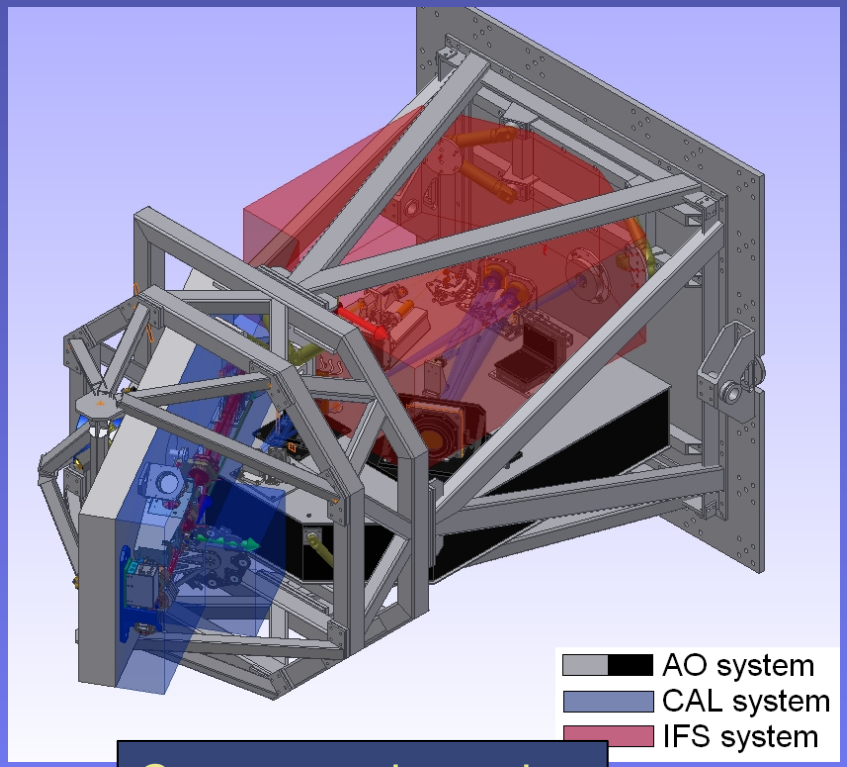


Gemini Planet Imager

Super-smooth optics reduce scattered starlight

Infrared integral field spectrograph (UCLA & U. Montreal) makes images and spectra of planets

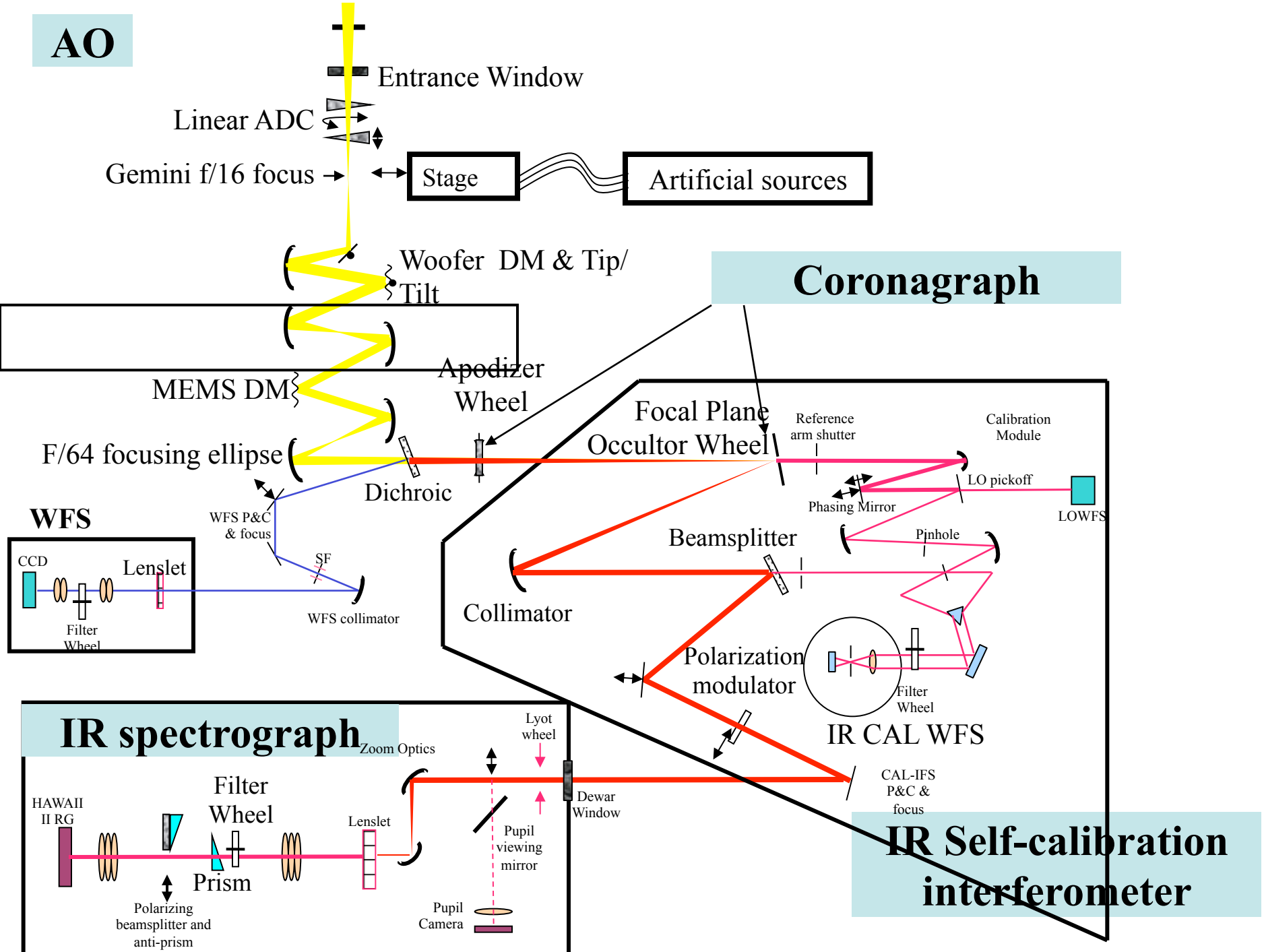
Infrared calibration sensor (JPL) measures small systematic erorrs



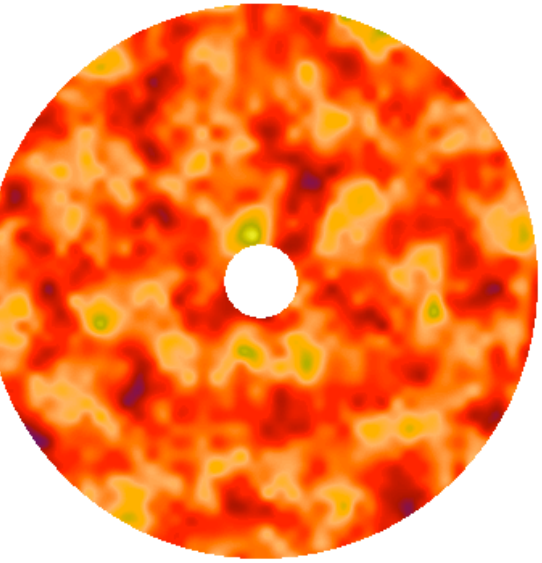
Mechanical structure and top-level software (NRC Canada) holds and connects subsystems

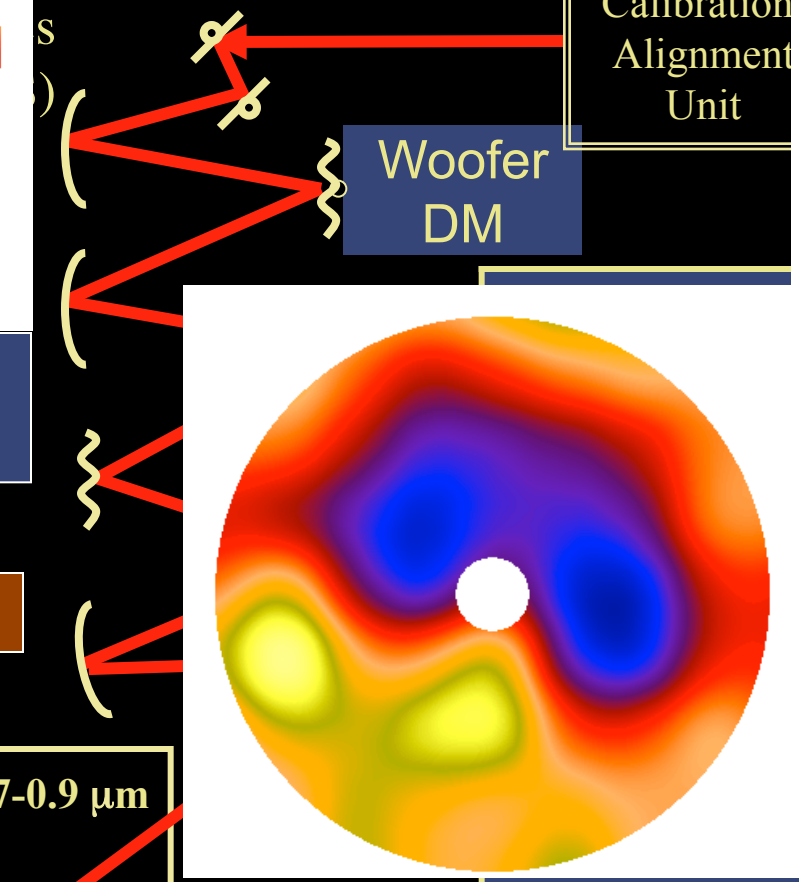
Adaptive optics system (LLNL) corrects for atmospheric turbulence and optical imperfections

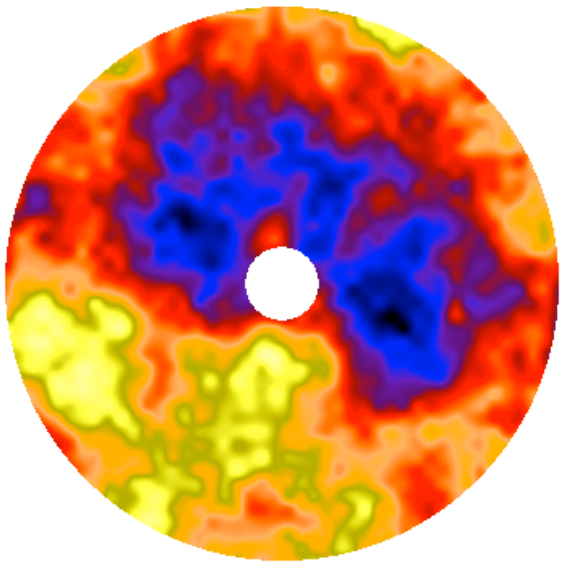
Coronagraph masks (AMNH) block diffracted light from the star


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

GPI AO architecture

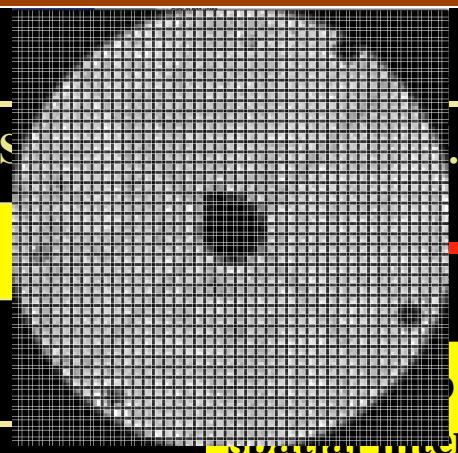






MEMS deformable mirror

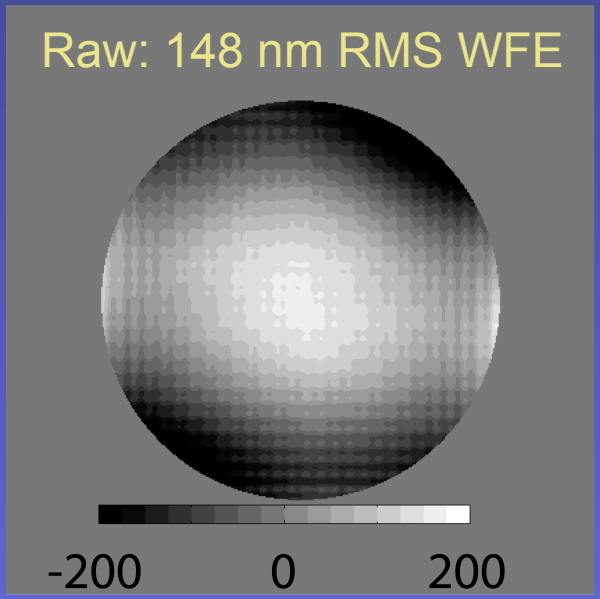
16-core Intel system

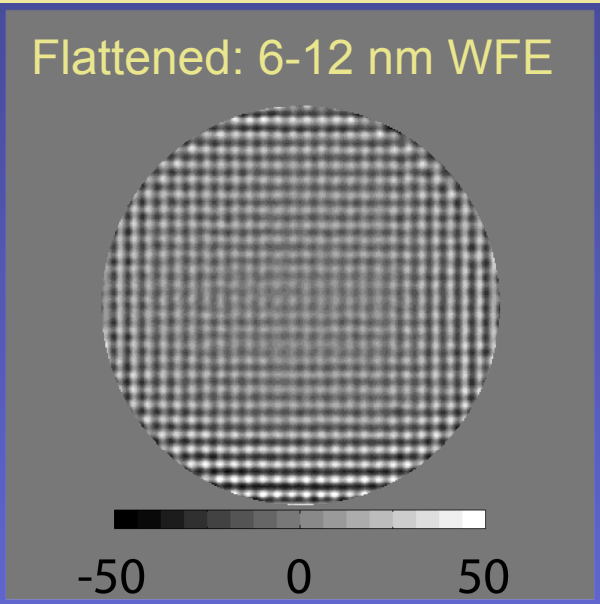


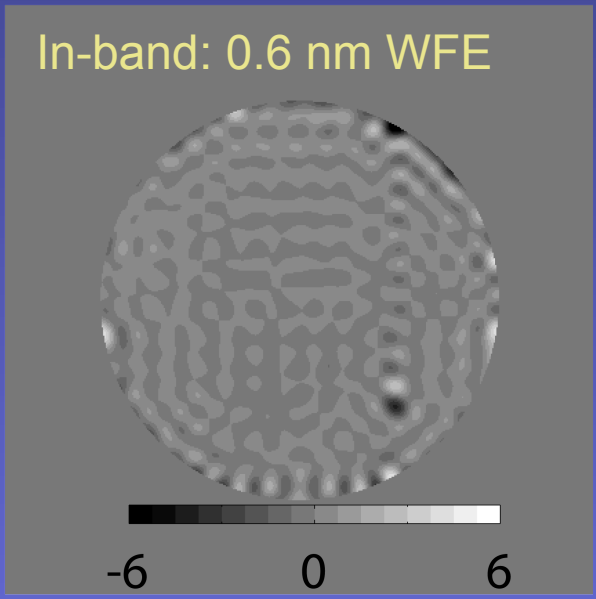
Spatial filter
λ/d=0.9”

	N=8 actuators, tip/ tilt platform
	MEMS 0.4 mm pitch, N=43.2 actuators
hm	Modal Fourier control + matrix woofer offload
	Spatially-filtered SH 700-900 nm
WFS detector	LL CCID-66, 160x160 pix, ~3 e- noise
Frame rate	1000 Hz (goal 1300)

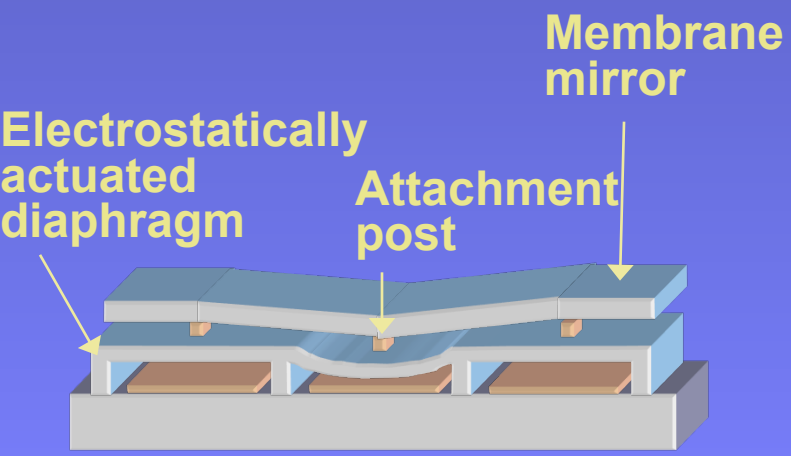
Boston Micromachines MEMS deformable mirror

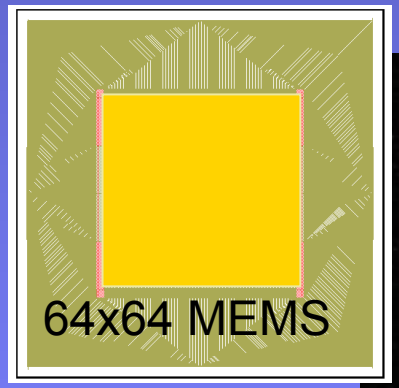


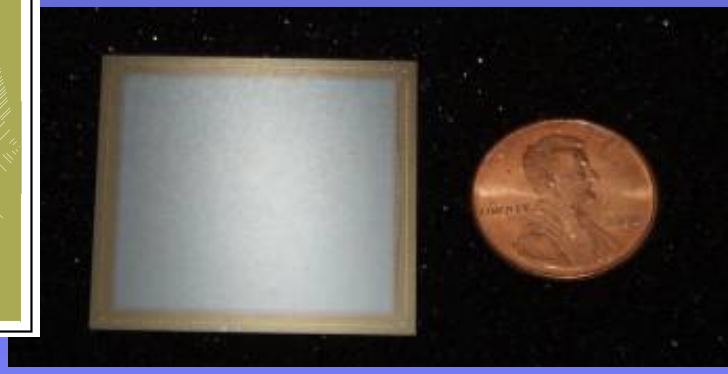




32x32 MEMS Evans et al 2006 Optics Exp. 14 55

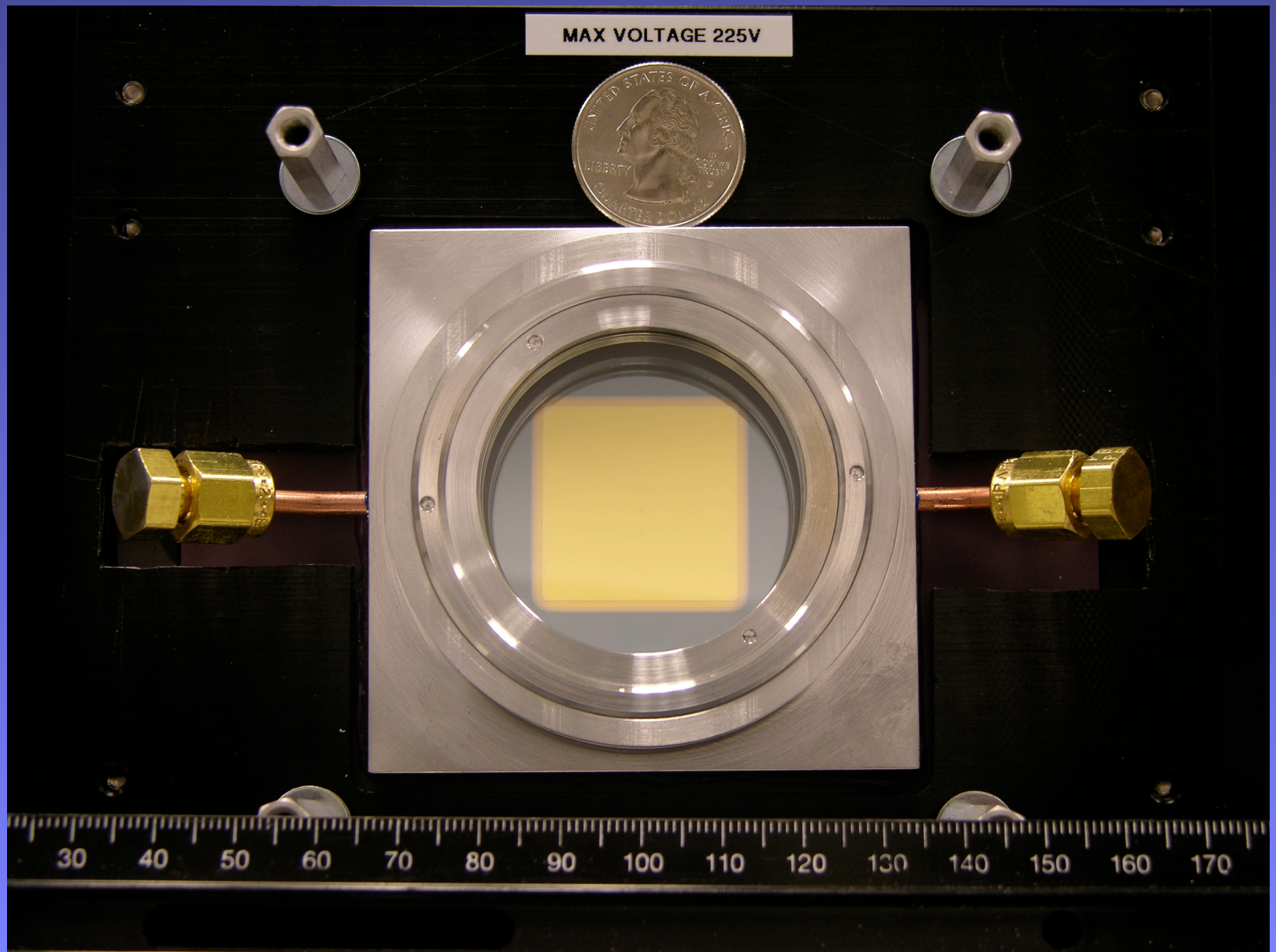






64x64 MEMS unwired model

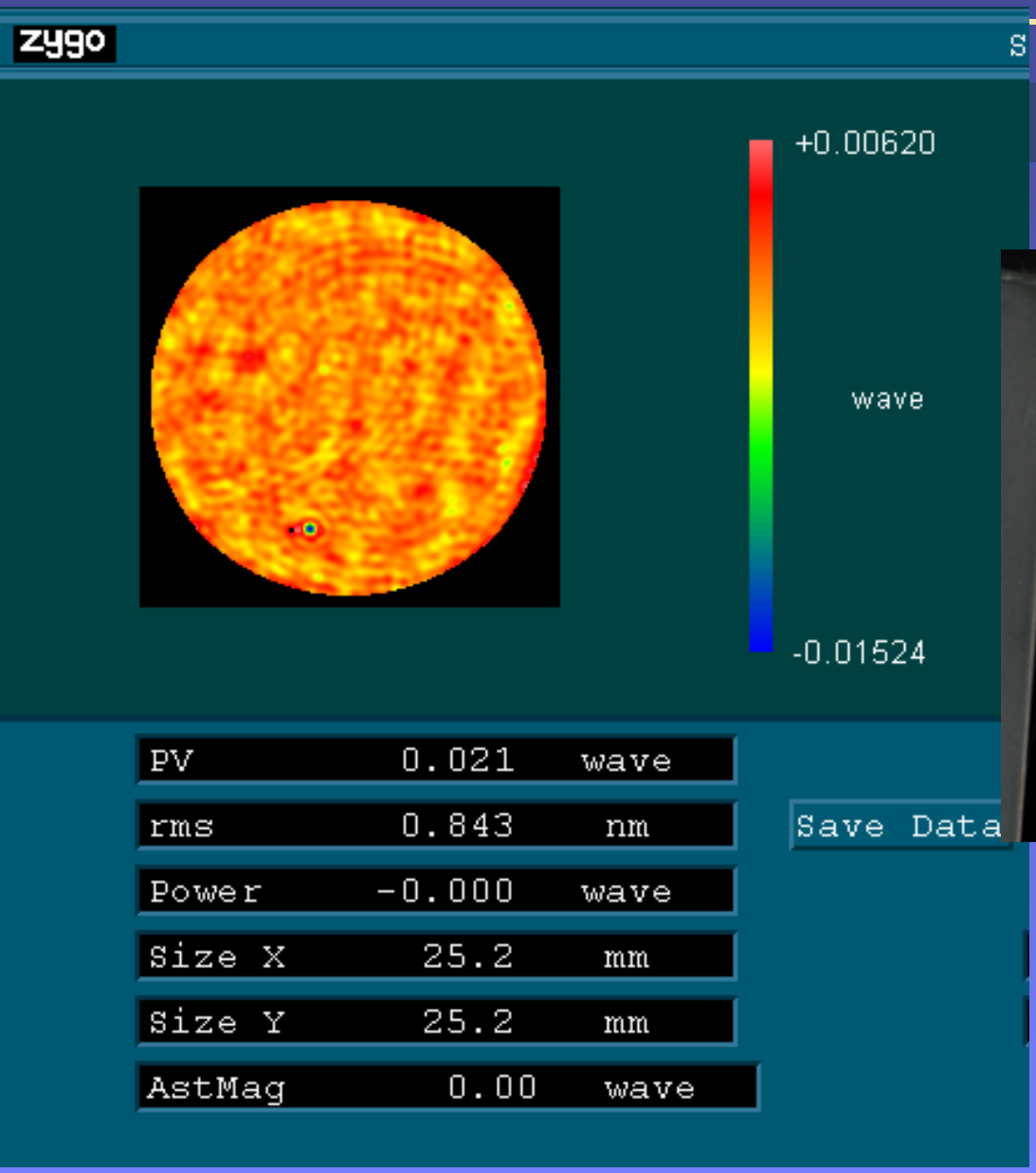
64 x 64 MEMS mirror

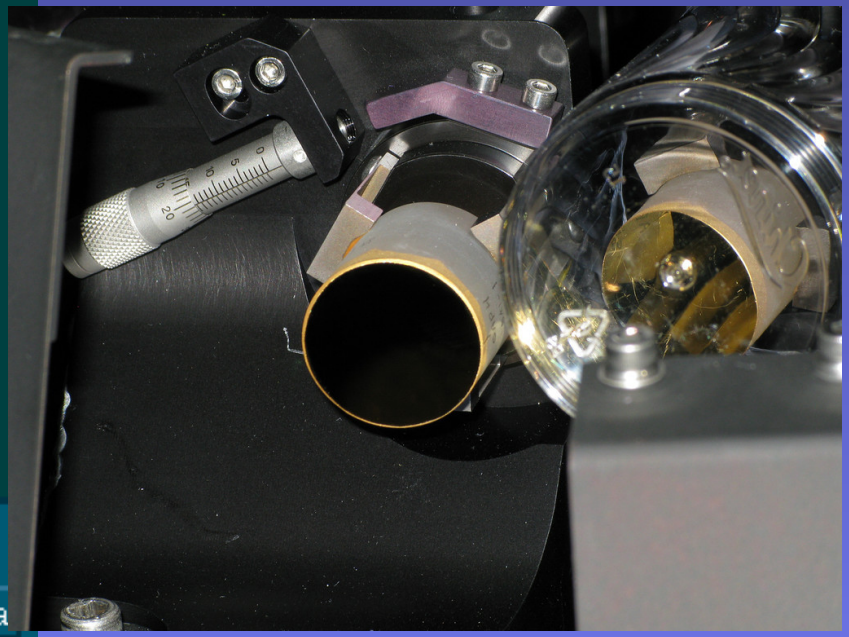


NRC·CNRC
Herzberg Institute of Astrophysics

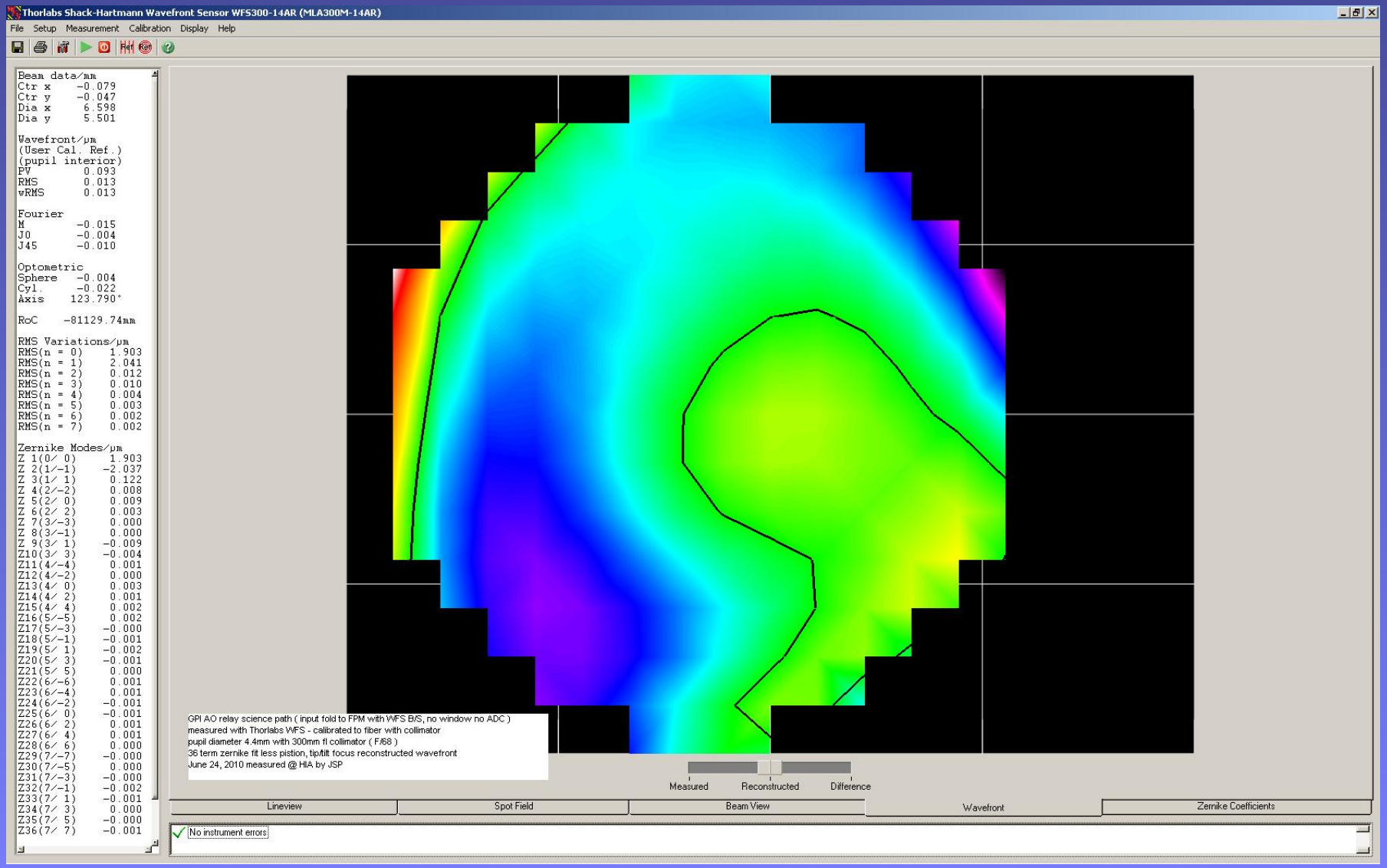
AO bench + Optomechanical superstructure

Individual optics (Precision Asphere)
< 1 nm RMS wavefront error

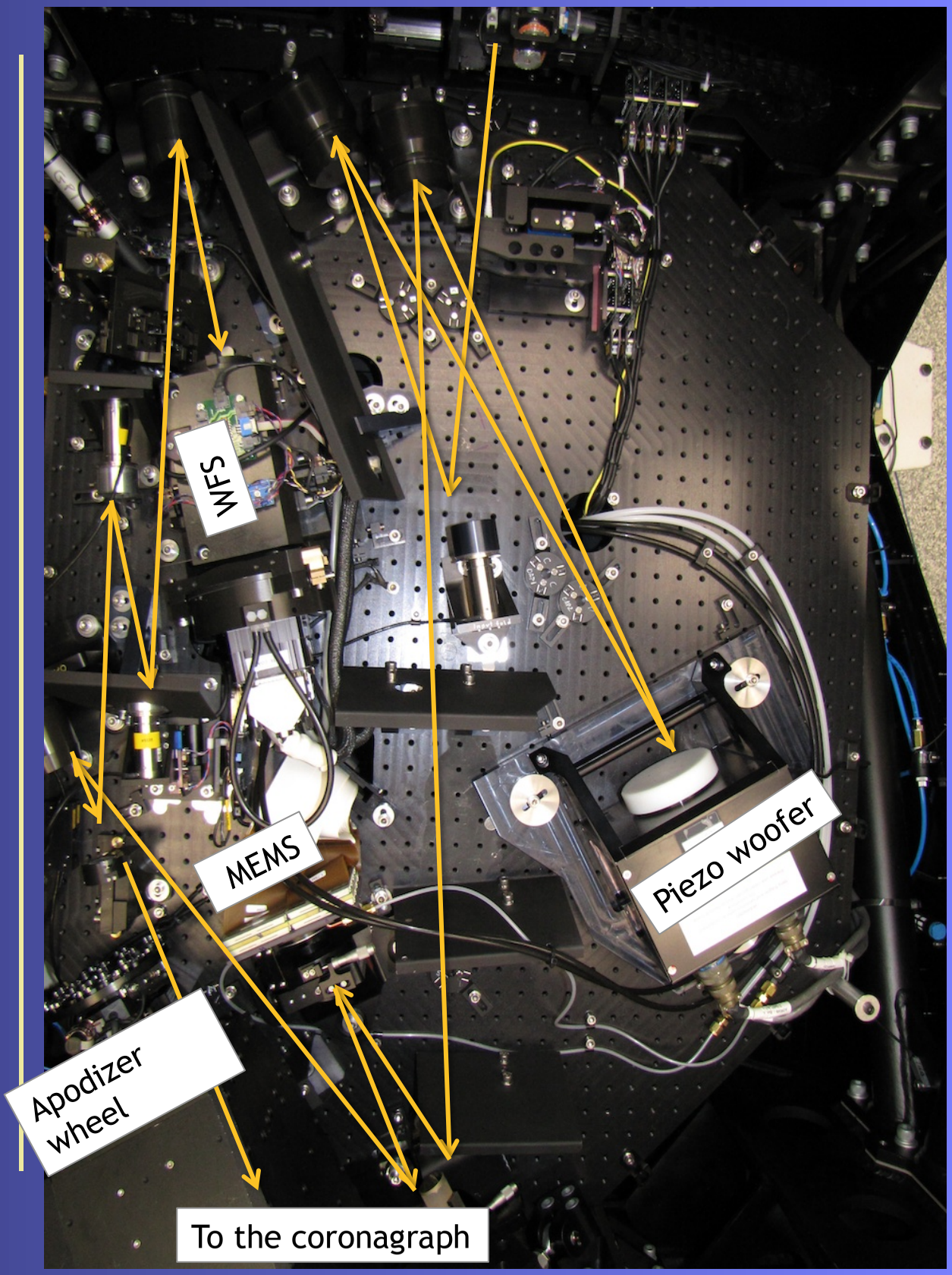




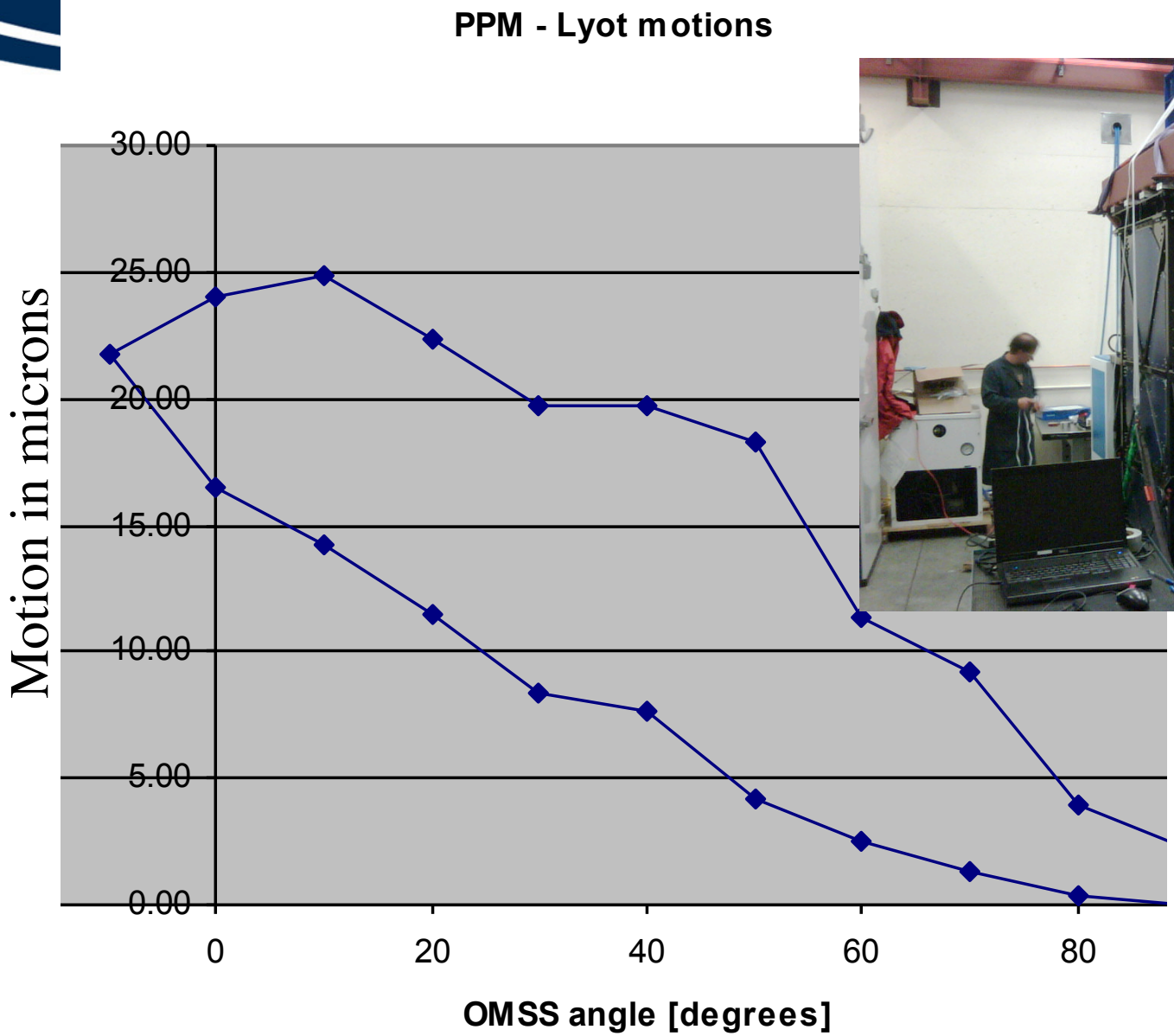
Total science path (to coronagraph)
13 nm RMS WFE post-alignment

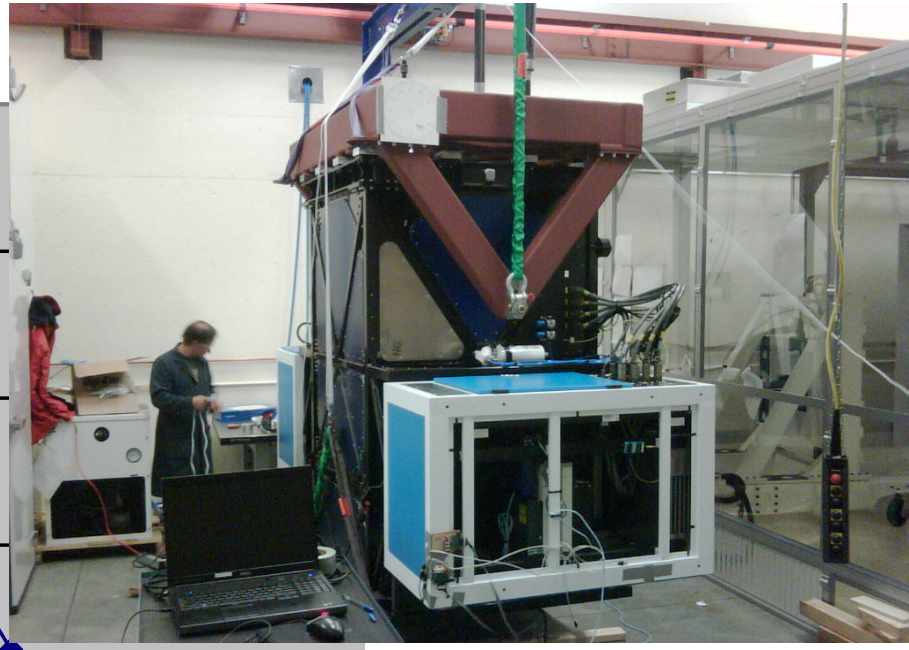


Gemini Planet Imager

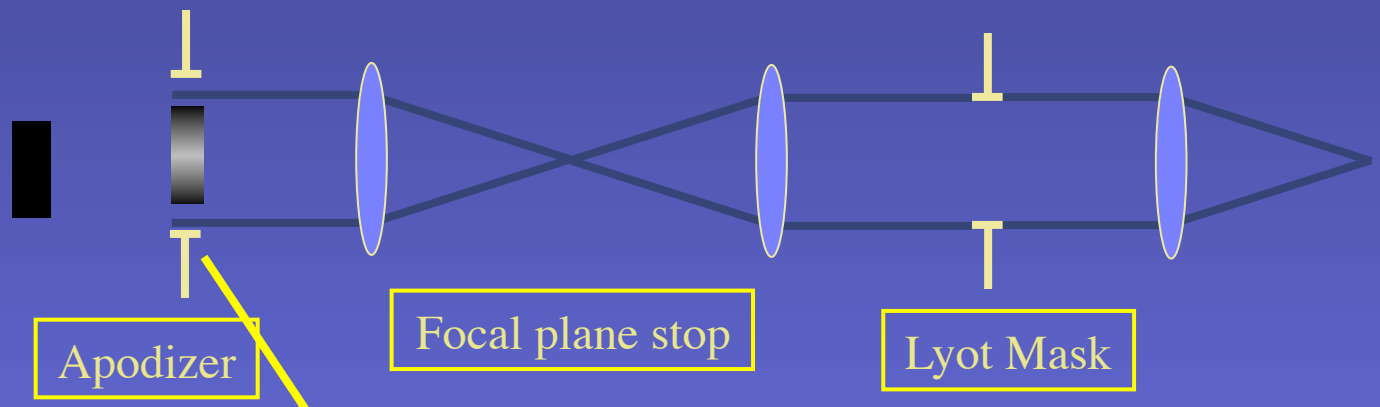


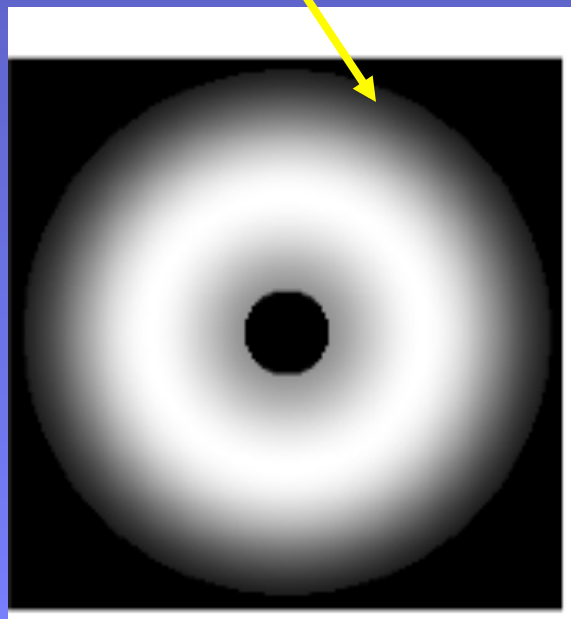
Flexure testing (Victoria)

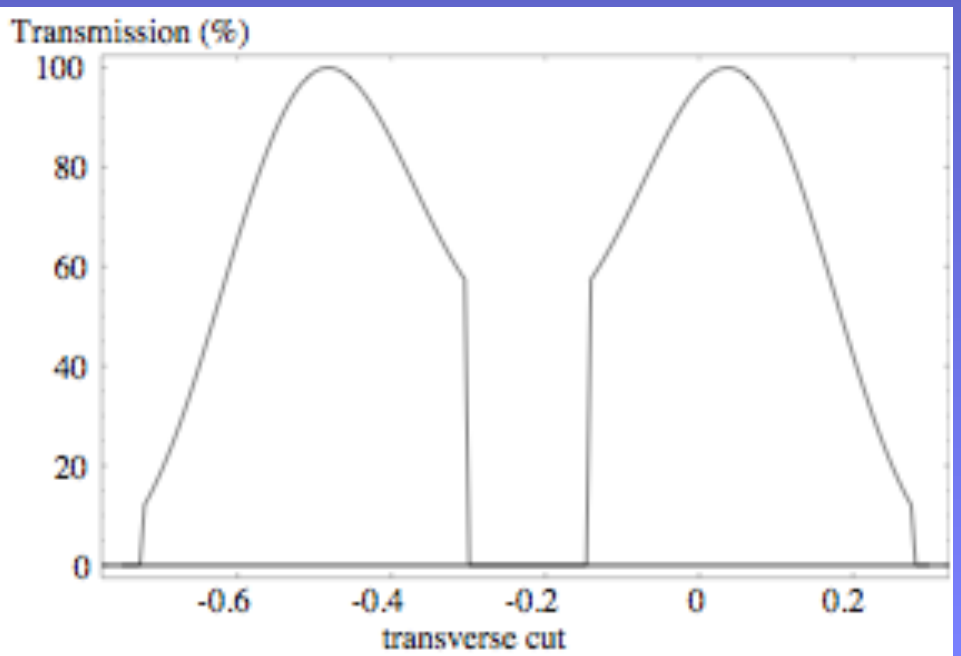


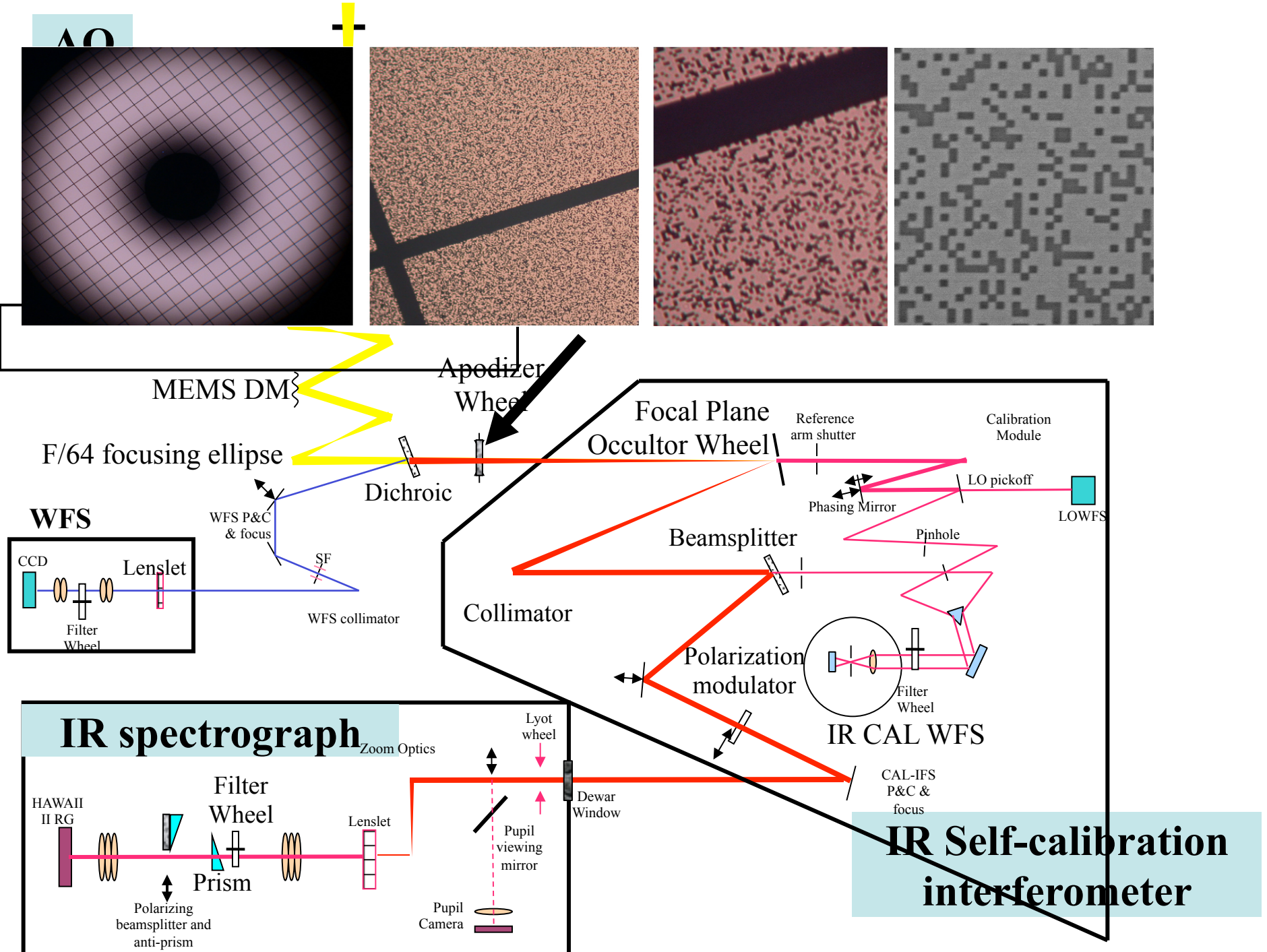


Apodized-pupil Lyot coronagraph (Soummer 2005)

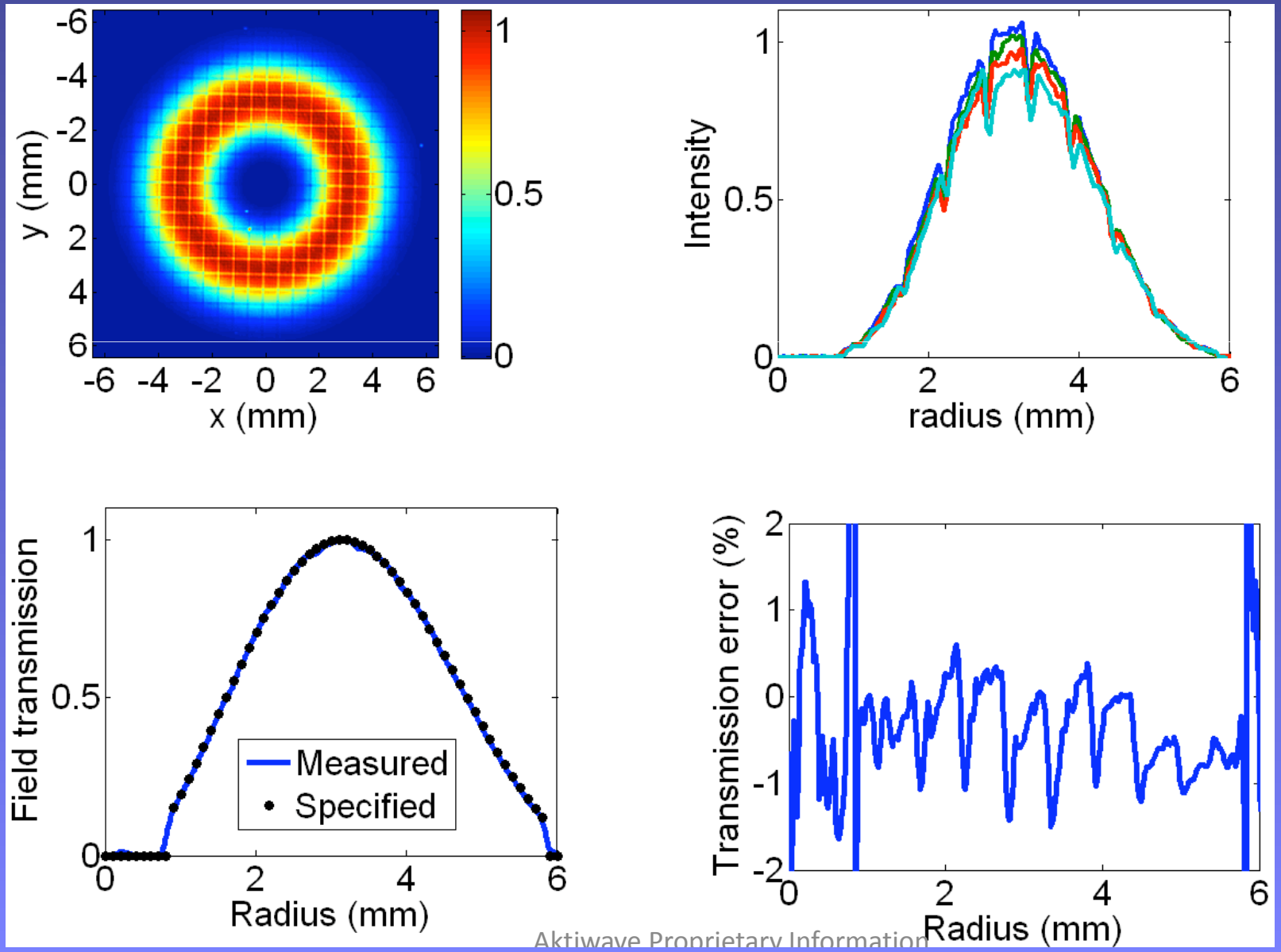




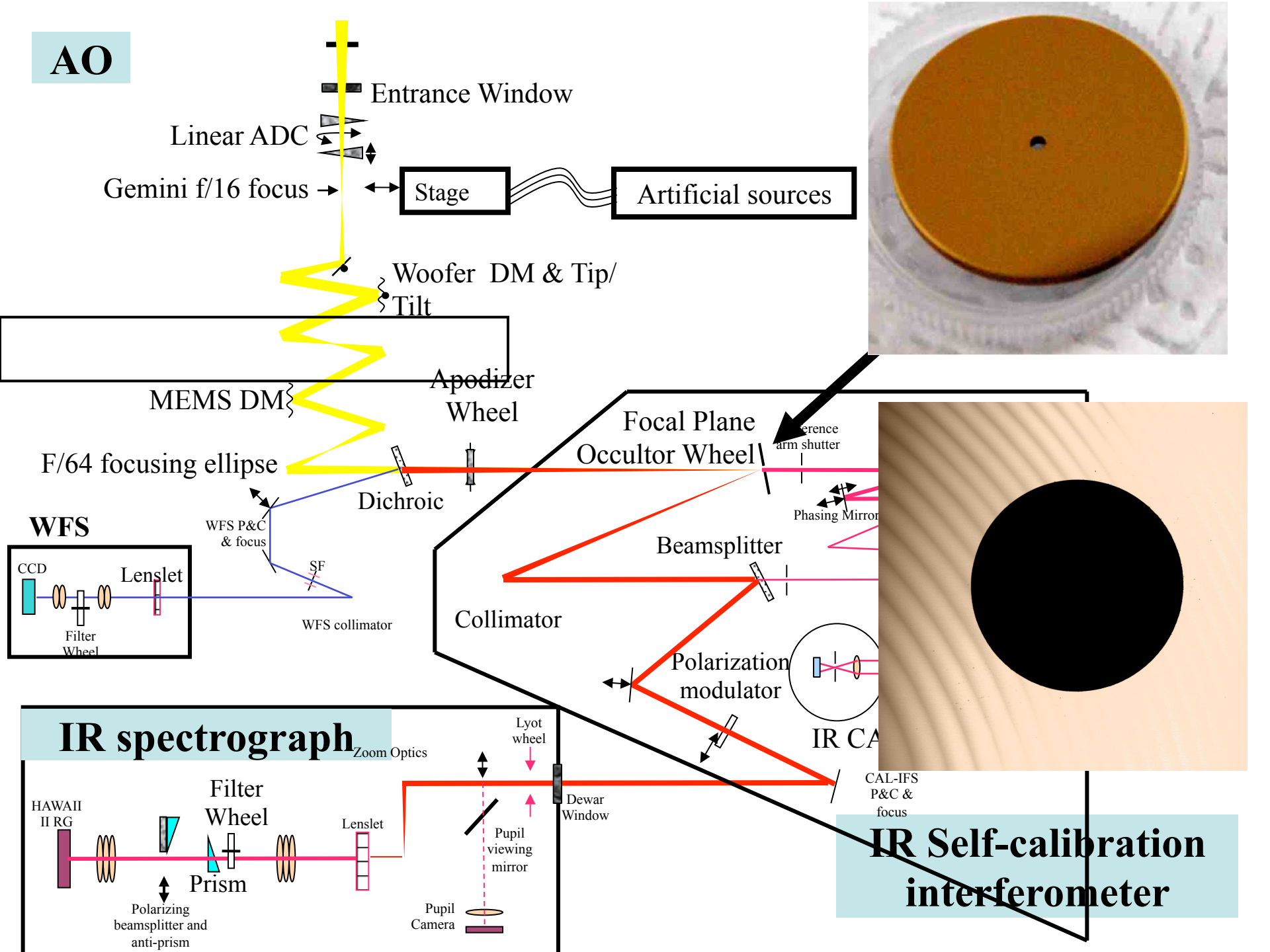


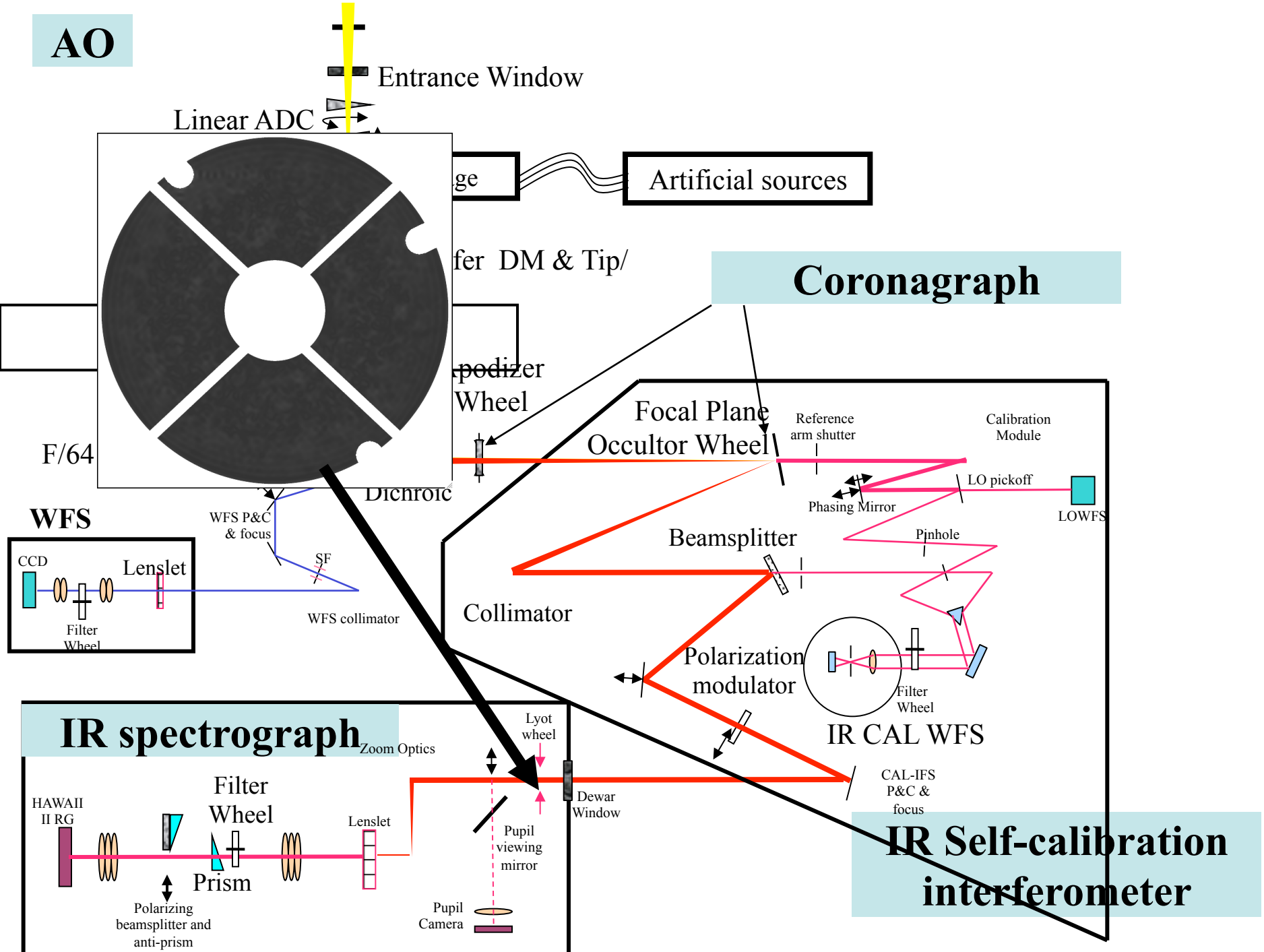

AO
+
MEMS DM
Apodizer Wheel
F/64 focusing ellipse
Dichroic
WFS
WFS P&C & focus
SF
CCD
Lenslet
Filter Wheel
WFS collimator
Focal Plane Occultor Wheel
Reference arm shutter
Calibration Module
LO pickoff
Phasing Mirror
LOWFS
Pinhole
Beamsplitter
Collimator
Polarization modulator
Filter Wheel
IR CAL WFS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

Apodizer measurements (BNL)



Aktiwave Proprietary Information


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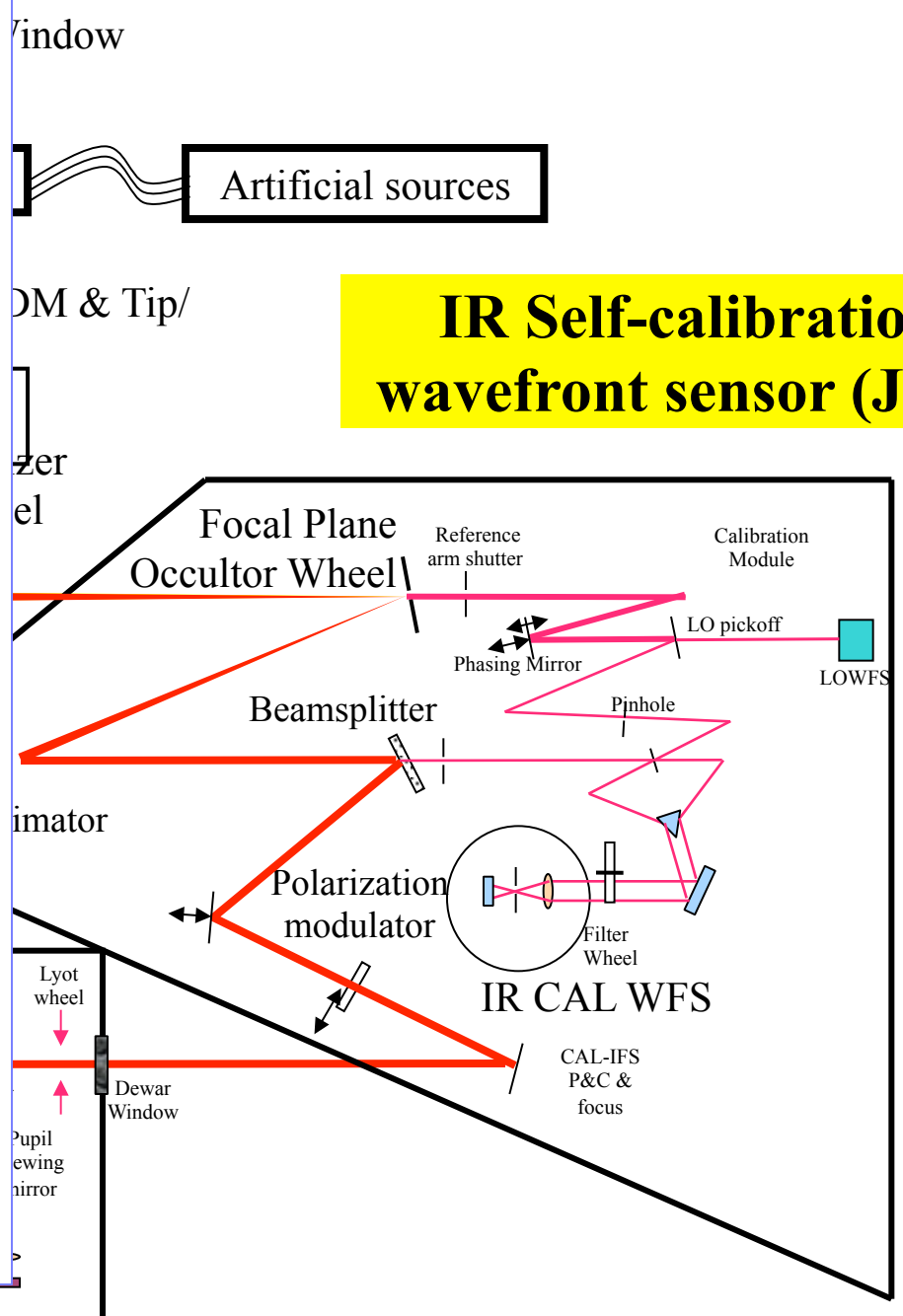
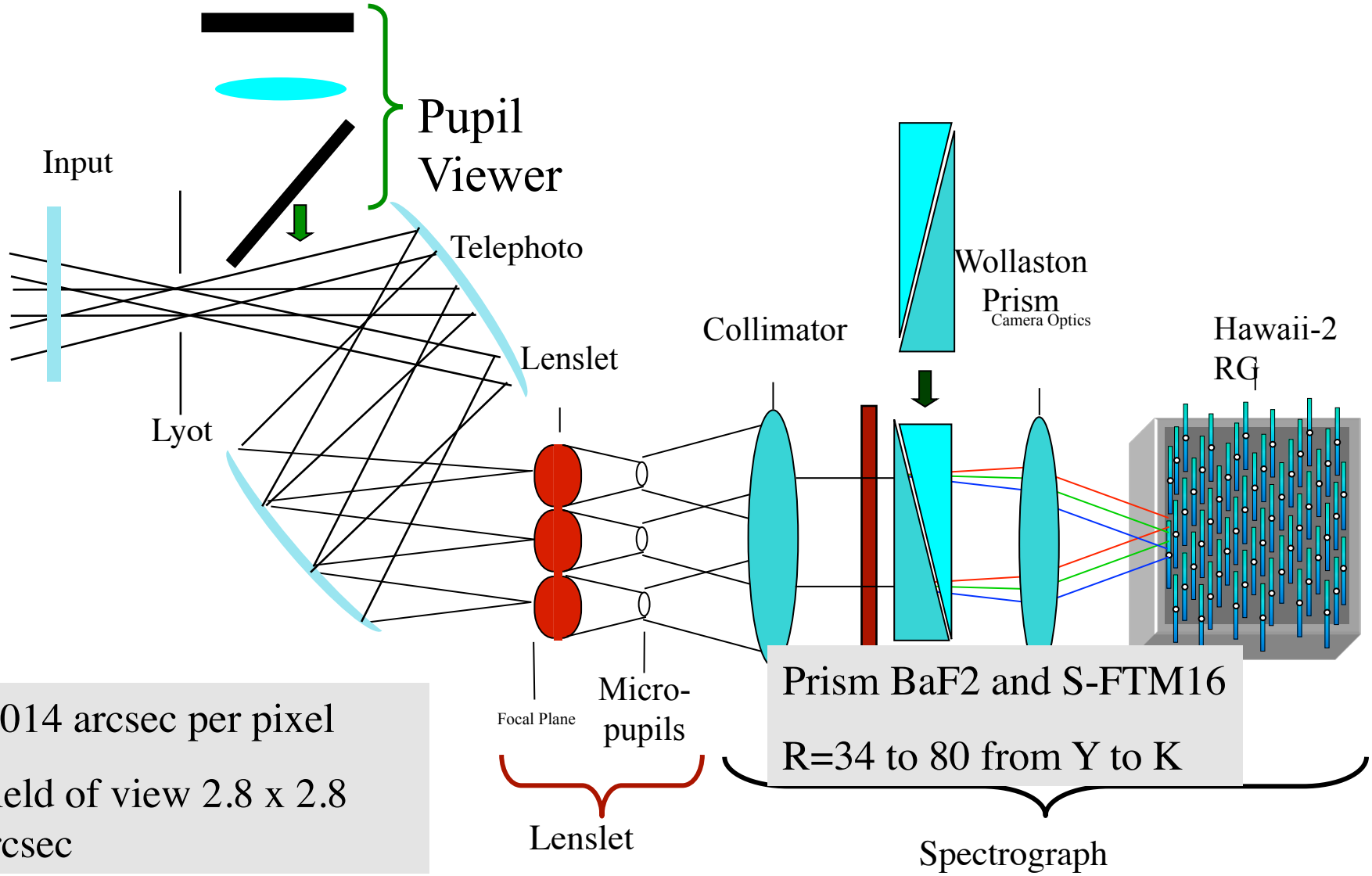
Wheel
IR CAL WFS
IR spectrograph
Zoom Optics
Lyot
wheel
CAL-IFS
P&C &
focus
Dewar
Window
HAWAII
II RG
Filter
Wheel
Lenslet
Pupil
viewing
mirror
Prism
Polarizing
beamsplitter and
anti-prism
Pupil
Camera
IR Self-calibration
interferometer

- Controls pointing onto the coronagraph optics
- Low-order wavefront modes measured and corrected by LOWFS shack-hartmann sensor
- High-order measured by interferometer



Integral Field Spectrograph

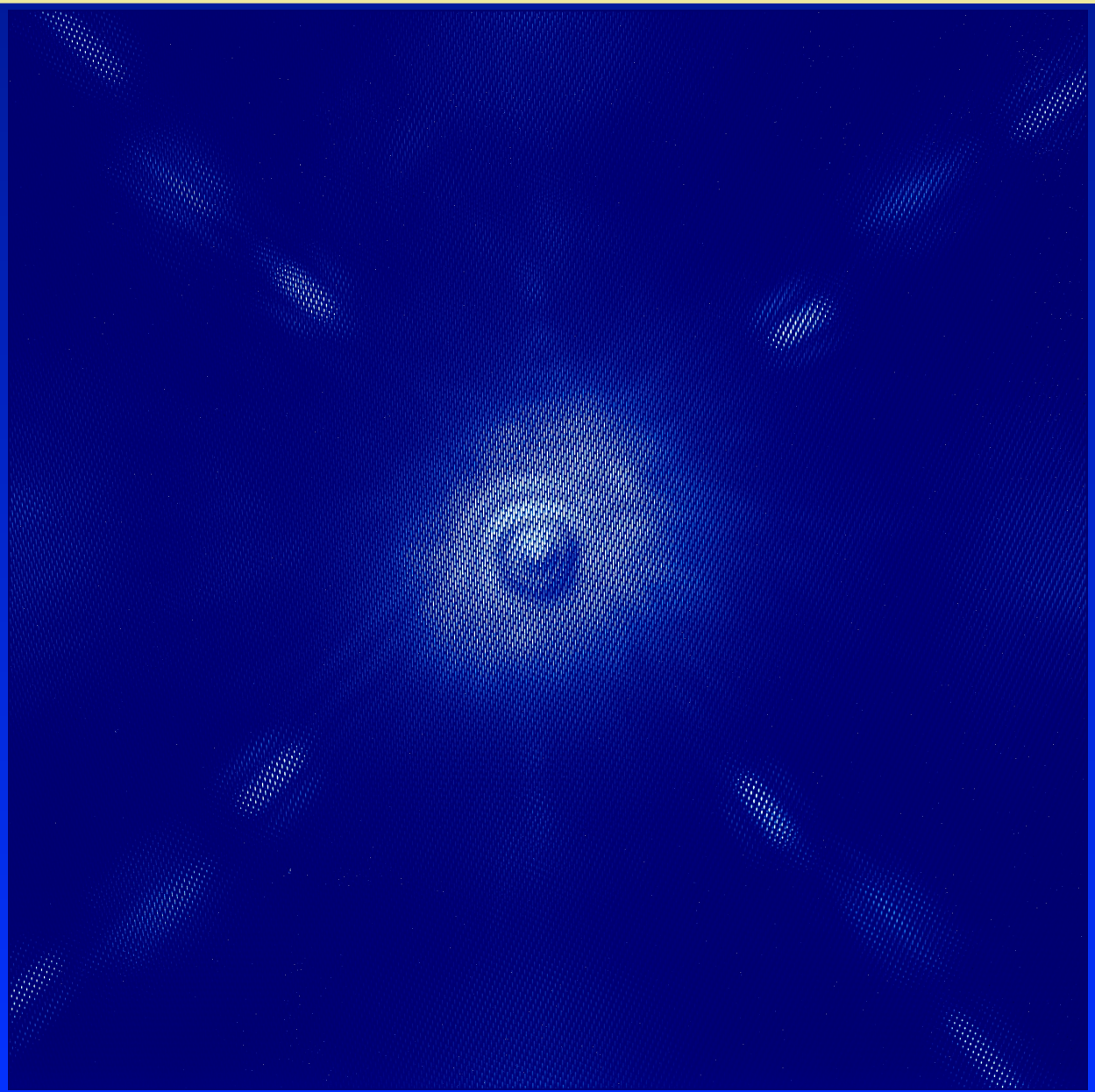


0.014 arcsec per pixel

Field of view 2.8 x 2.8 arcsec

UCLA
U Montreal

Raw GPI data



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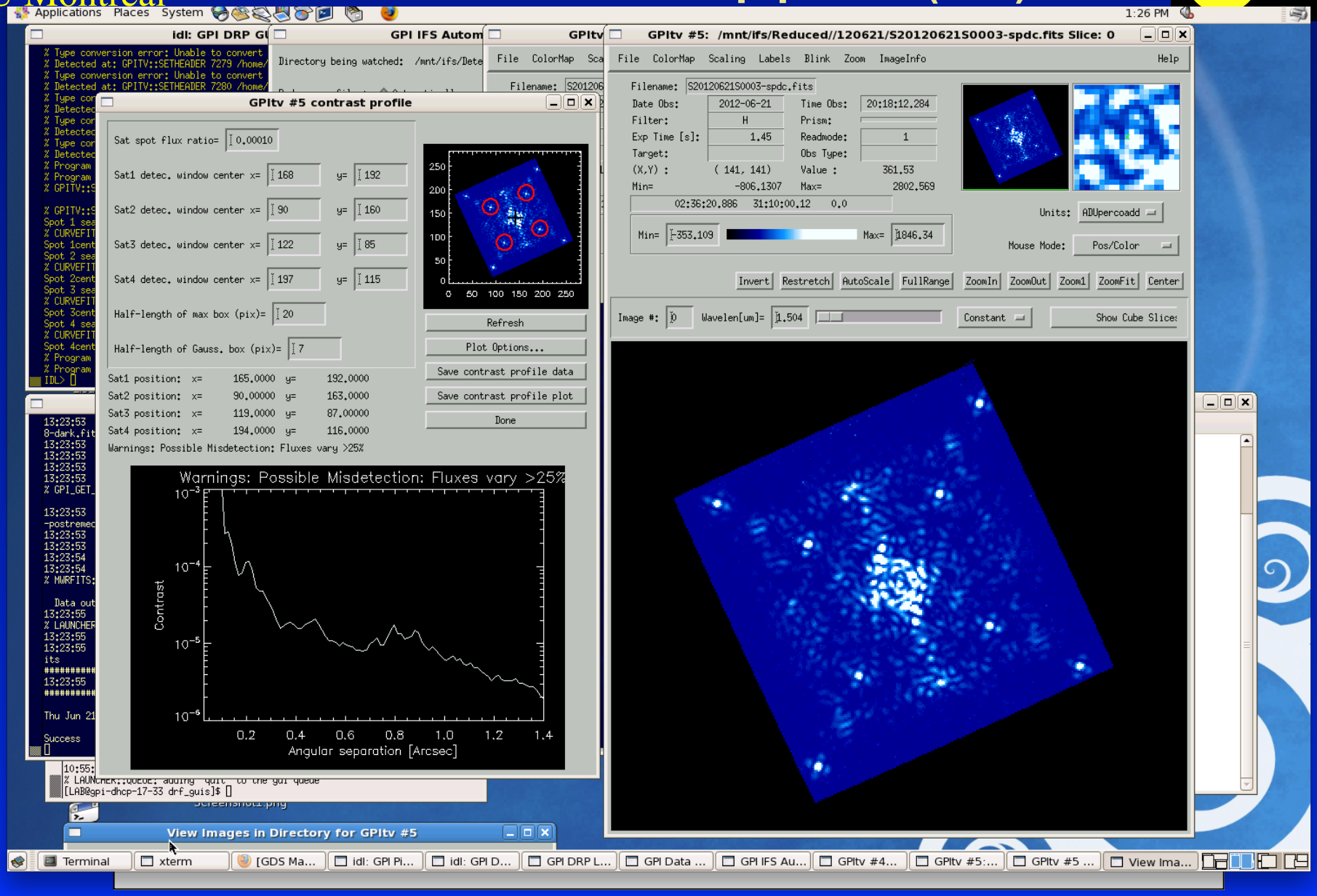
Data flow and data pipeline (IDL)

Gemini Planet Imager



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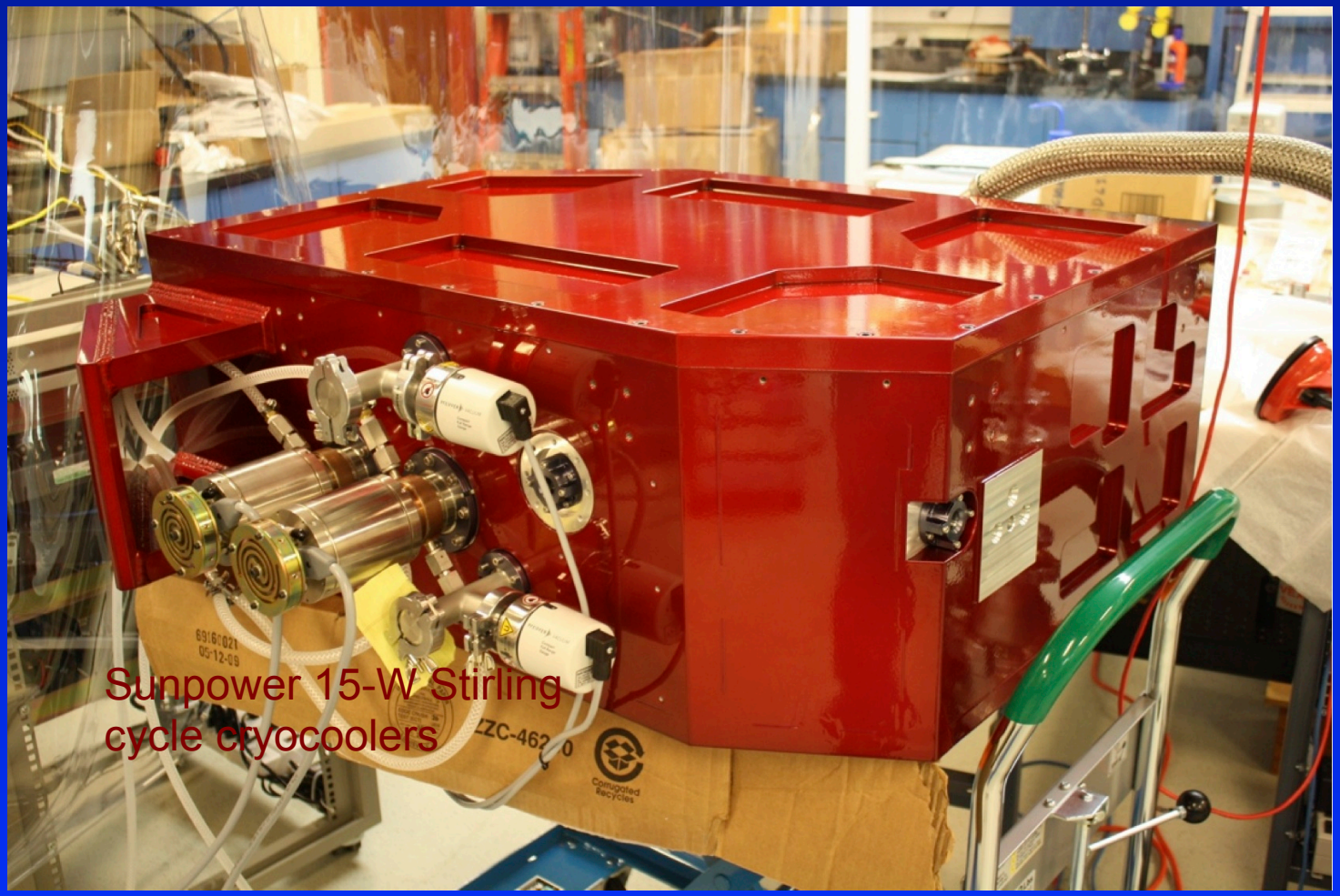
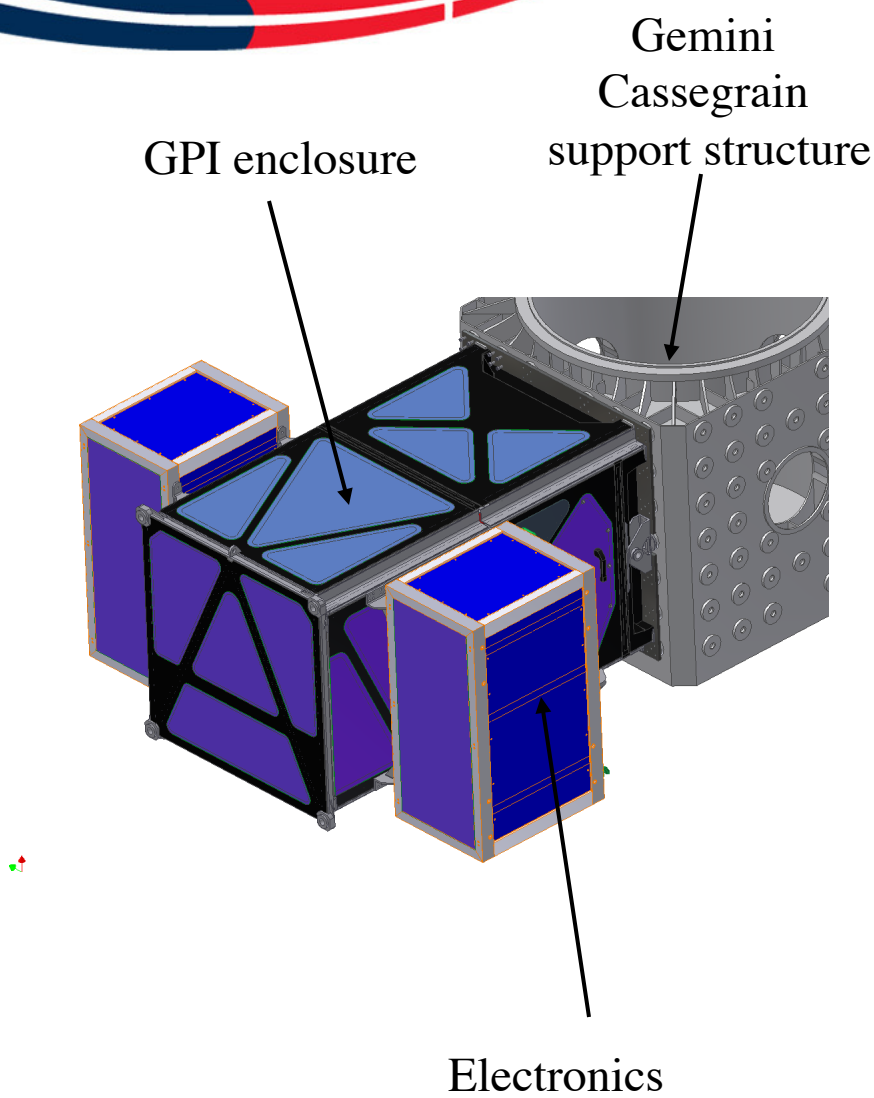
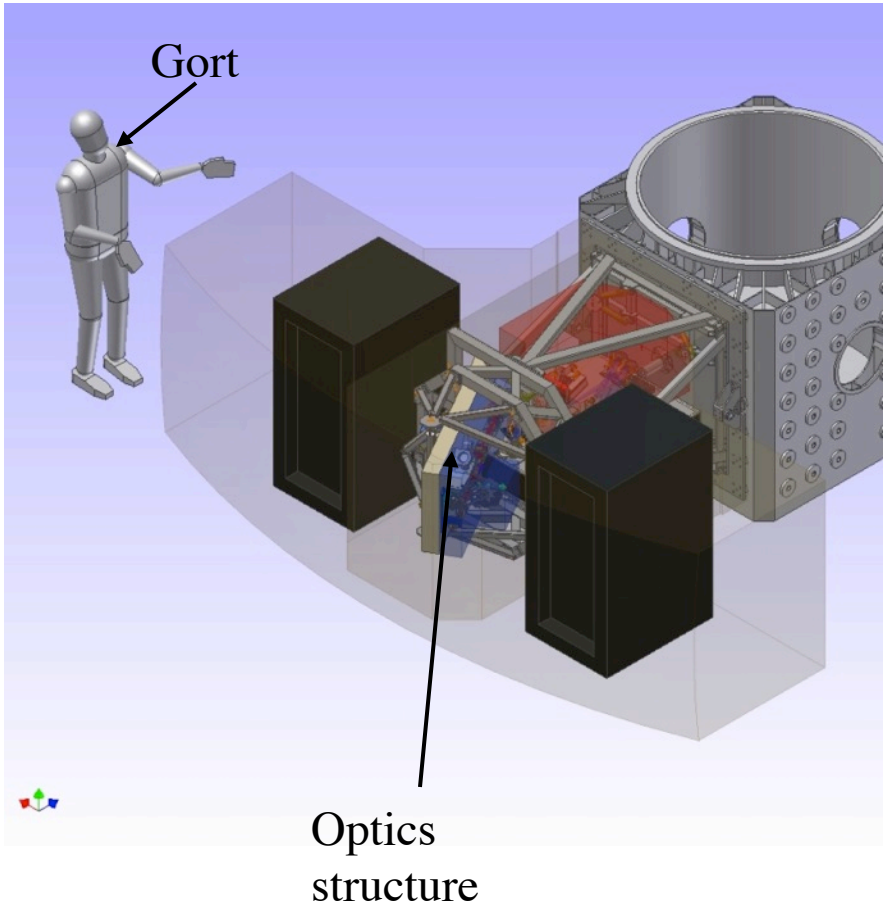
Integral field spectrograph

Gemini Planet Imager

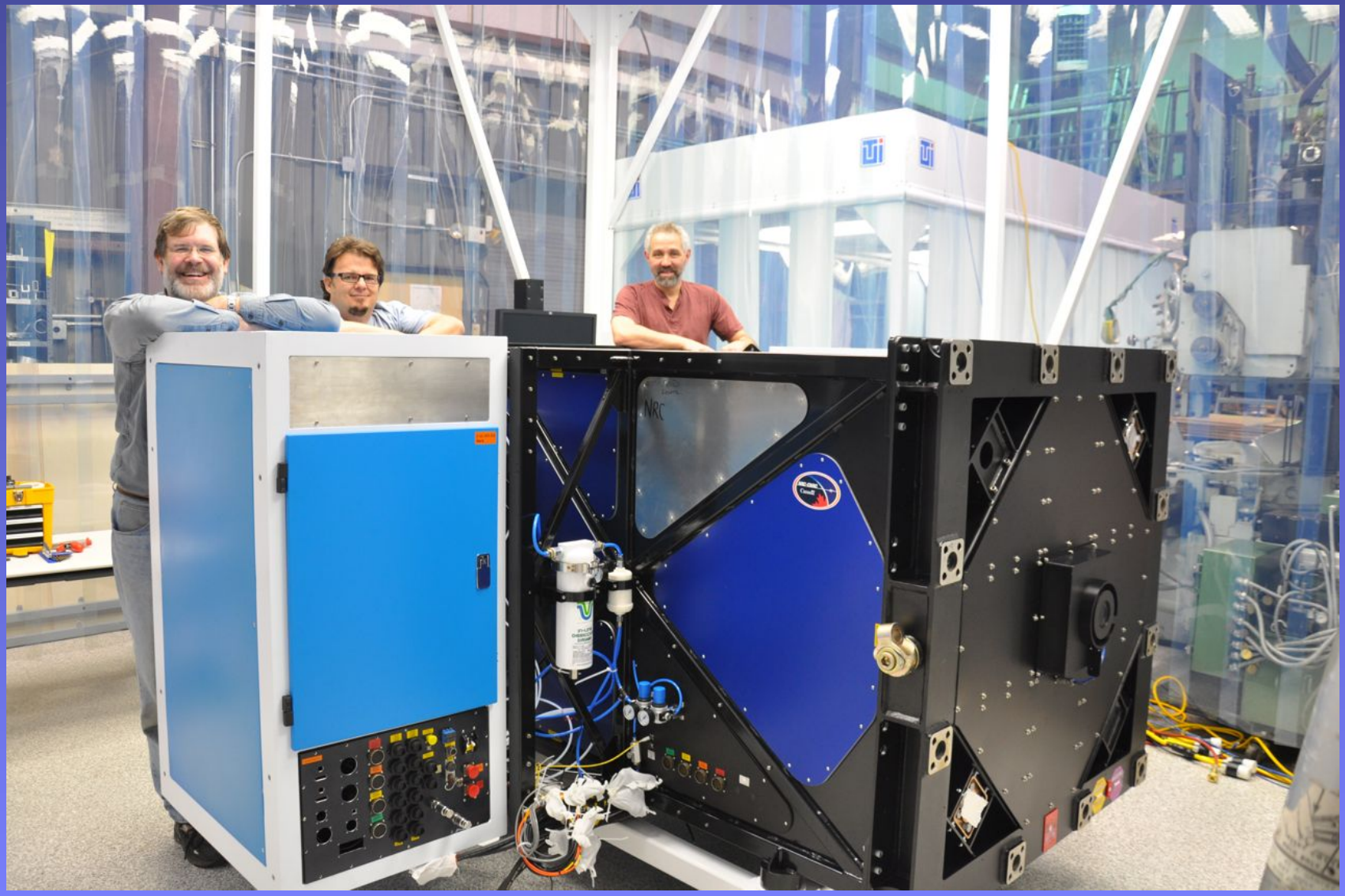


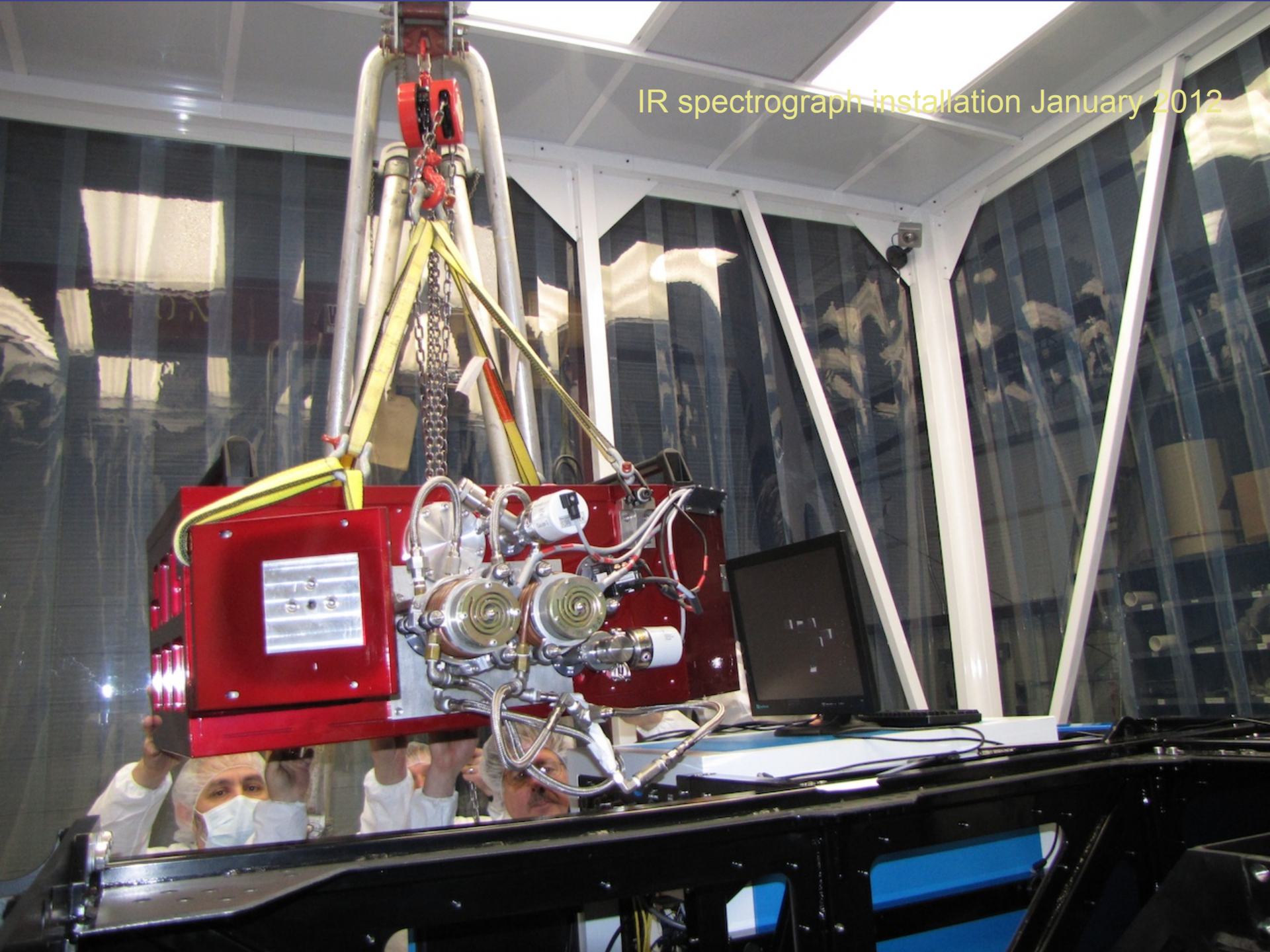
GPI mechanical design





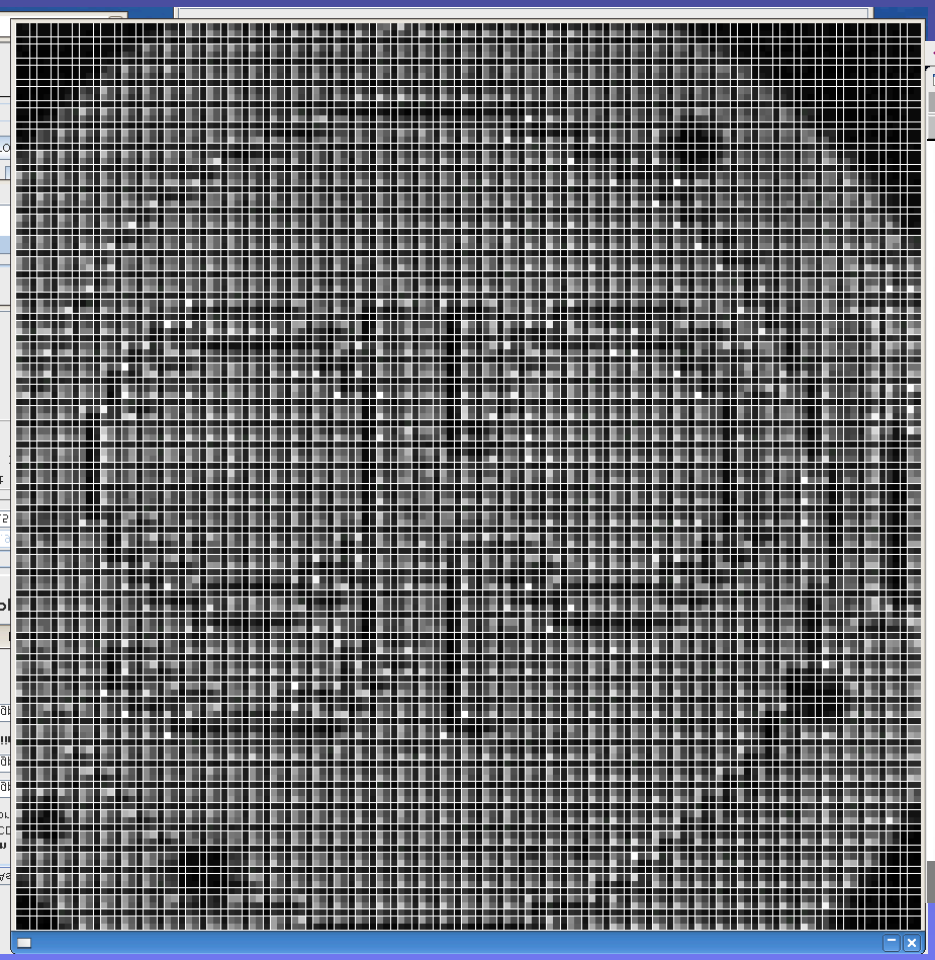
GPI integrated and tested at UC Santa Cruz 2011-2013



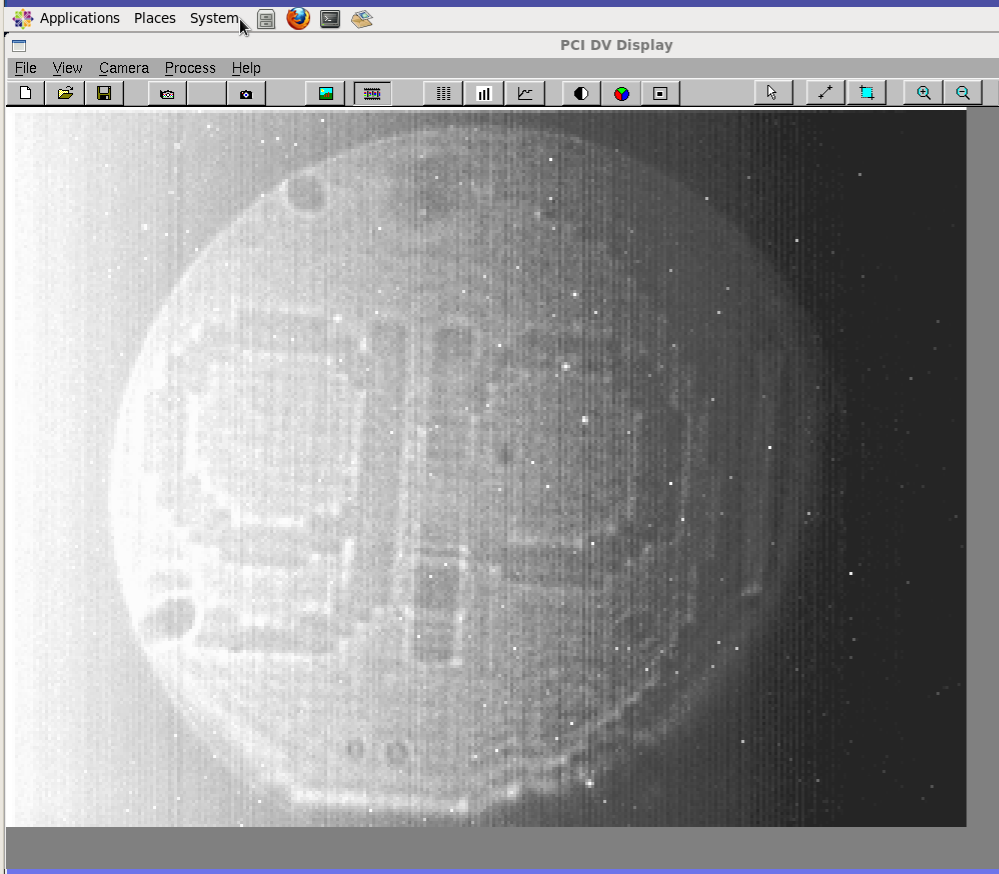

IR spectrograph installation January 2012

JAN.31.12 11:44:59AM

GPI First Light



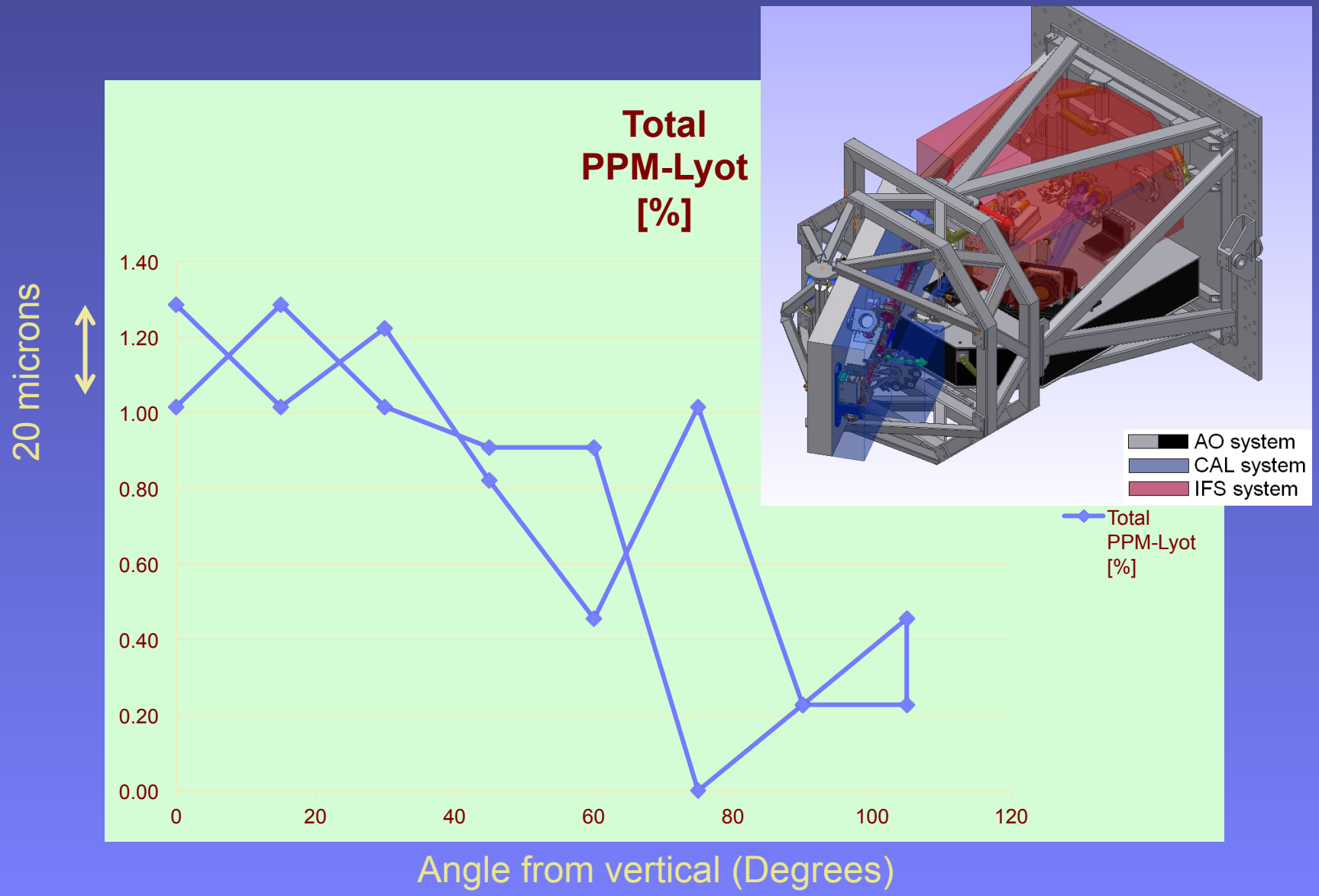
Wavefront sensor



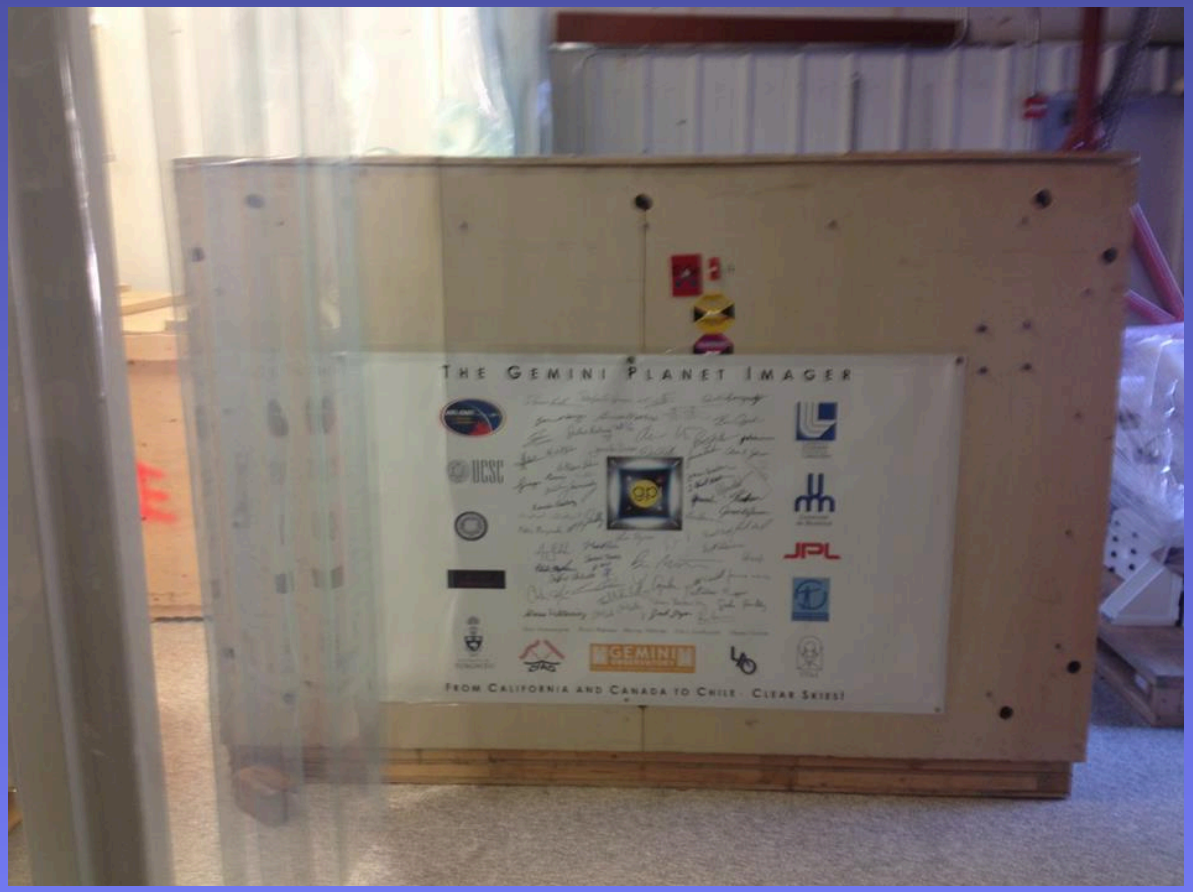
Pupil viewing camera

Cold & Flexure testing March-May 2013

Flexure testing – residual beam motion between IFS and AO



Packing & Shipping



Loading

Truck

This way up
FRAGILE
DO NOT
DROP
FRAGILE
DO NOT DROP
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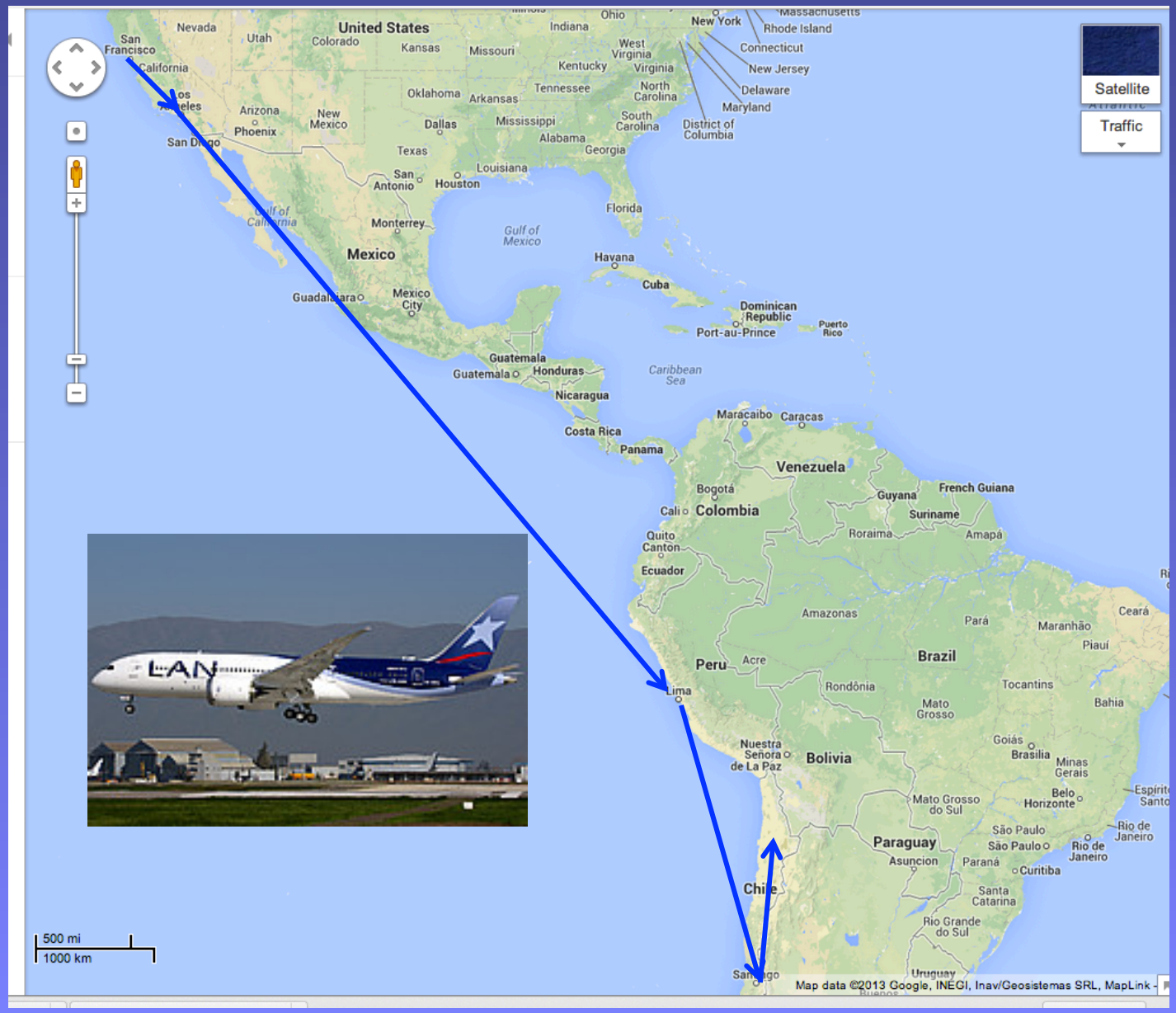
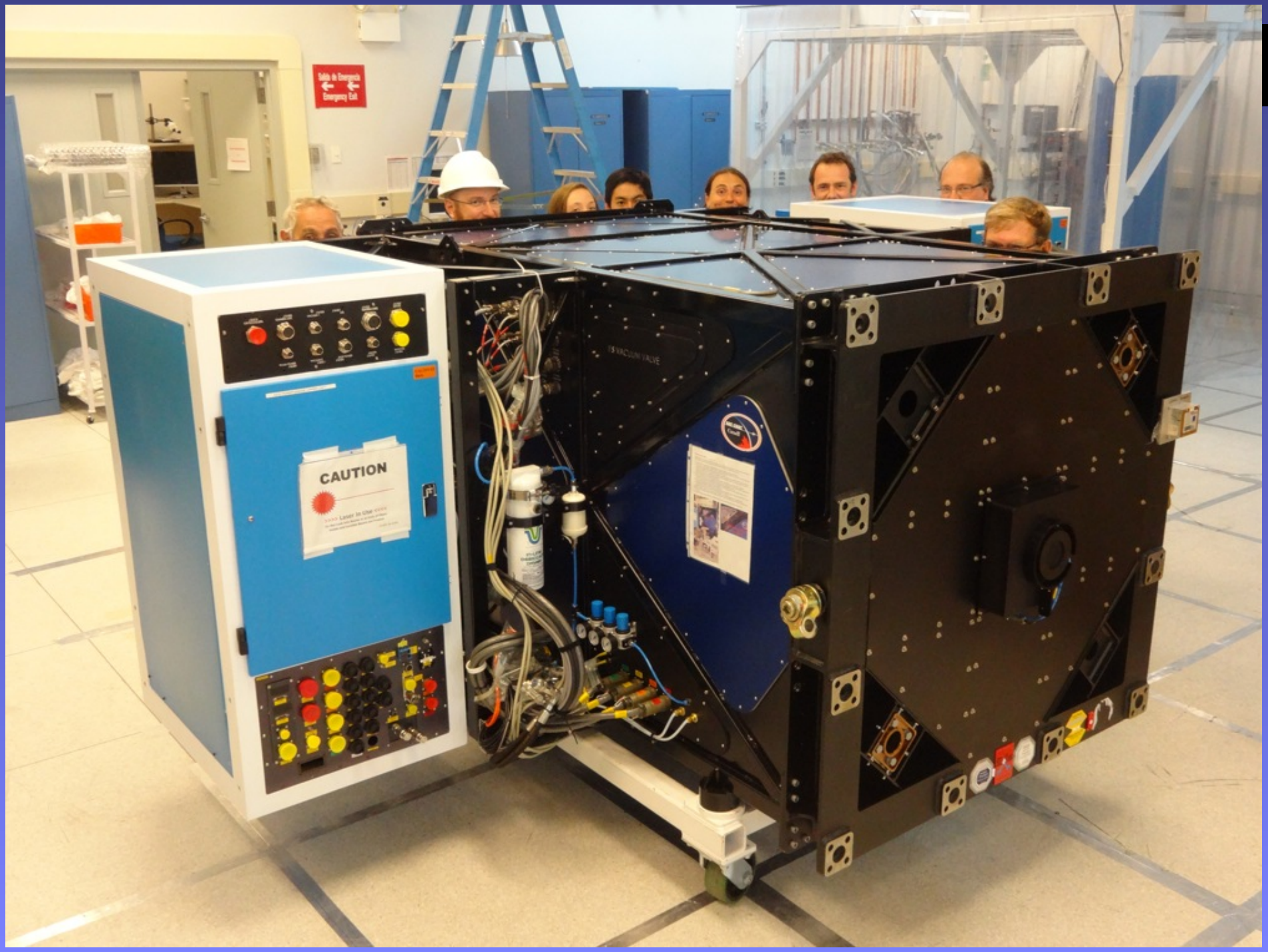
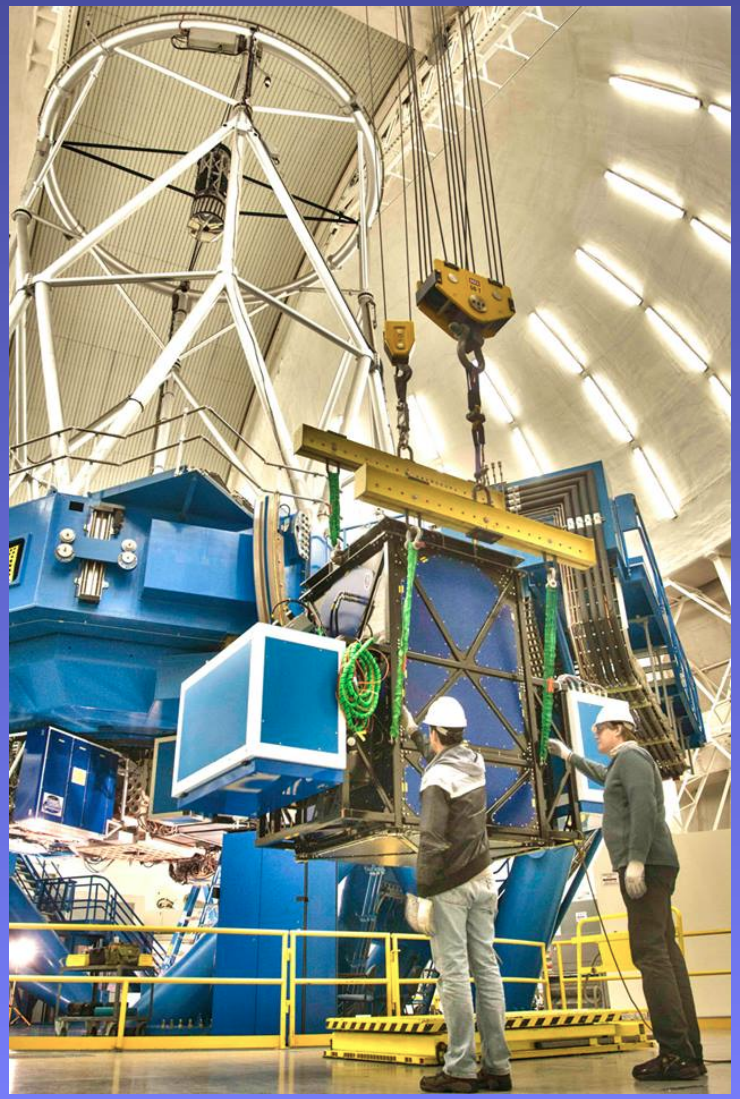
DO NOT
DROP
FRAGILE

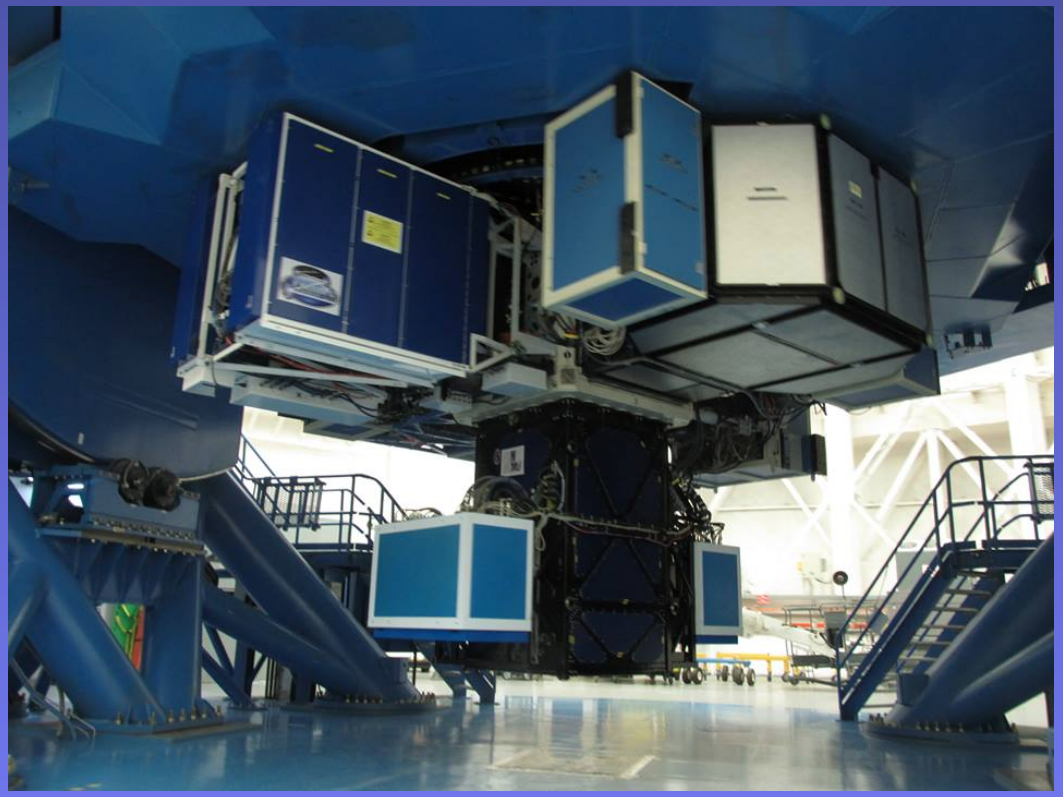
Travel to Gemini




Safety & Emergency
Emergency Exit
CAUTION
Laser in use

Telecsope integration October 2013





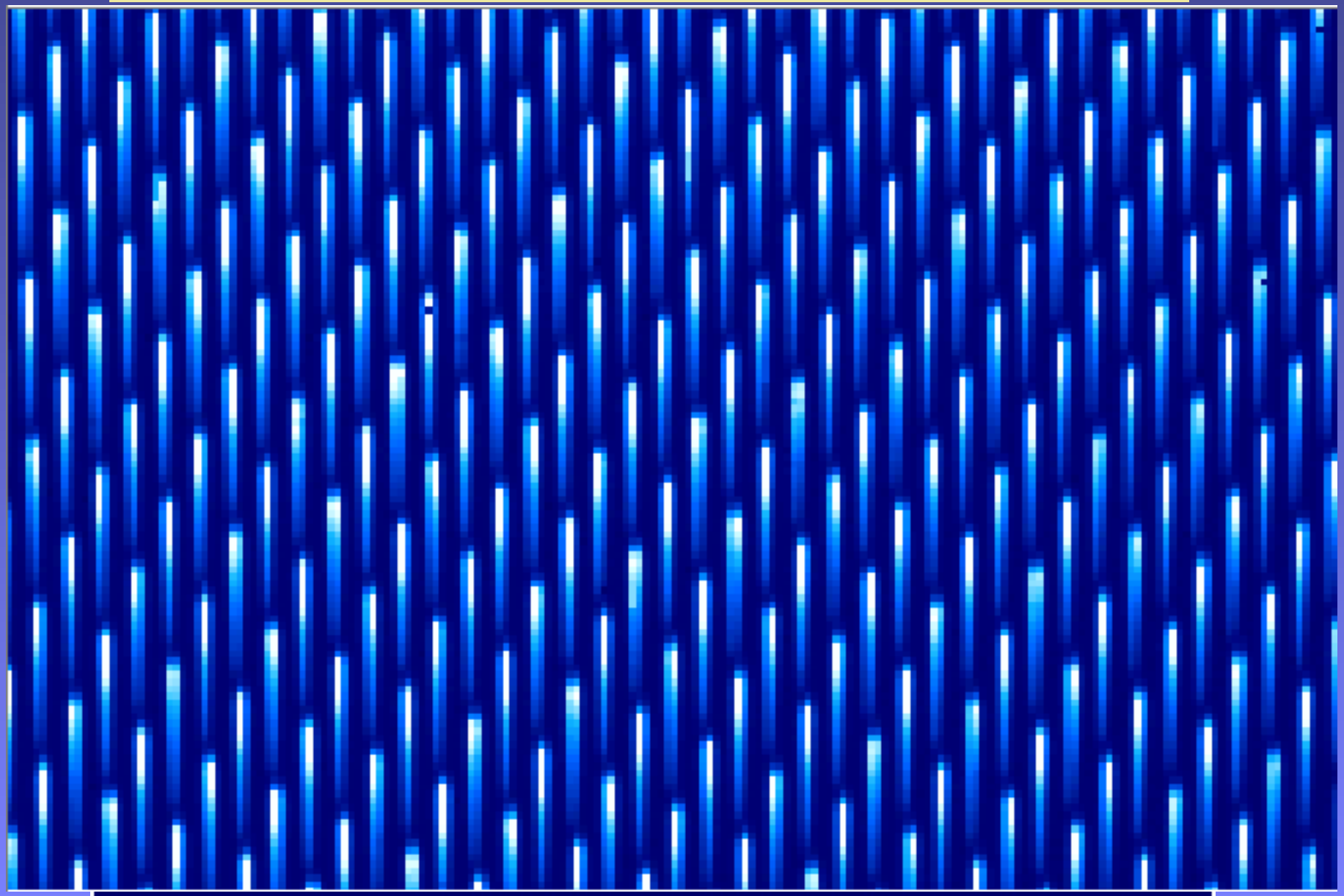
Facebook: Gemini Planet Imager
http://planetimager.org

"First Light" November 11-17 2013

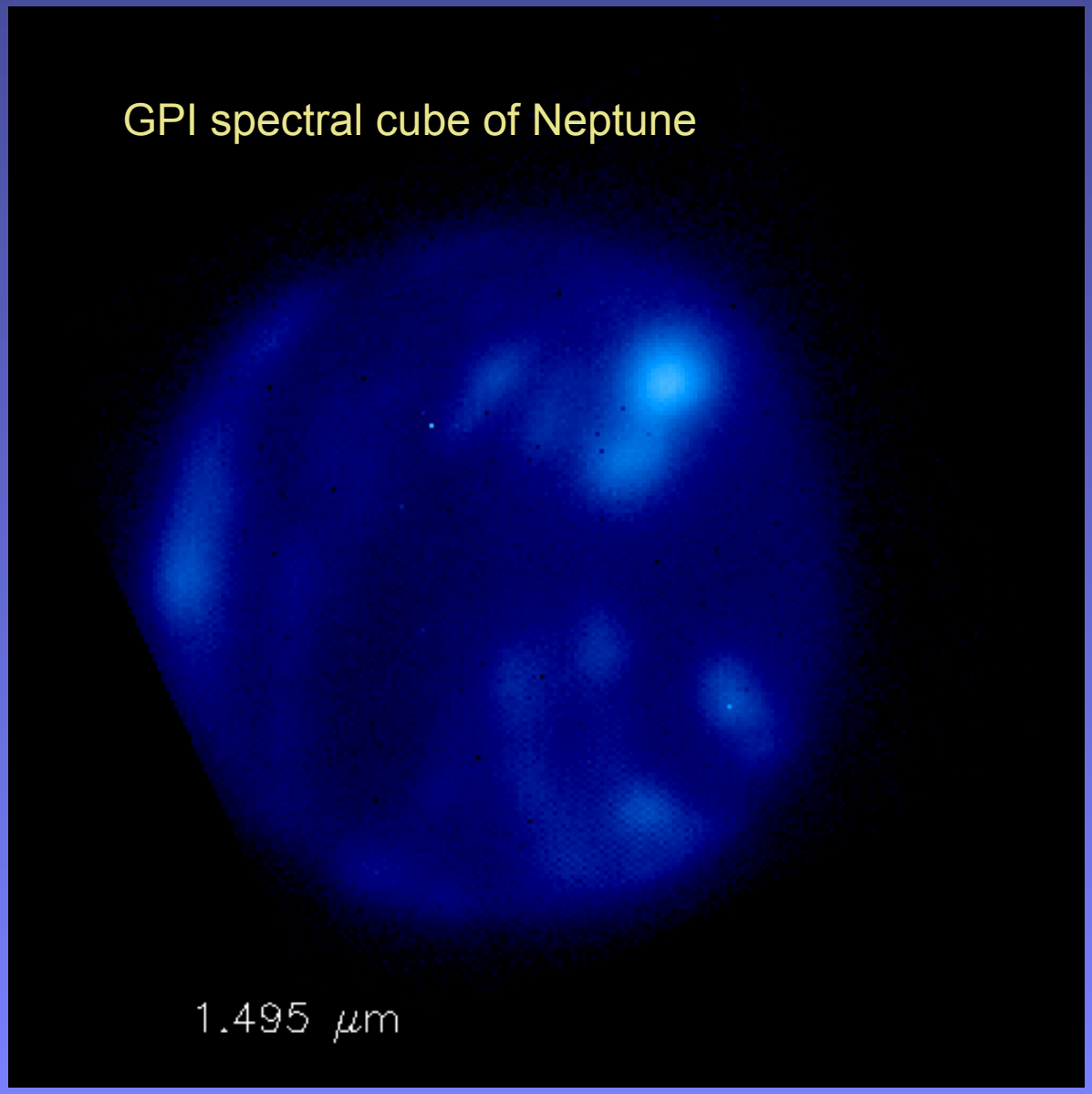
GPI operated smoothly right out of the box – "best Gemini 1st light ever"

Science verification concentrated on known exoplanets

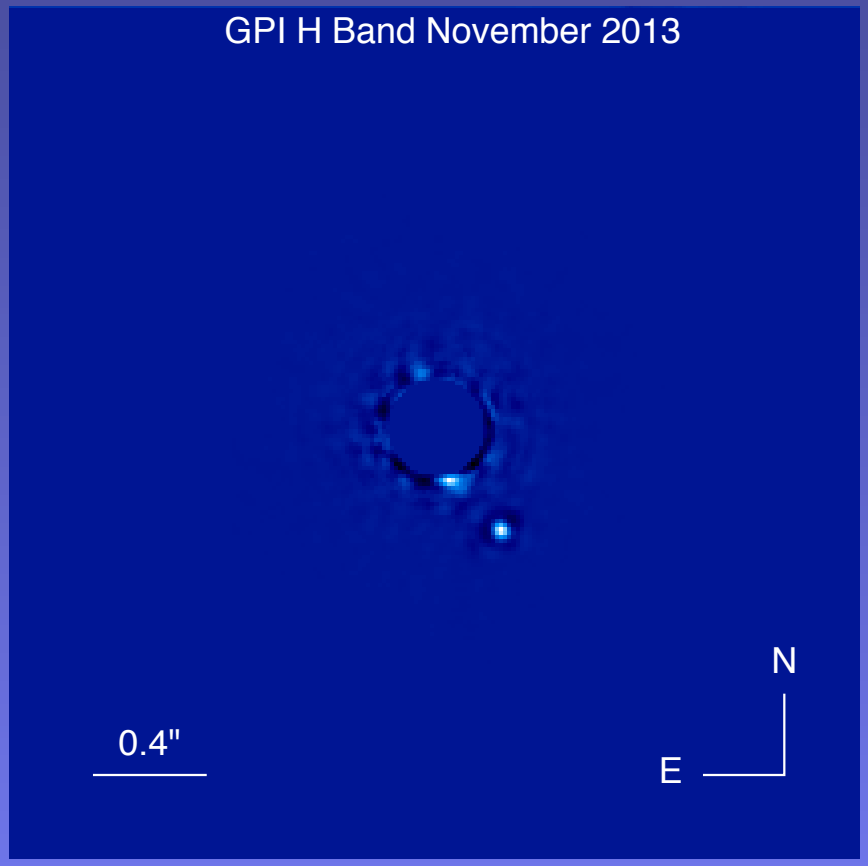
Raw IFS data



Integral Field Spectrograph (UCLA) produces a spectrum of every pixel

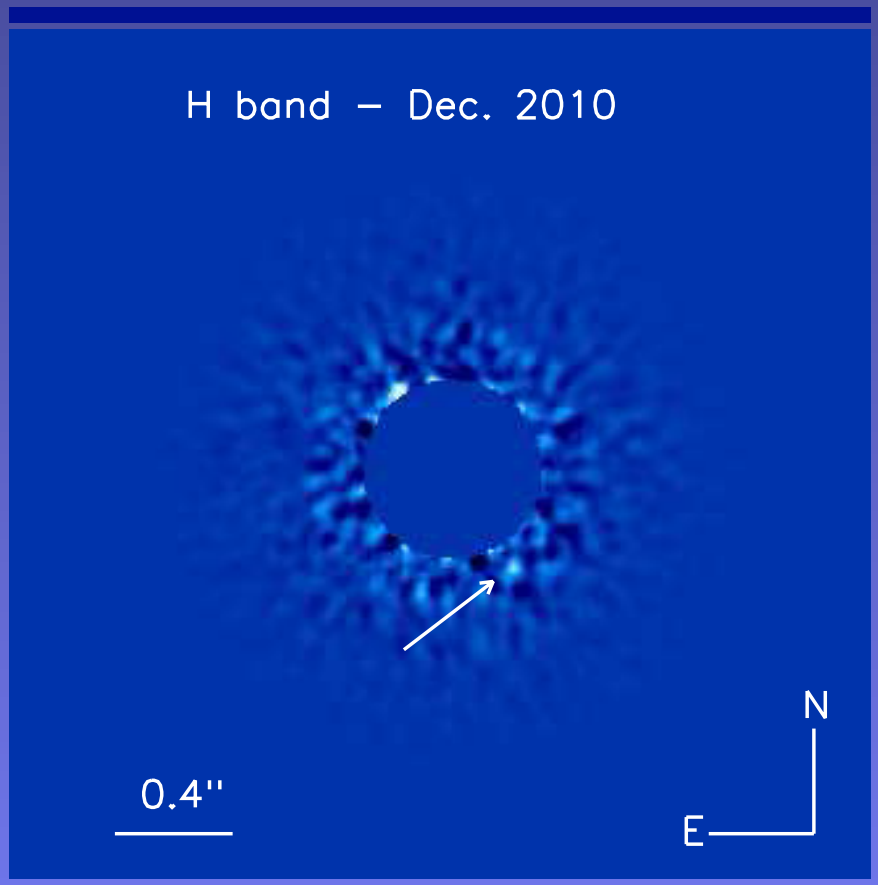


Massive planet orbiting Beta Pictoris b



Gemini Planet Imager

1980 seconds



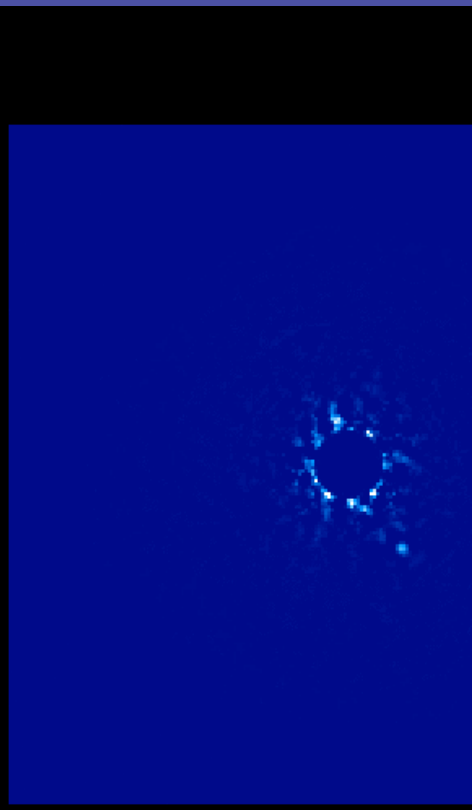
Gemini NICI (previous generation)

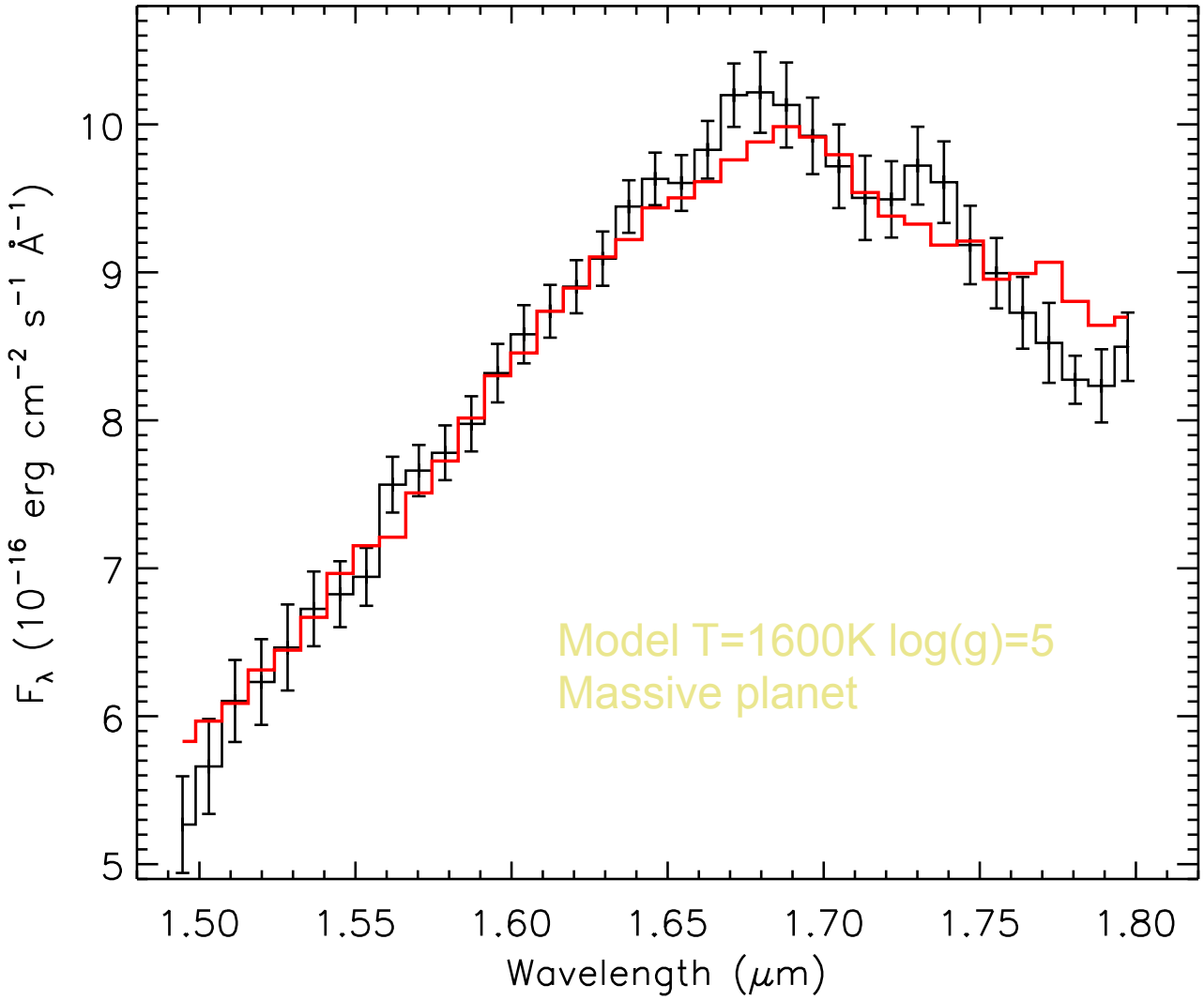
3952 seconds

Reaction to first planet images

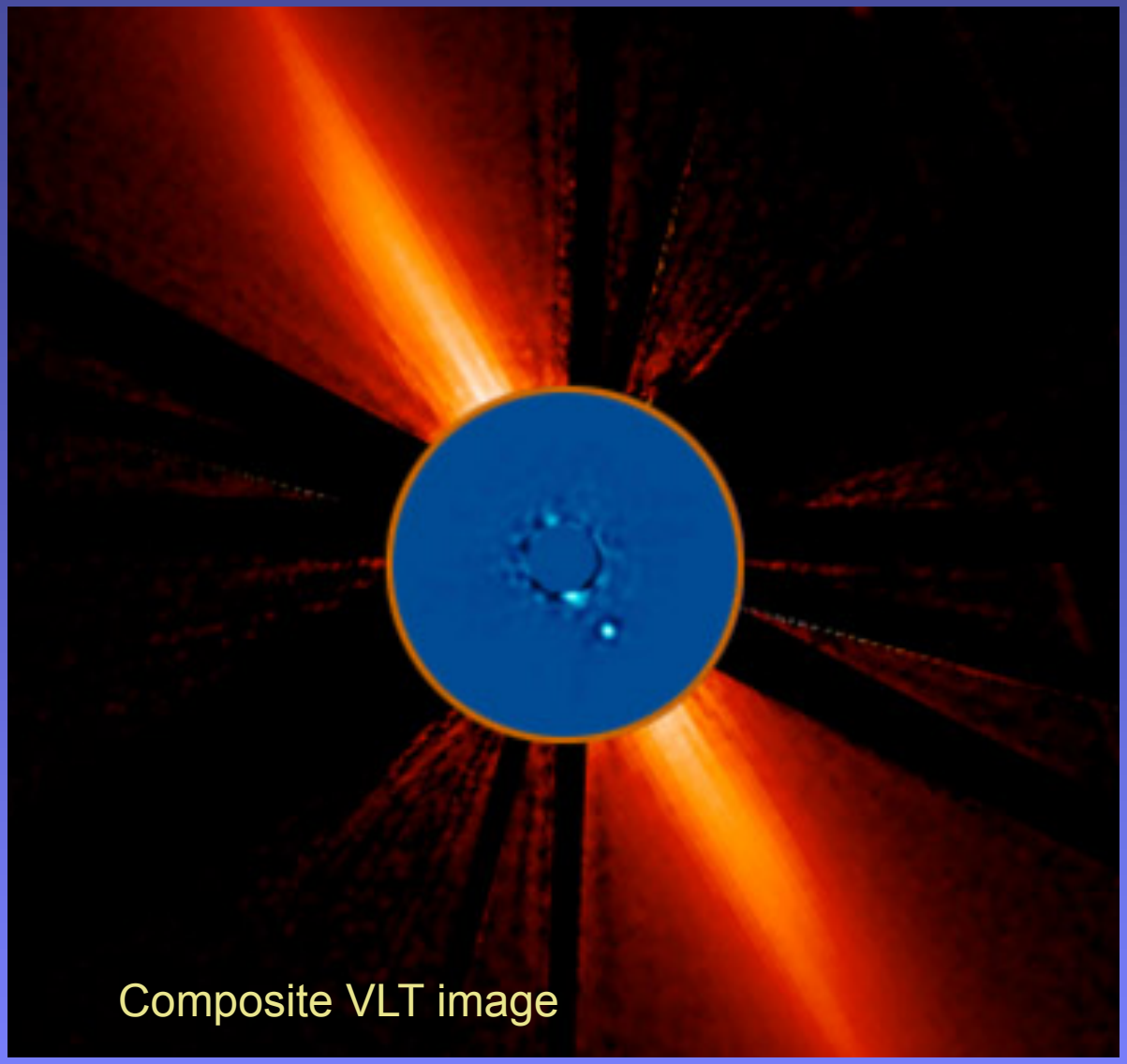
Gemini Planet Imager

Beta Pictoris b spectrum

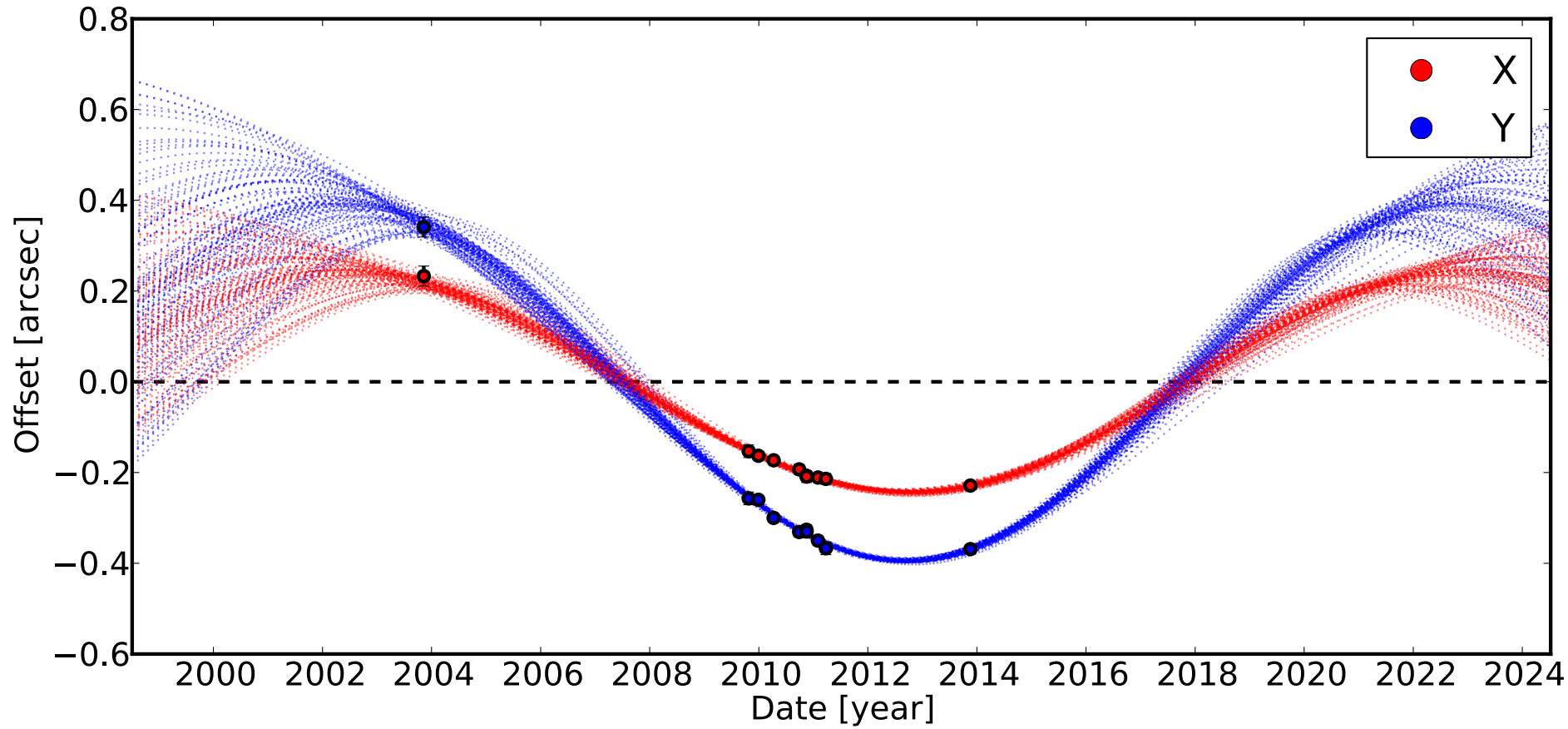




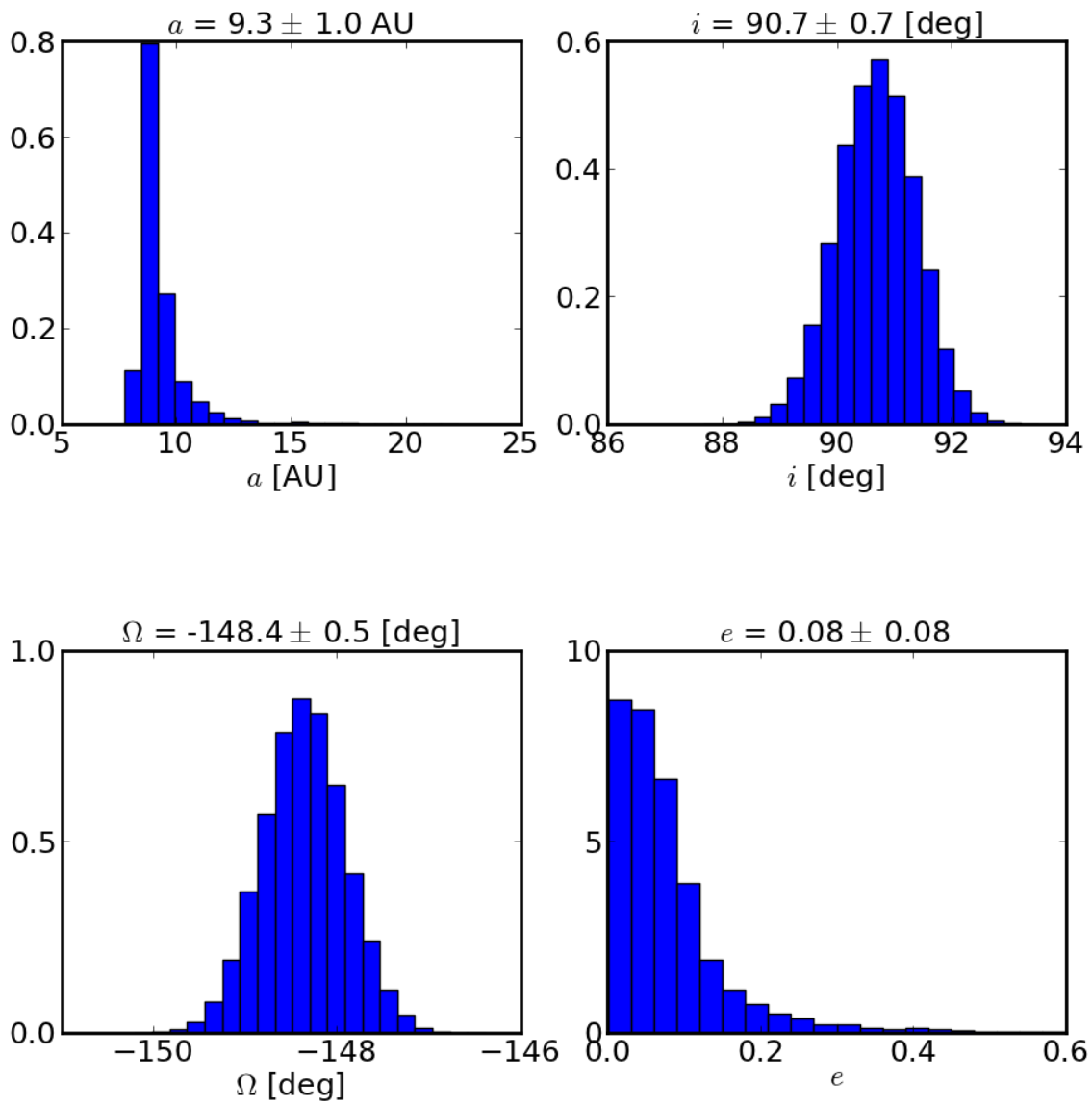
Beta Pic planet aligned with disk



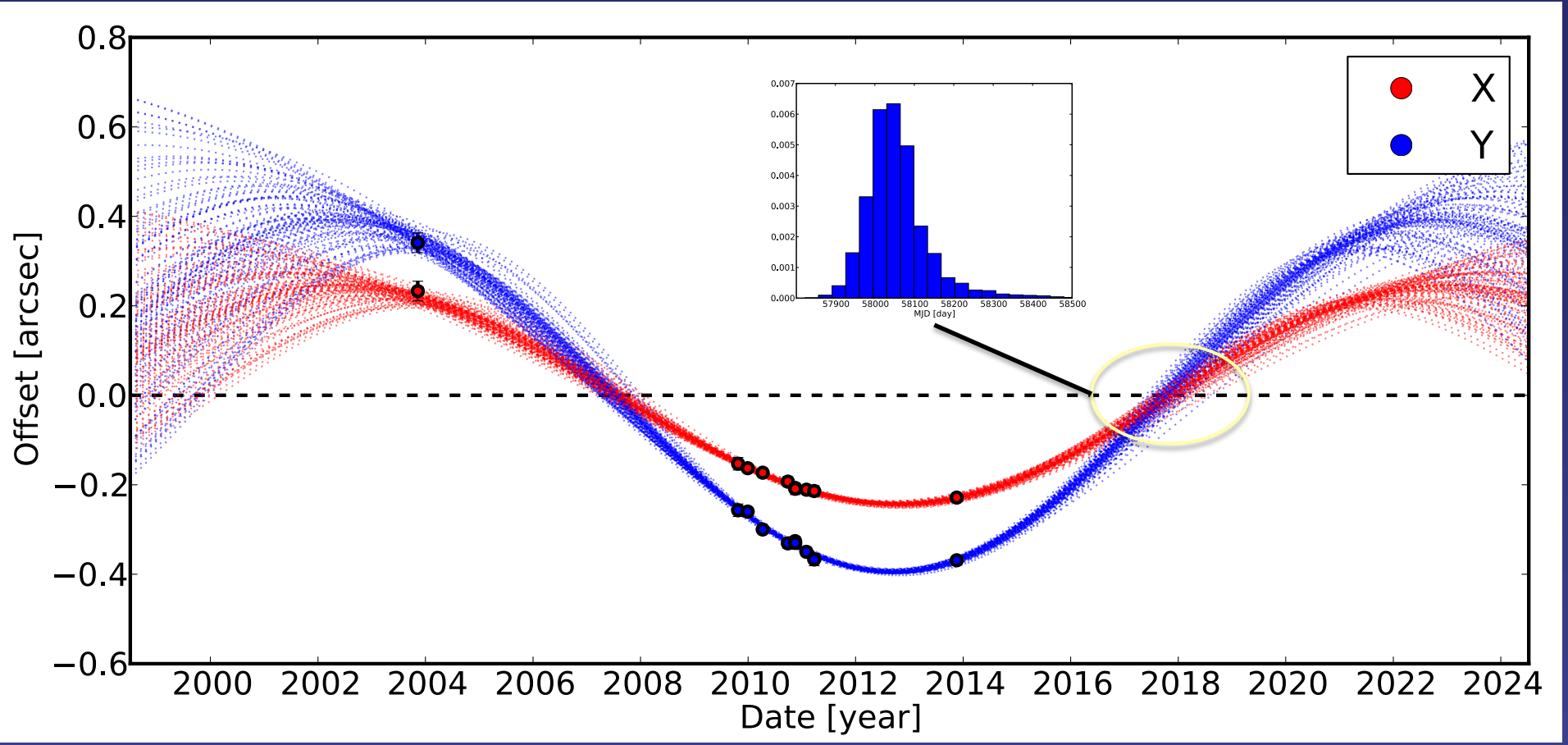
Orbit fitting with GPI + VLT



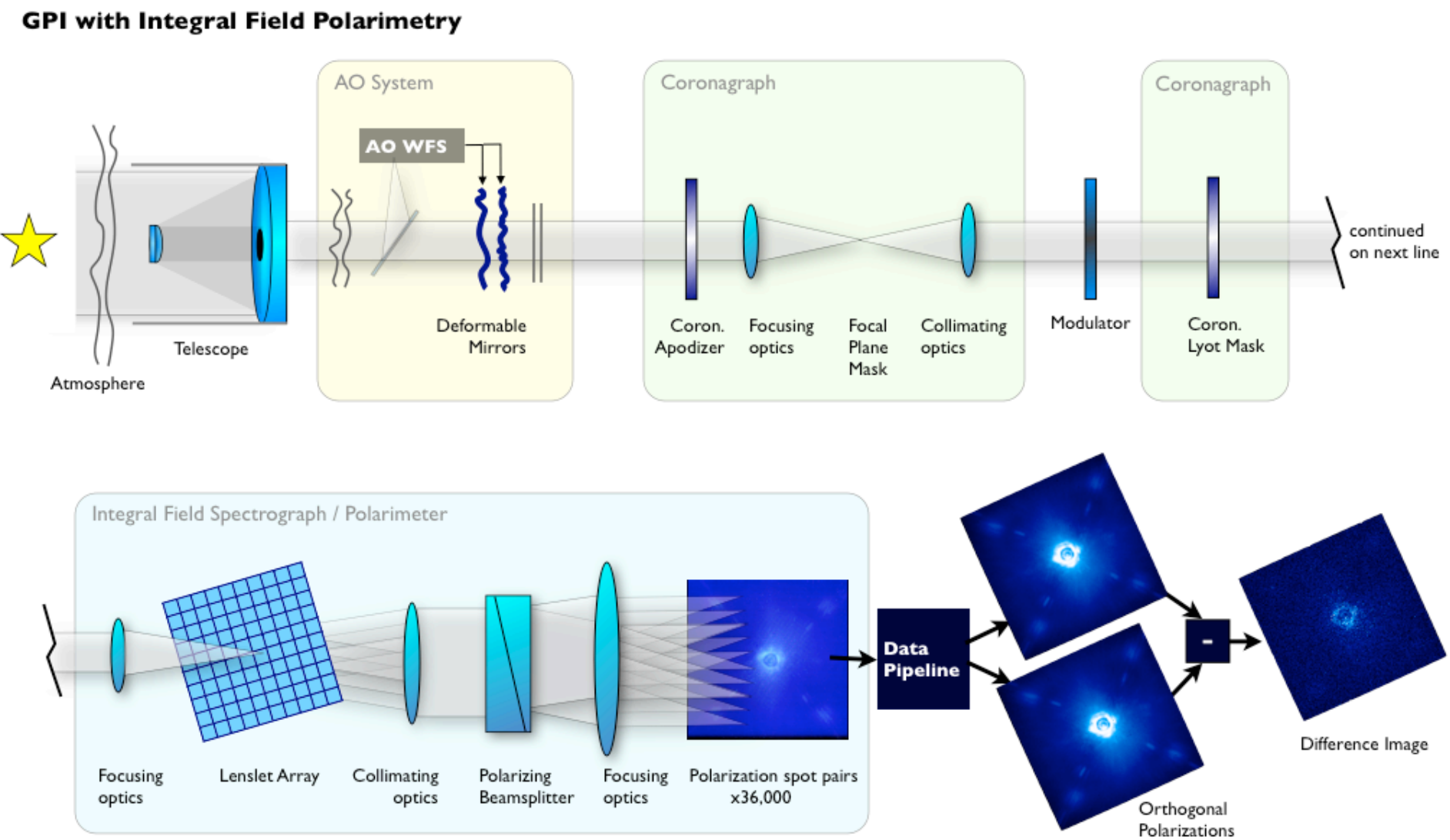
GPI data shows edge-on circular orbit



Transit?

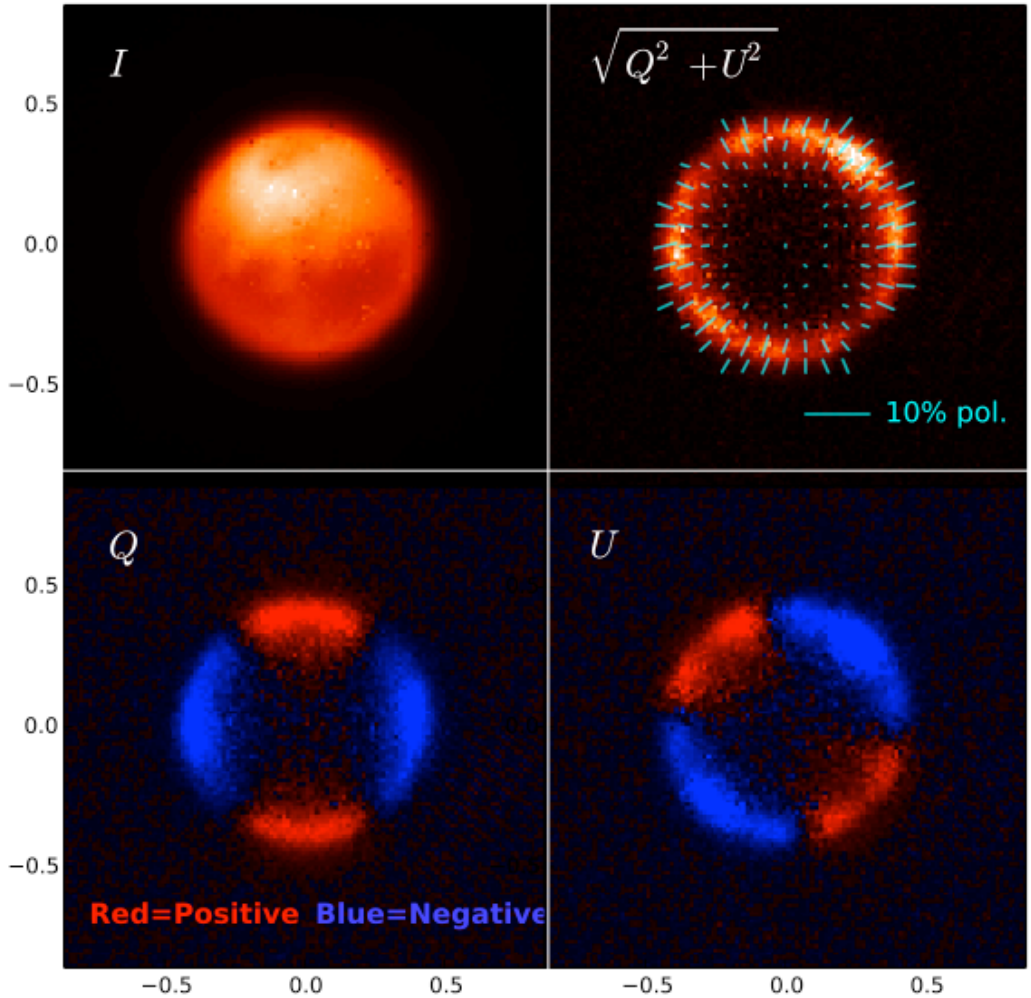

0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
Offset [arcsec]
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020
2022
2024
Date [year]
X
Y
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.000
57900
58000
58100
58200
58300
58400
58500
MJD [day]

Imaging polarimetry mode

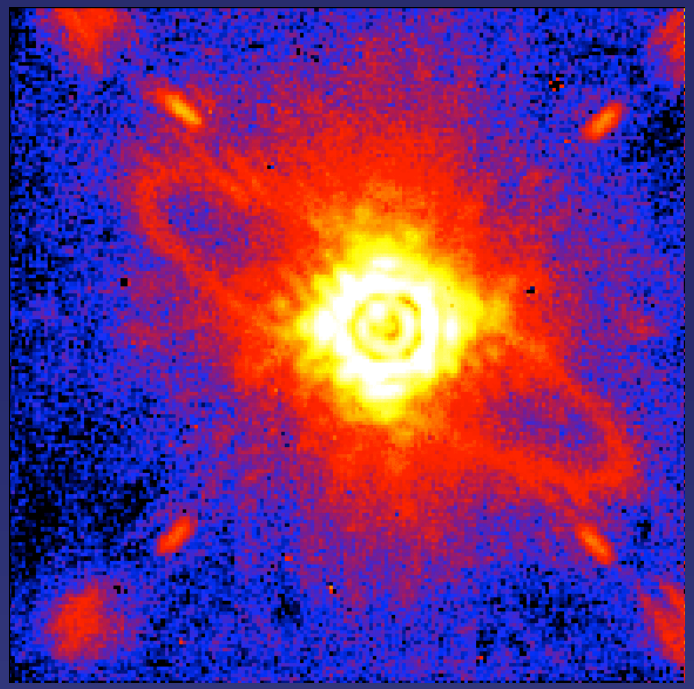


Perrin et al. 2010, 2014 in prep.

K-band polarimetry of Titan



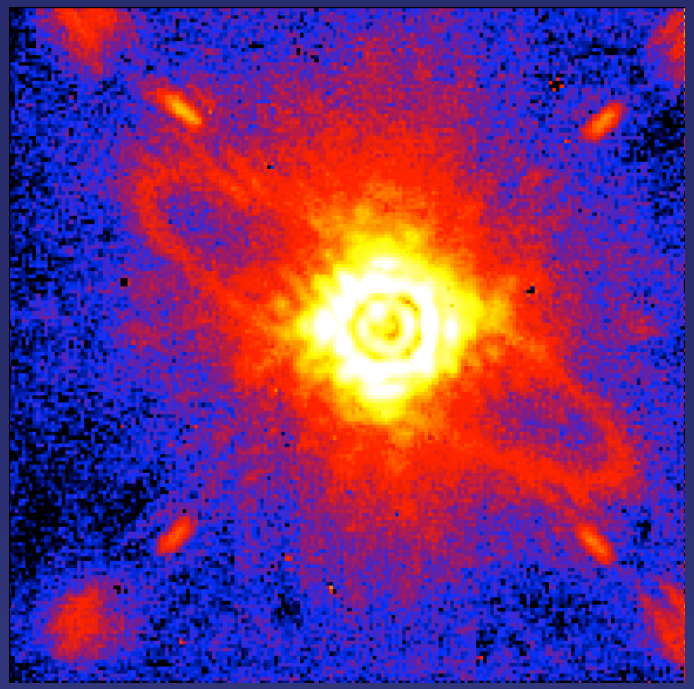
GPI Observations of HR 4796A



Individual 60 s images
One linear polarization shown.
Waveplate rotates 0, 22.5, 45...
& the parallactic angle changes

Slide by Marshall Perrin

GPI Observations of HR 4796A



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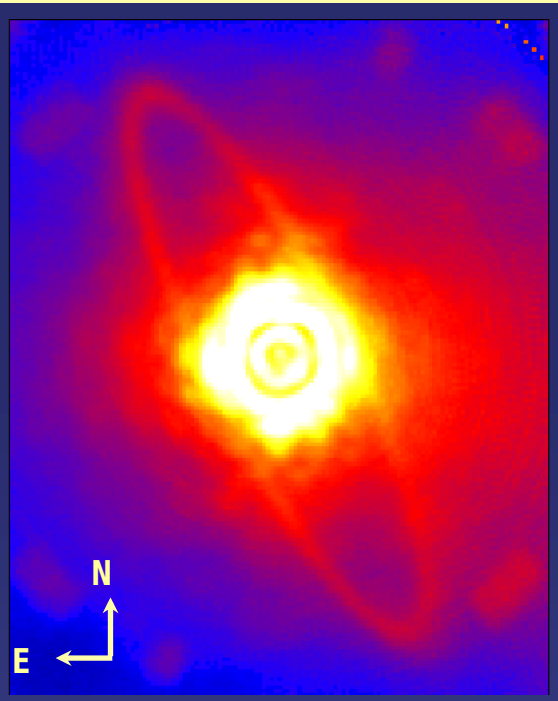
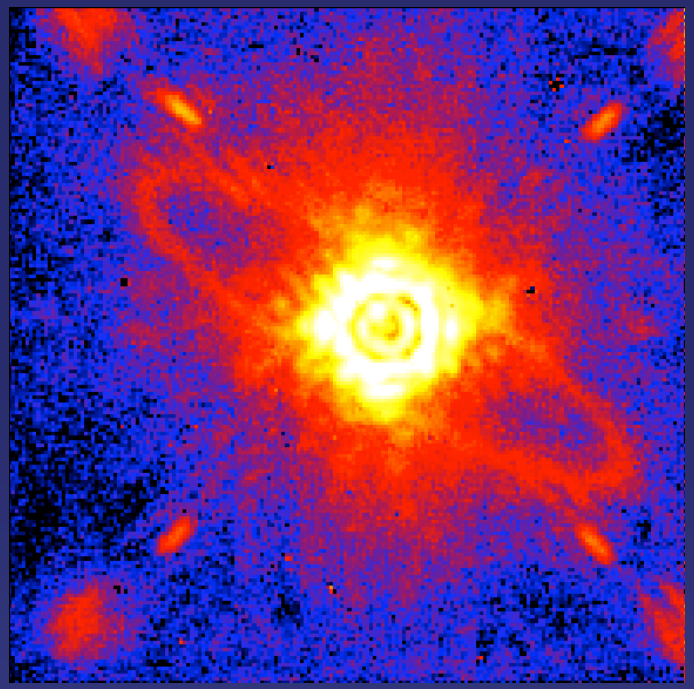


Combined 12 minutes
Total intensity

Slide by Marshall Perrin

GPI Observations of HR 4796A



Individual 60 s images
One linear polarization shown.
Waveplate rotates 0, 22.5, 45...
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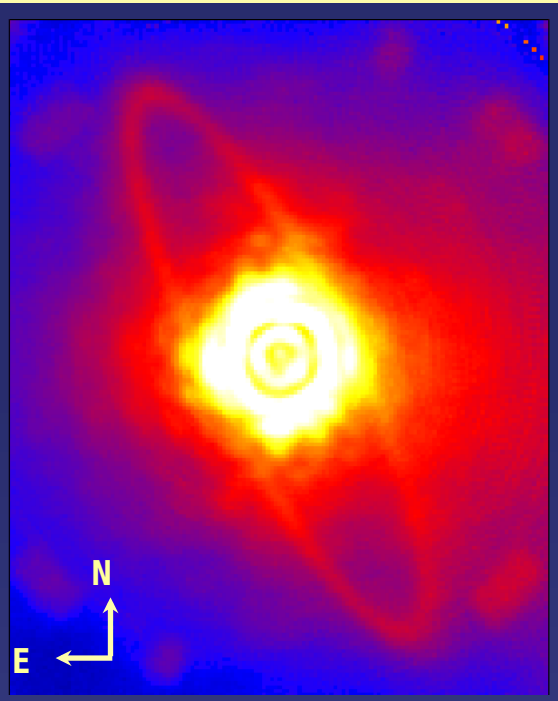
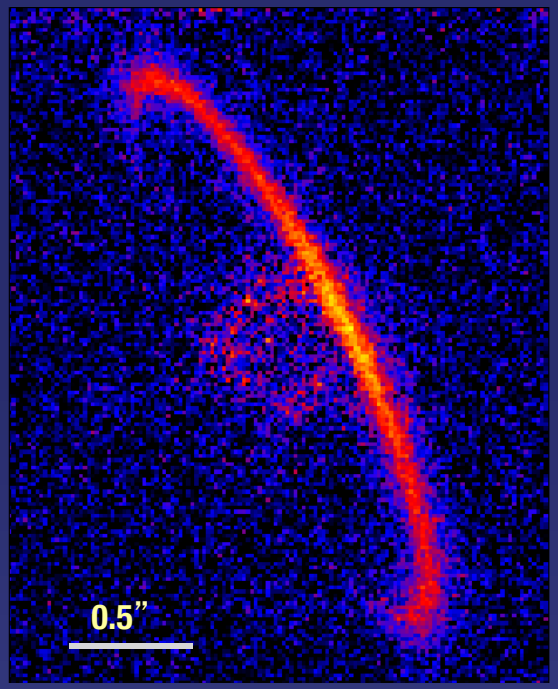


Combined 12 minutes
Total intensity

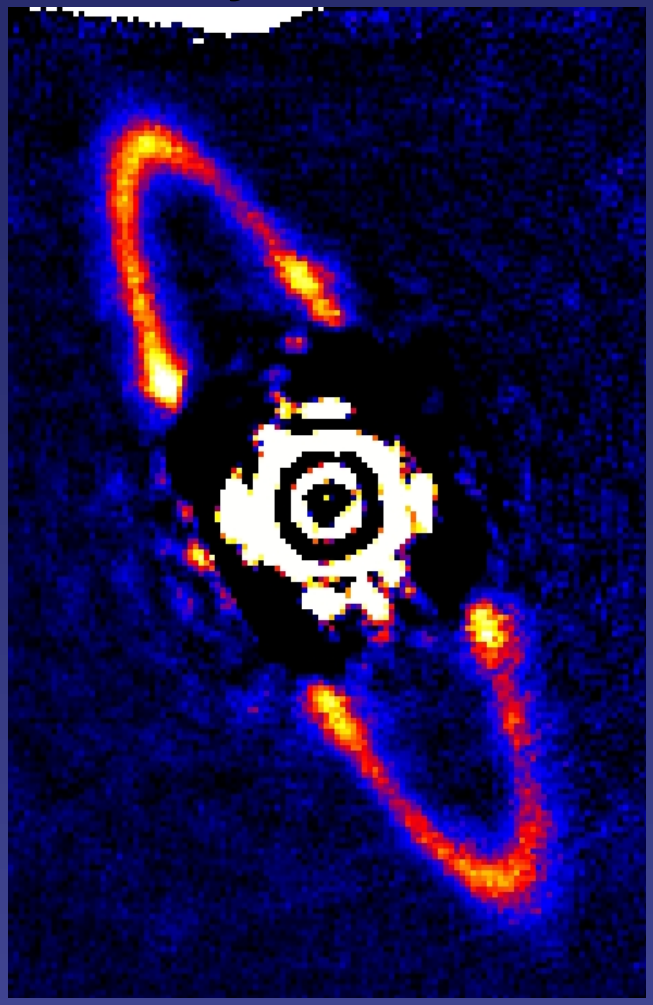


Combined 12 minutes
Linear polarized intensity

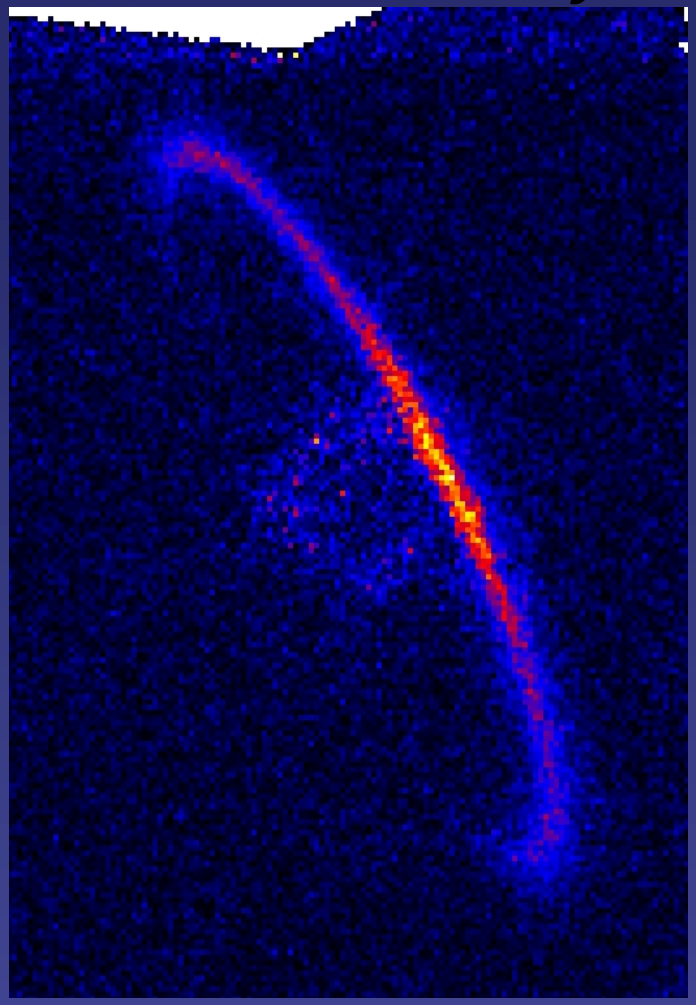
Slide by Marshall Perrin

Polarization imaging

Total intensity (PSF-subtracted)

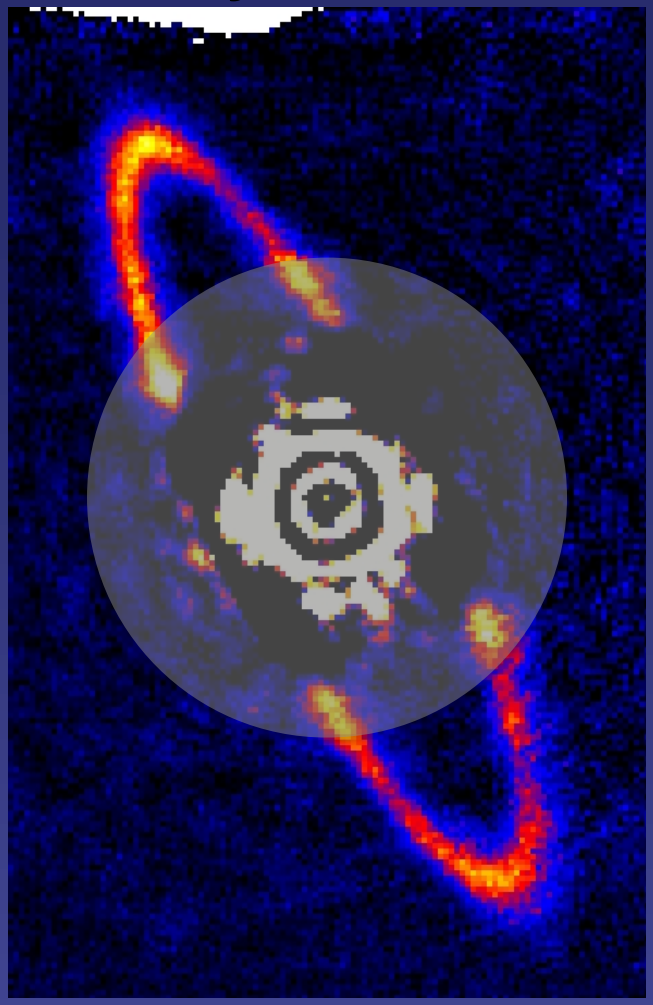


Polarized intensity

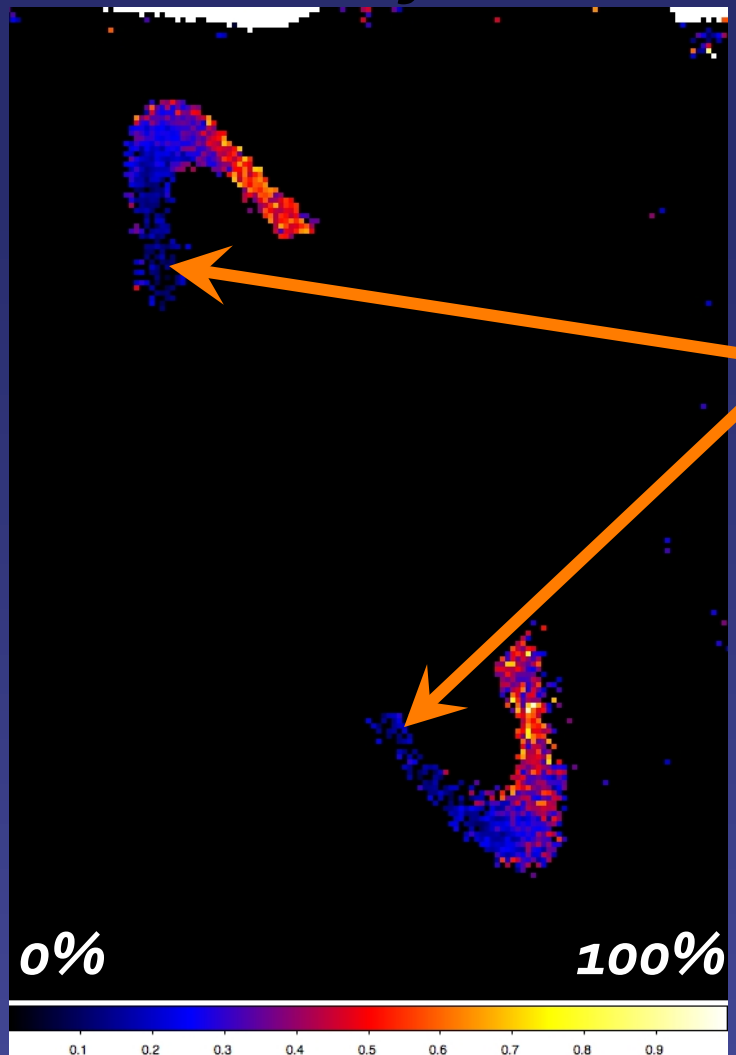


Polarization imaging

Total intensity (PSF-subtracted)

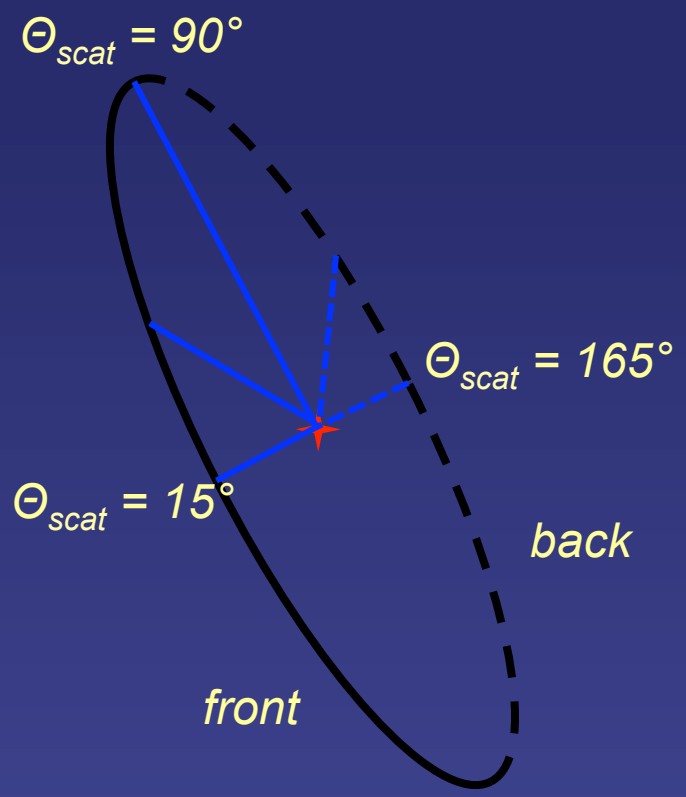


Polarization fraction

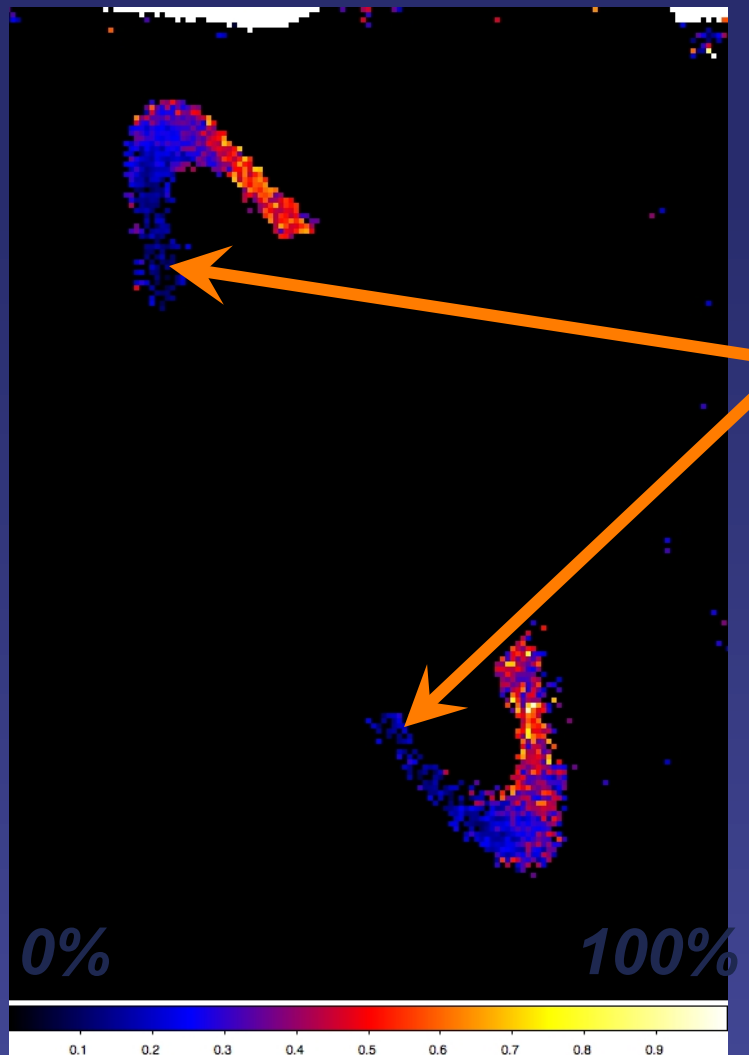


Upper limits

Polarization imaging

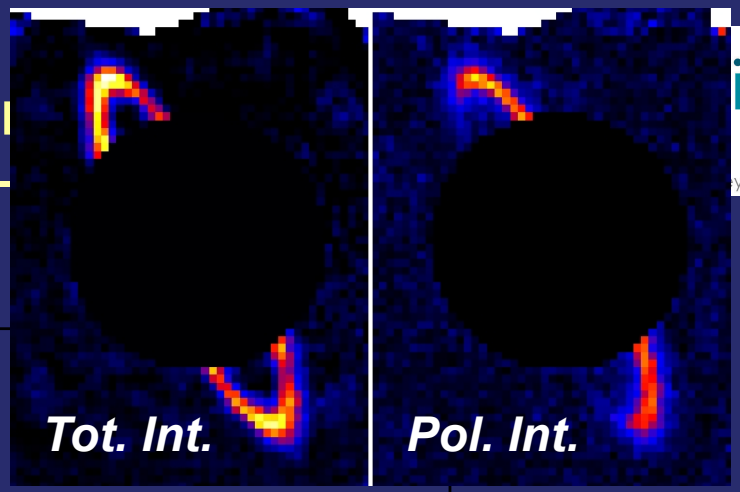


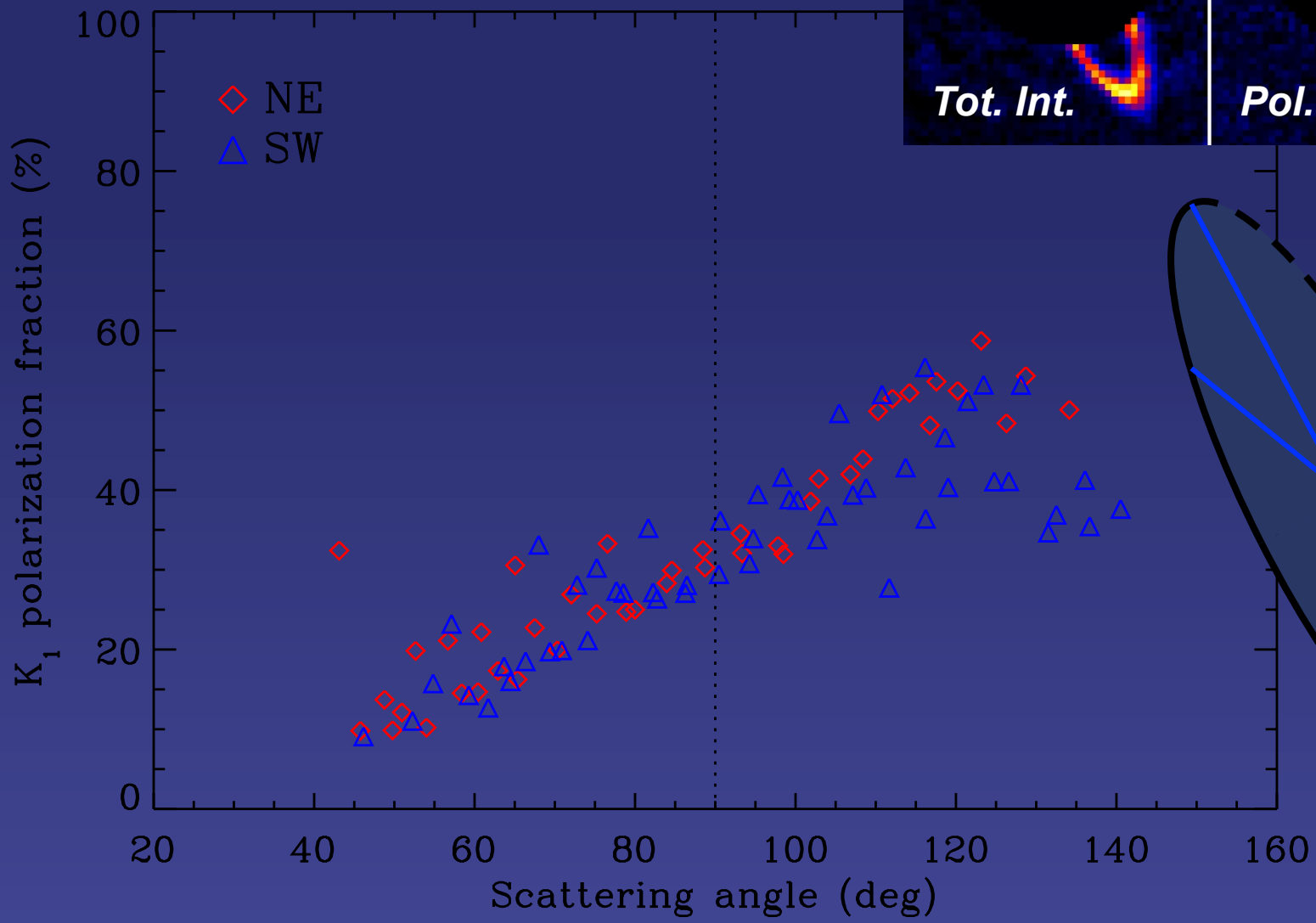
Polarization fraction

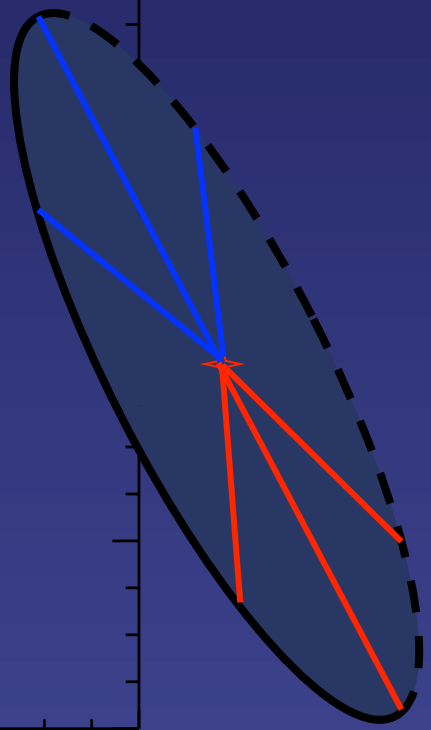


Upper limits

Polarization cu

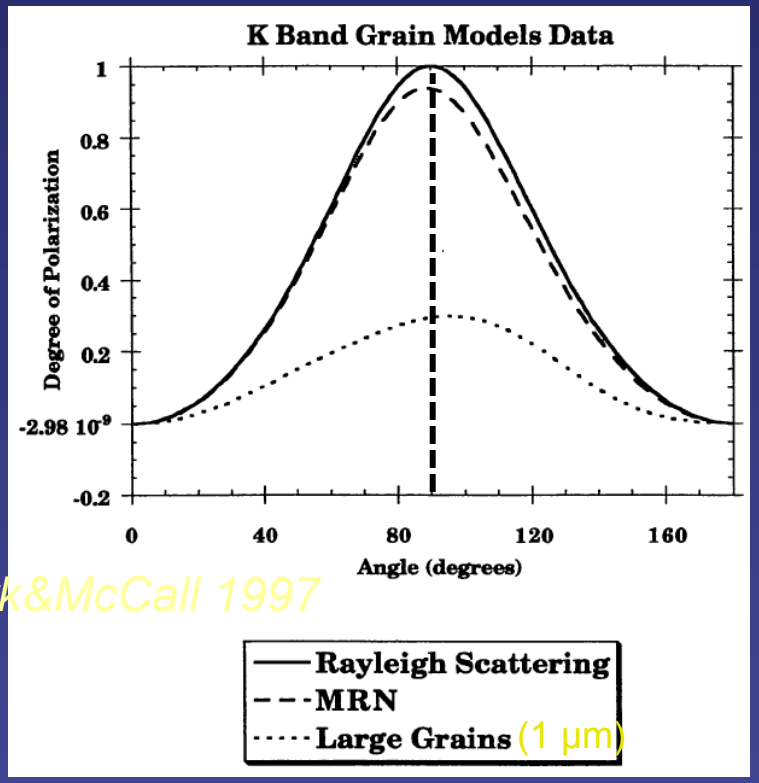




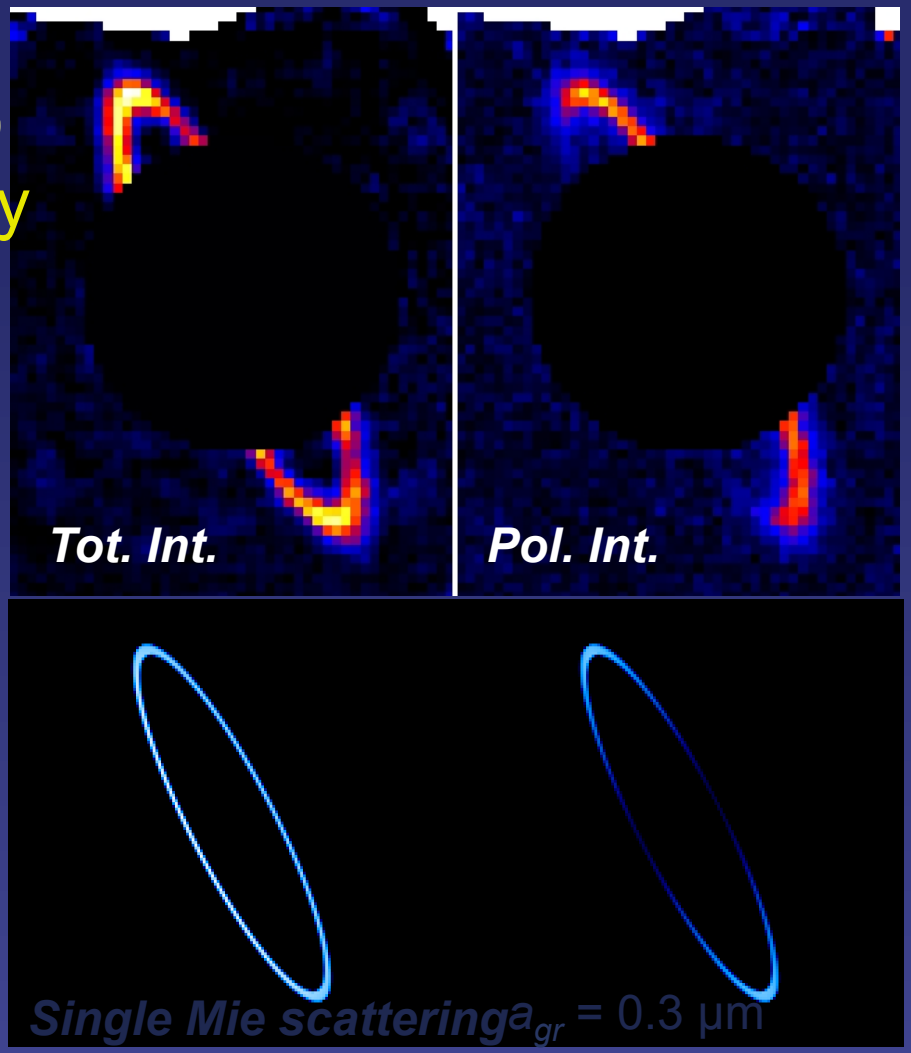


Implications

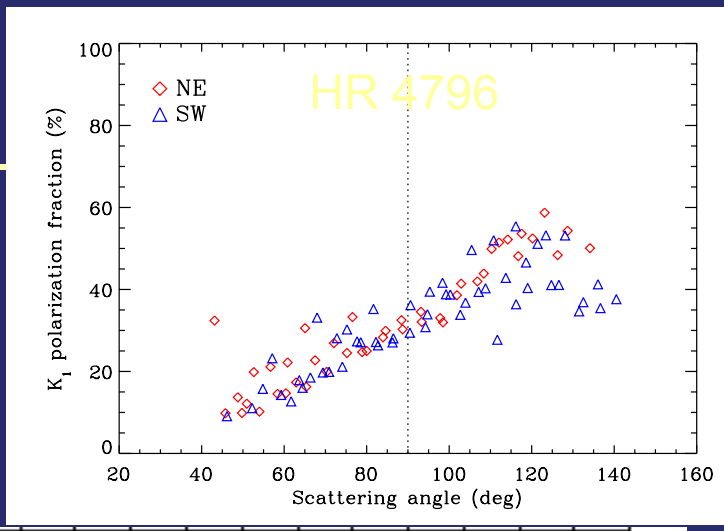
Total intensity image can be reproduced with small (sub-μm) dust grains but polarized intensity is inconsistent with this

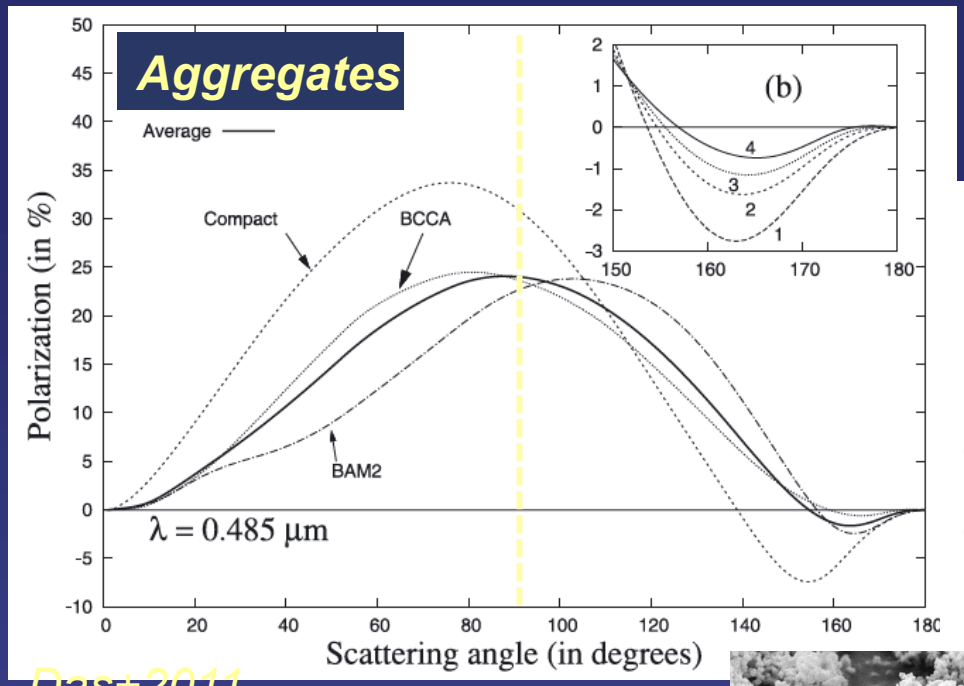


Clark&McCall 1997

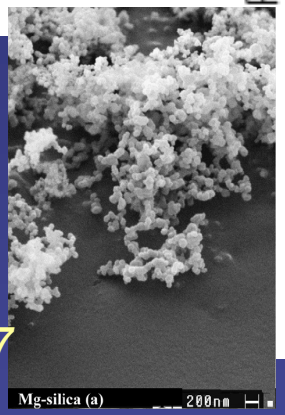


Mix including large

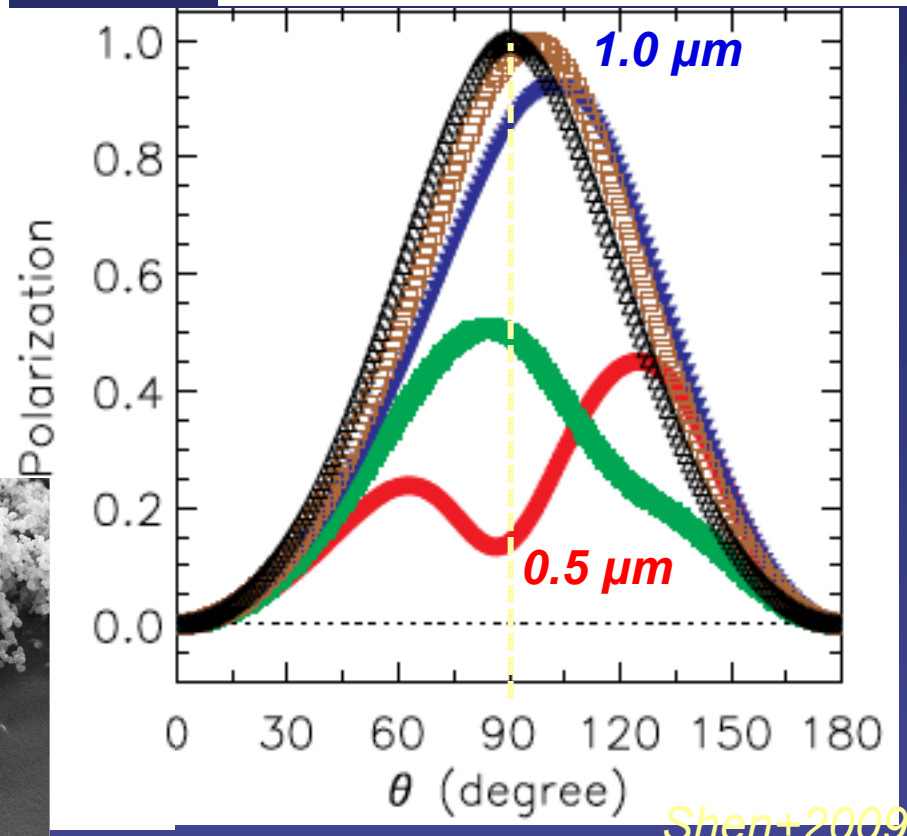




Das+2011



Hadamcik+2007



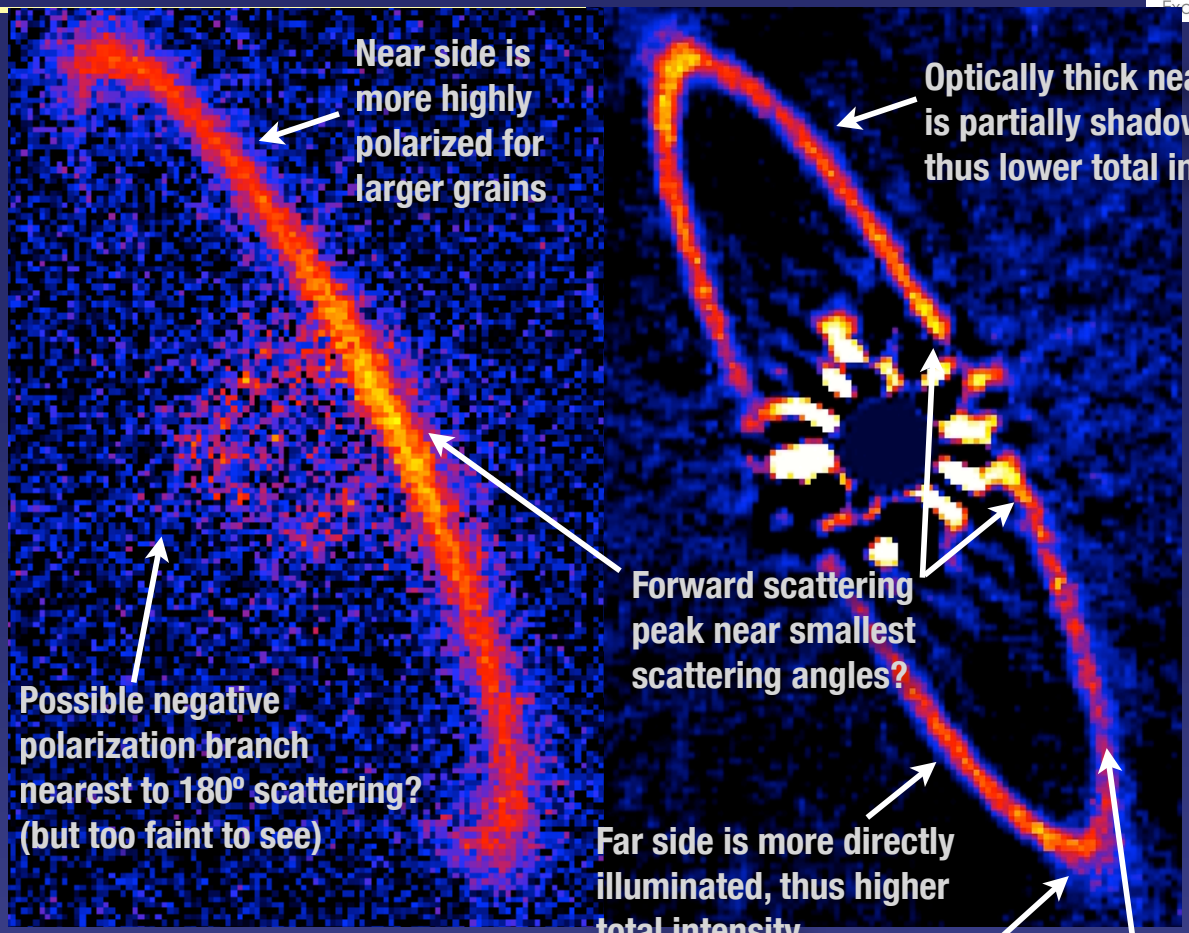
Shen+2009

HR 4796A's ring is:

- Probably slightly optically thick at 2 μm. ($\tau \sim 3\text{-}5?$)
- Dominated by dust particles ~5-10 μm, in the Fresnel scattering regime
- Geometrically narrow and dynamically cold

Predictions:

- Total intensity will strongly peak at the near side minor axis.
- Far side minor axis might exhibit negative polarization, similar to comet dust.

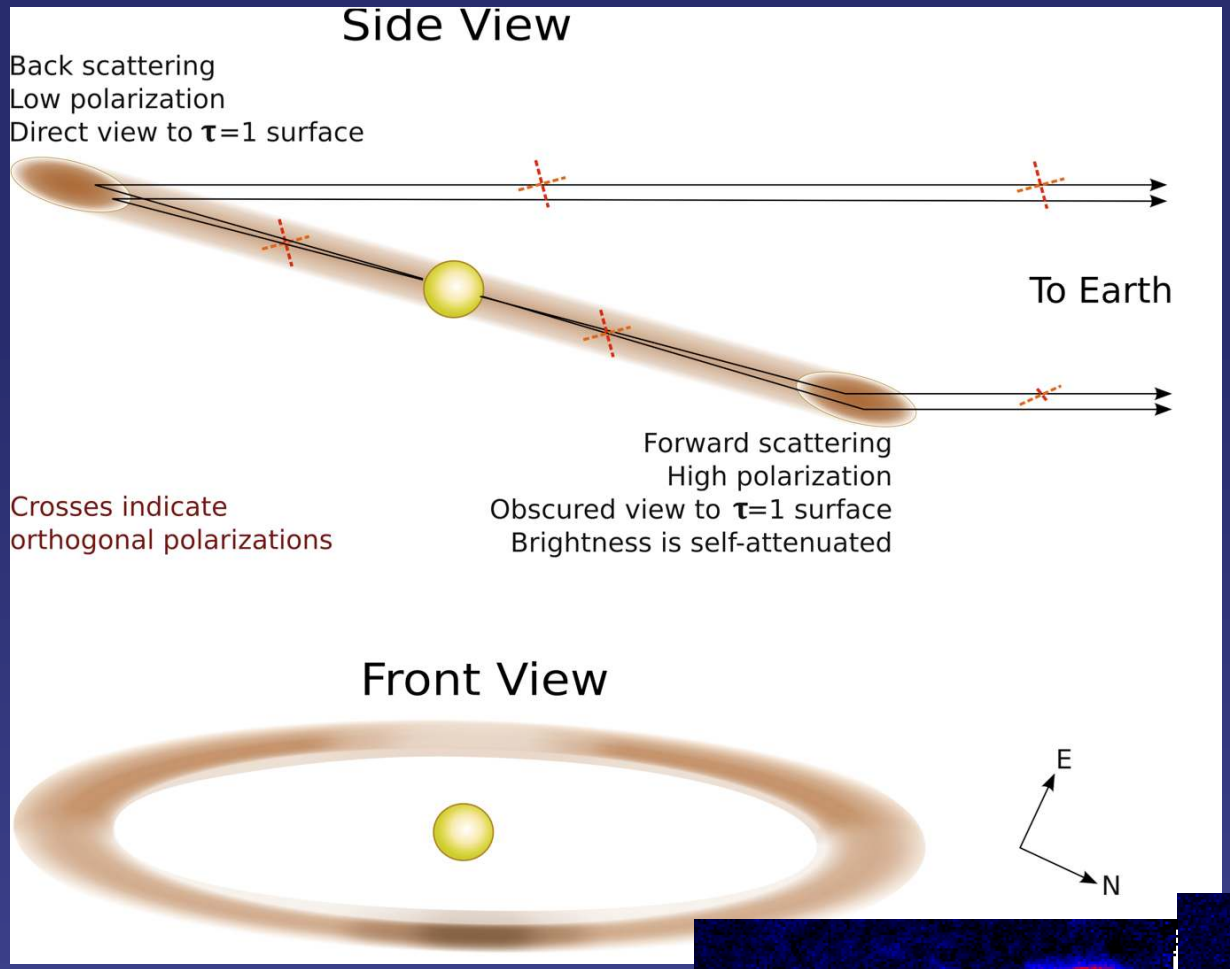


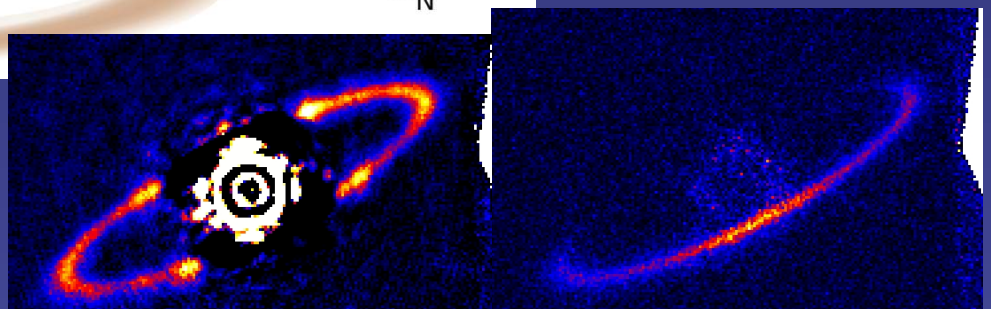
No major brightening near ansae because slightly optically thick

Previously noticed brightness minimum here is due to opt. thick shadowing.

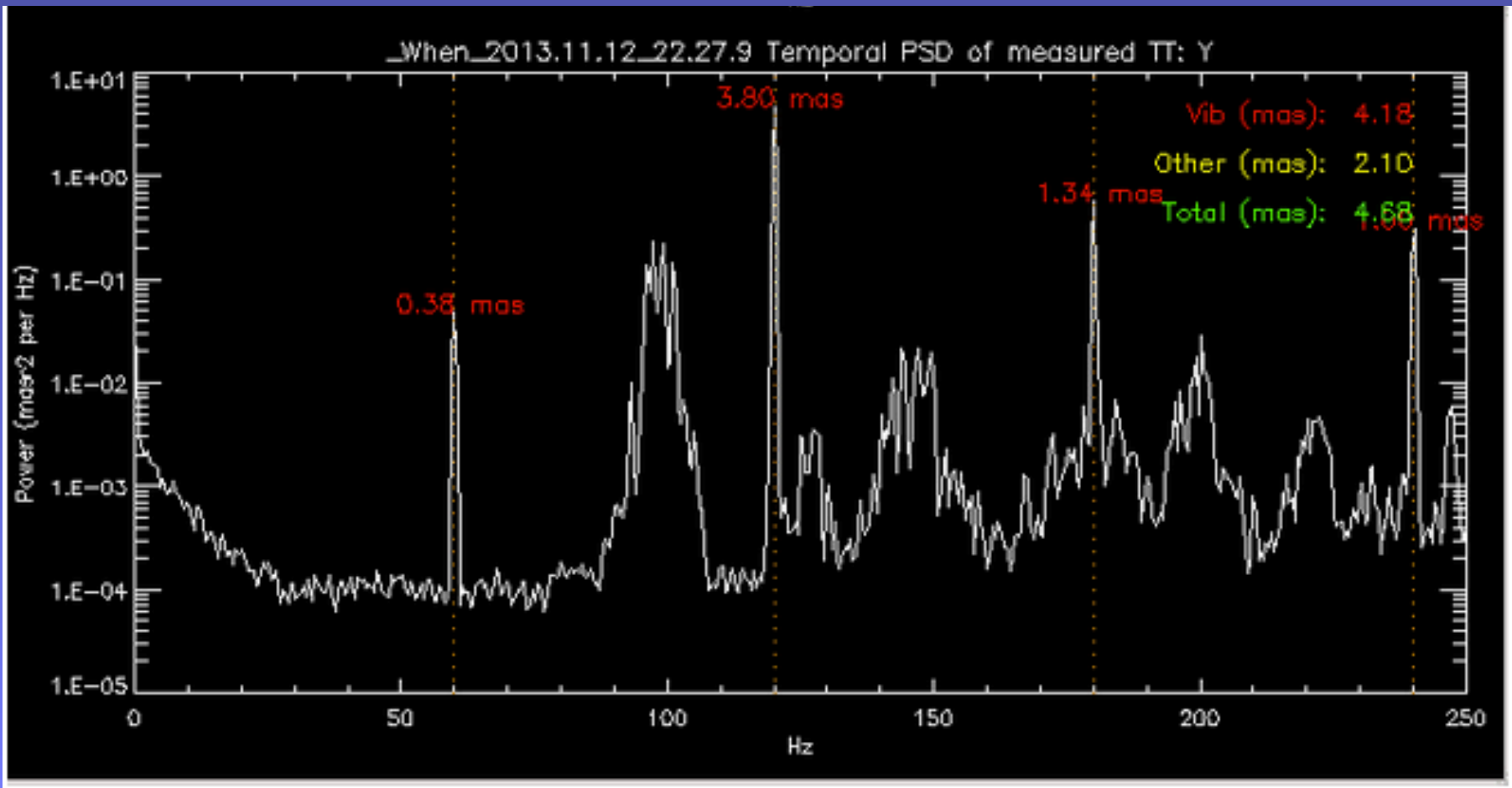
Slide by Marshall Perrin

Optically thick disk with large grains

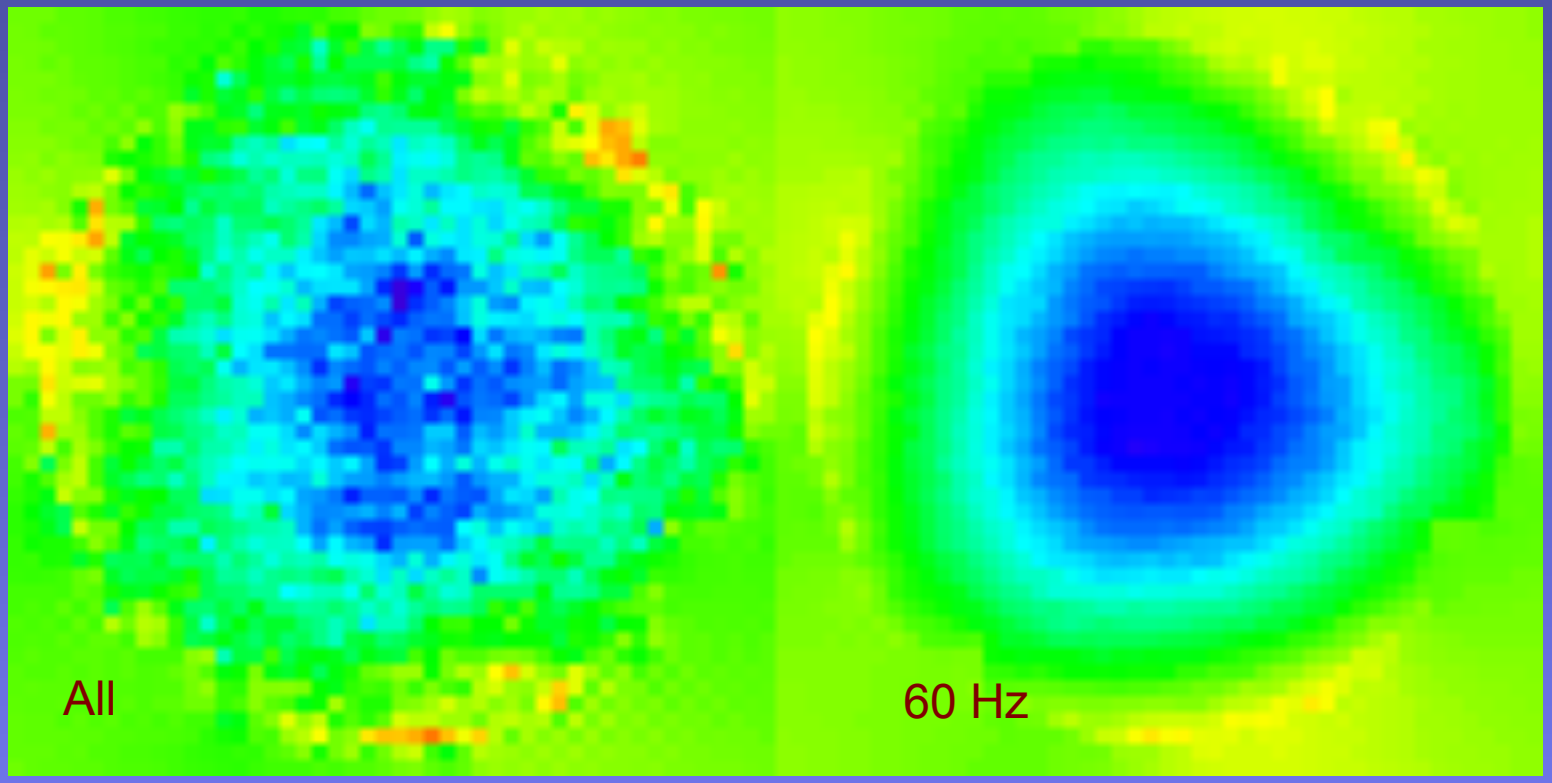




Vibration: tip/tit at 60 Hz cryocooler harmonics

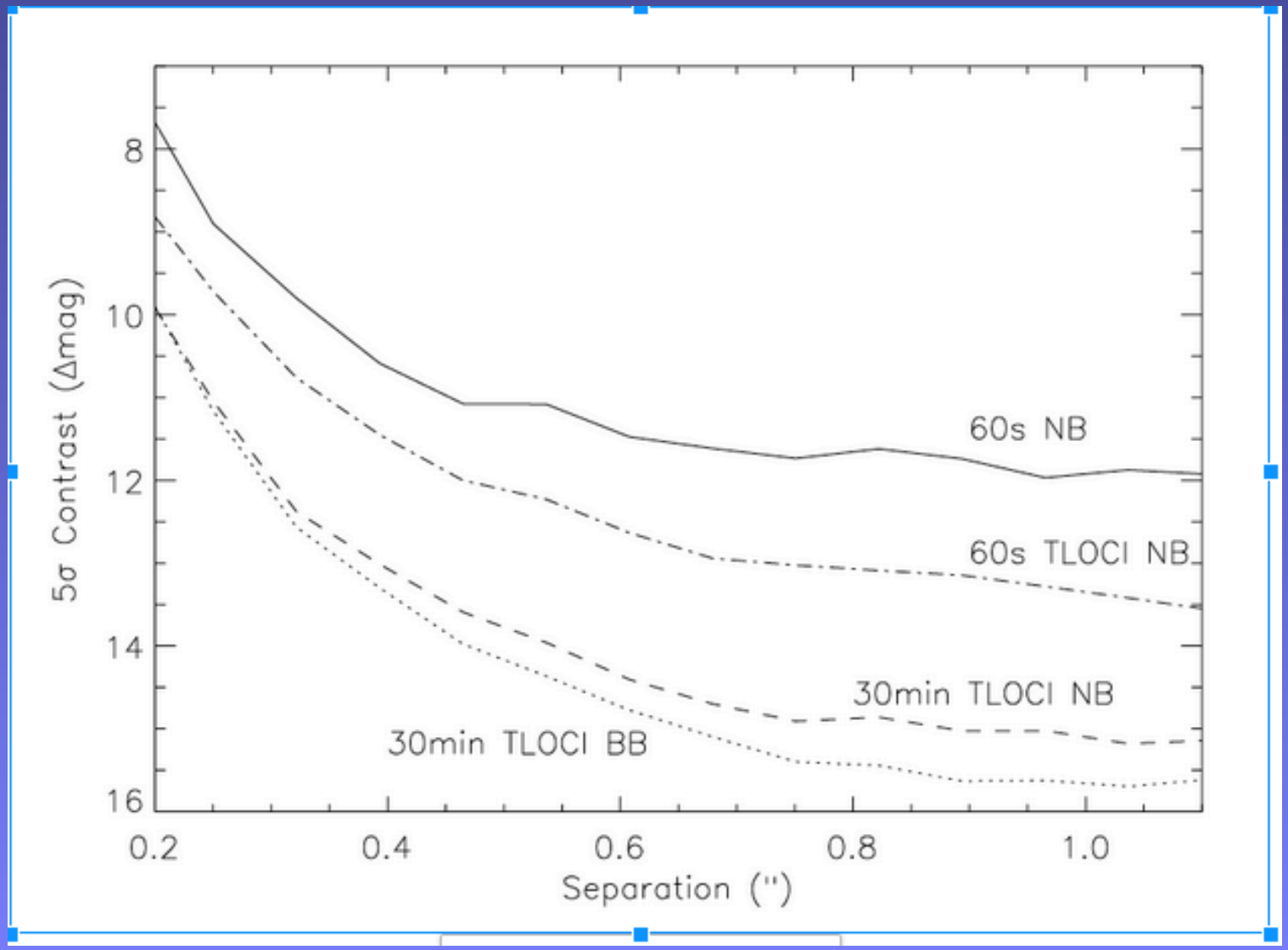


60 Hz vibration from cryocoolers couples into telescope structure

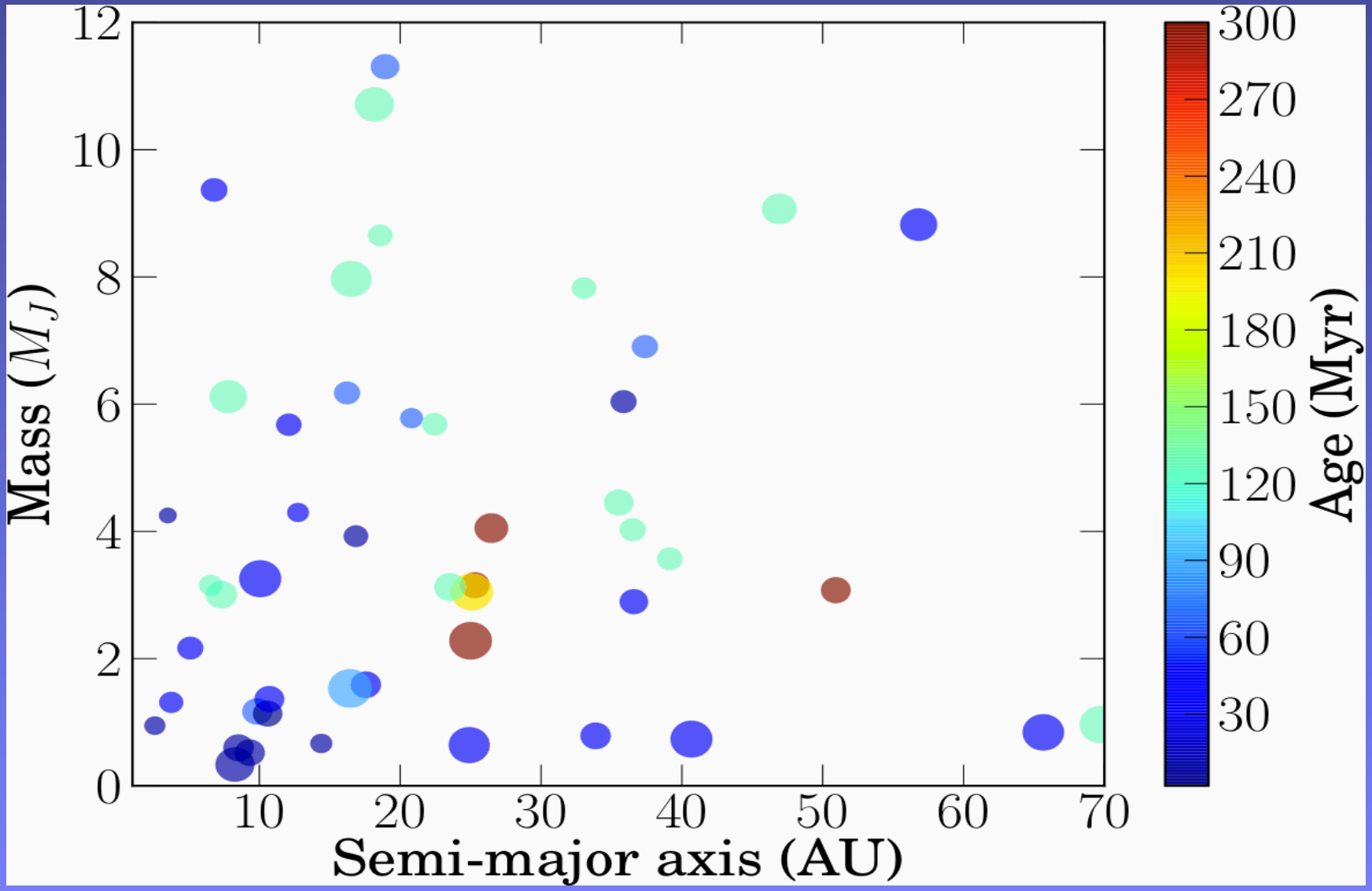


Wavefront reconstructed by AOWFS

Contrast ~10^-6 in 30 min

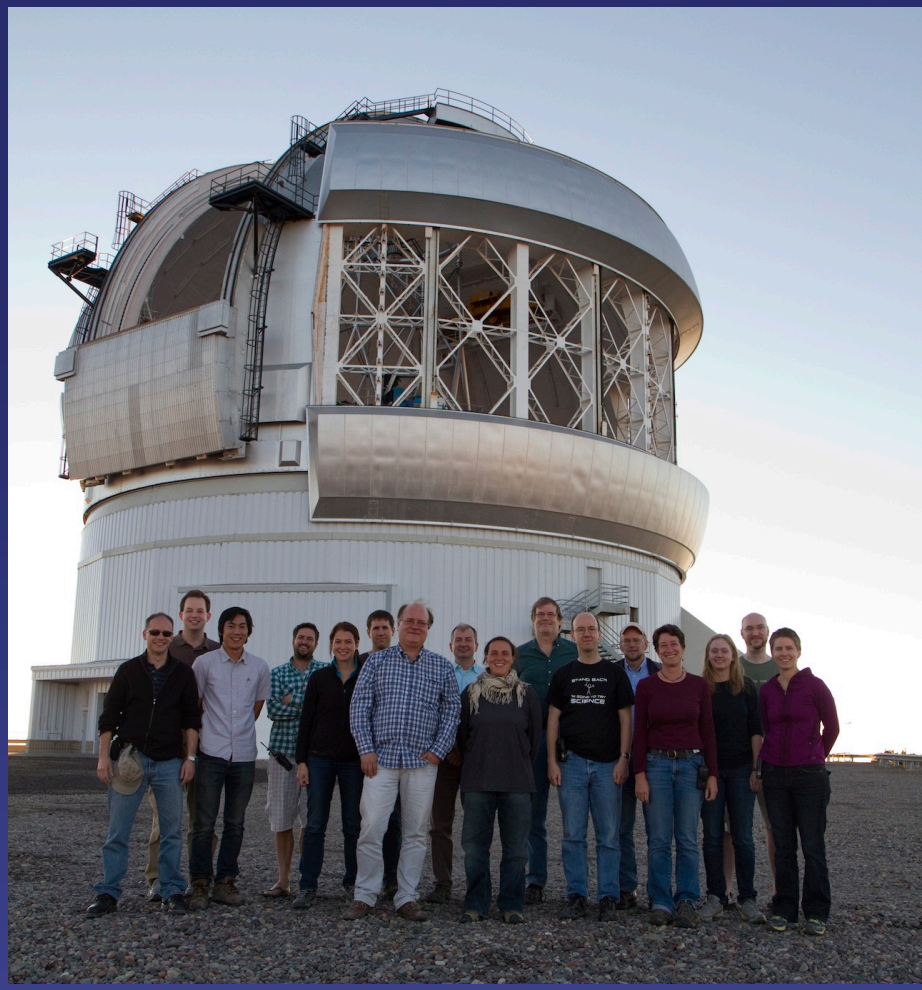


Model planet discoveries from a 600-star GPI campaign (McBride et al 2011)



Future

- **10+ science papers in press / accepted / submitted**
- **Campaign operations began November 2014**
  - 88 stars observed so far
  - 600 stars, 900 hours, 3 years



End of first light run

We would especially like to recognize the unique contributions of Gary Sommargren, Steven Varlese, Christopher Lockwood, Russell Makidon, Murray Fletcher, and Vincent Fesquet, who passed away during the course of this project.