eginning

ext step: The TRIDENT experiment at

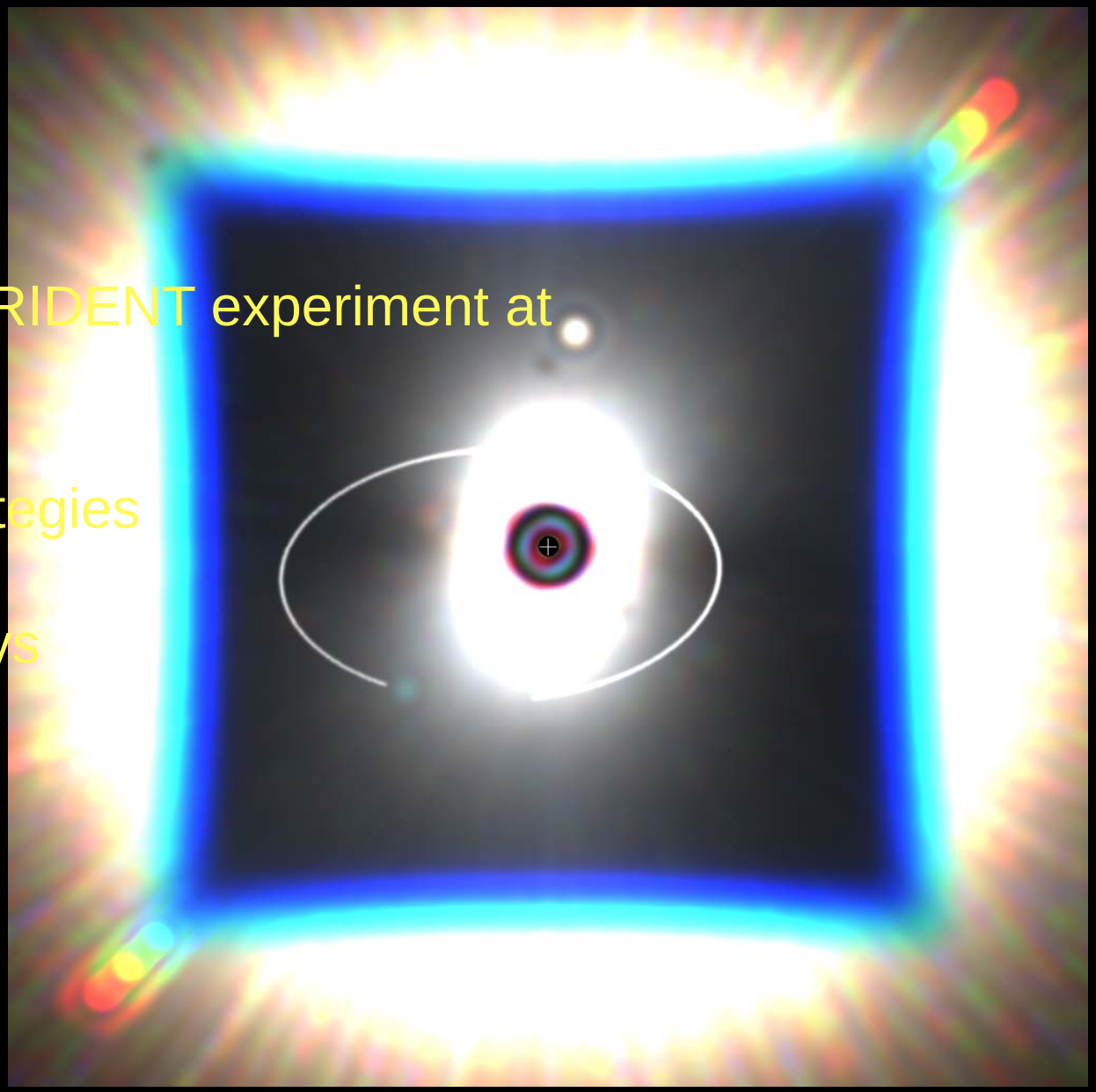
observing strategies

nd-based surveys

e

en instruments

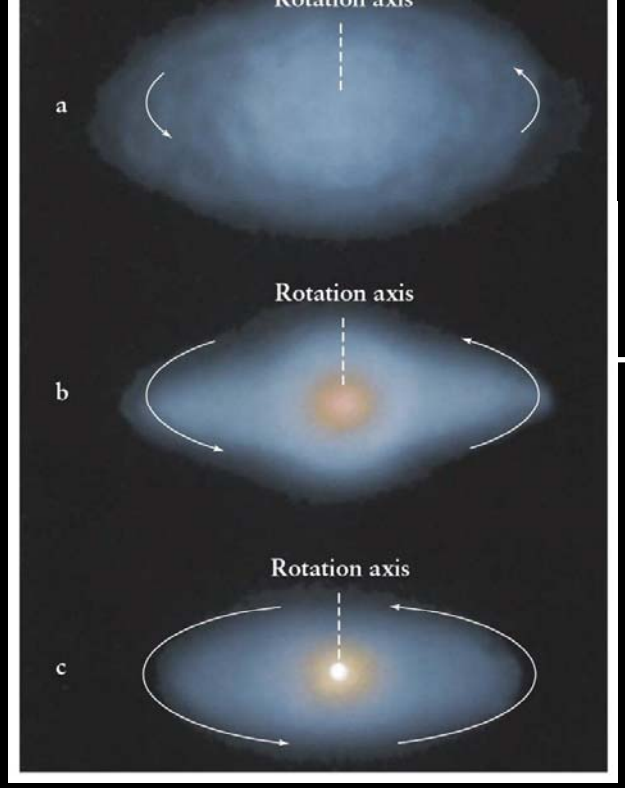
en telescopes

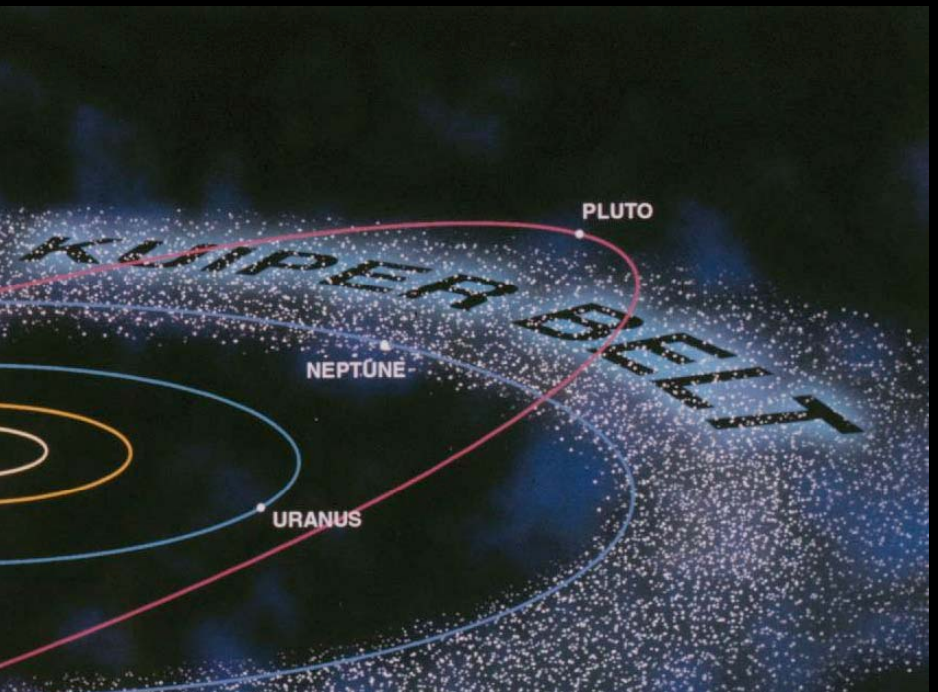


ne 5th, 2008

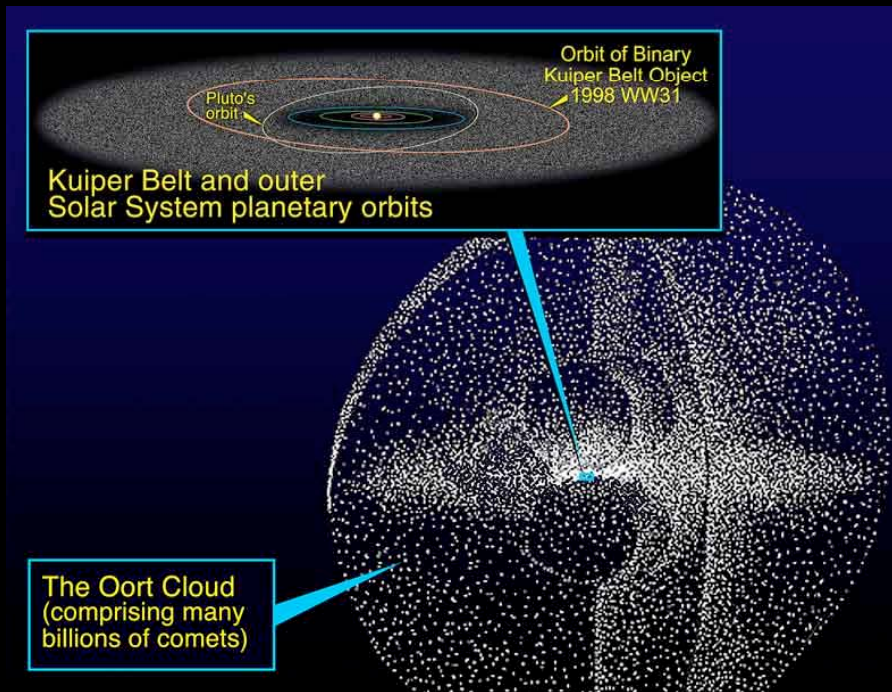
Christian Marois, HIA

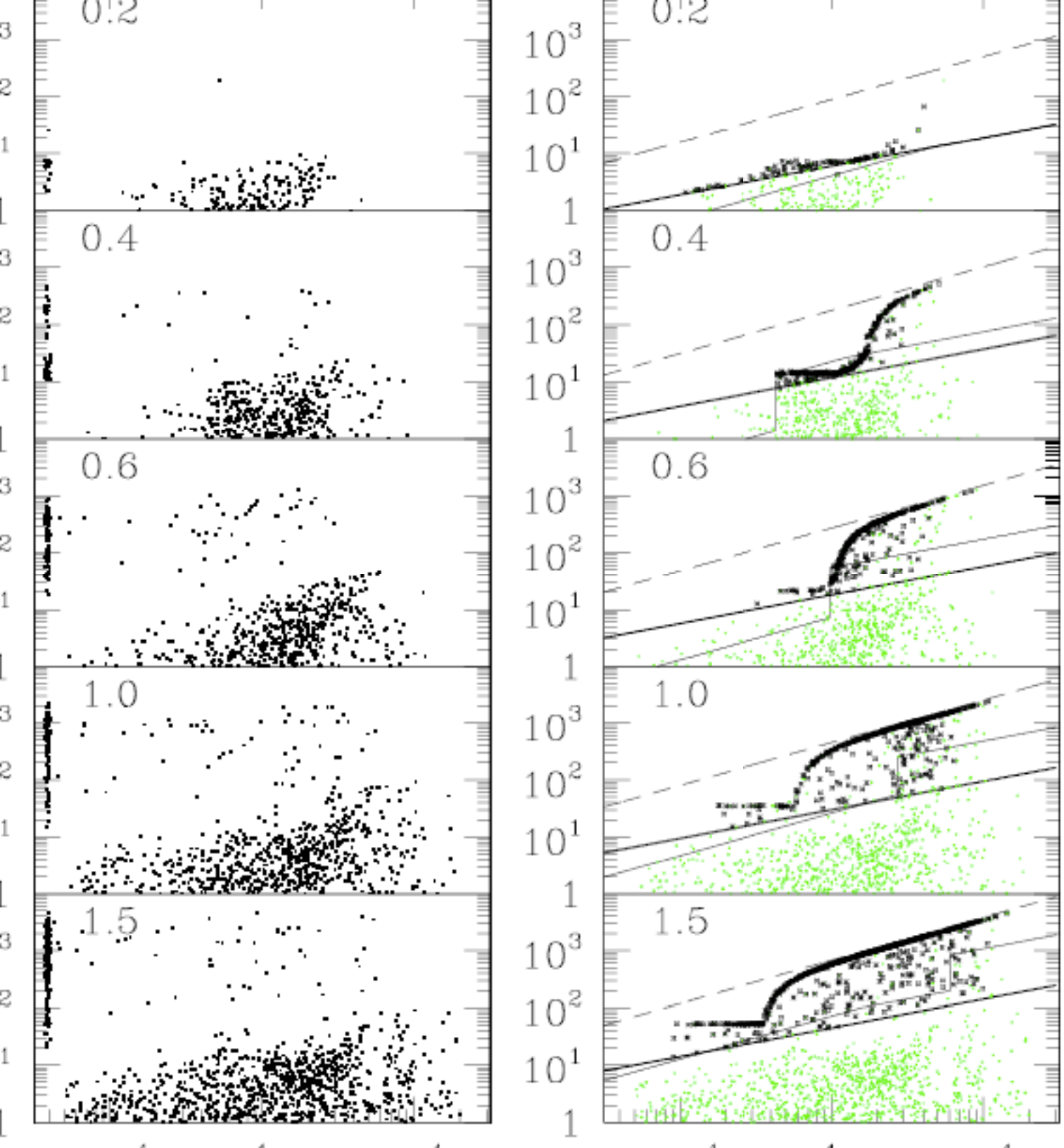
CNRC·NRC
Institut Herzberg d'astrophysique


Rotation axis
a
Rotation axis
b
Rotation axis
c

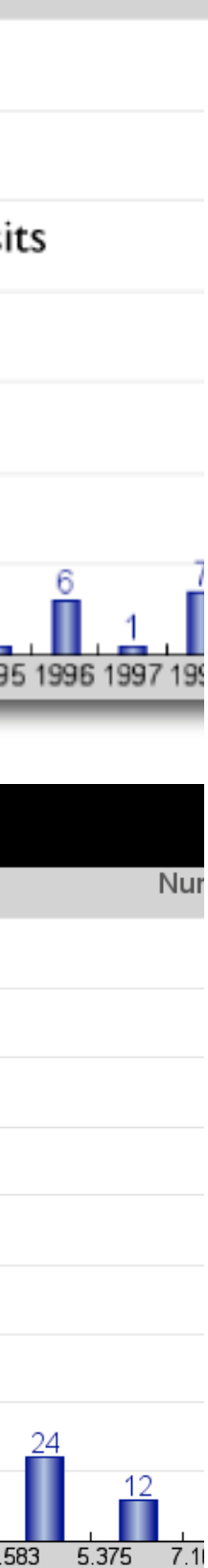

PLUTO
KUIPER BELT
NEPTUNE
URANUS

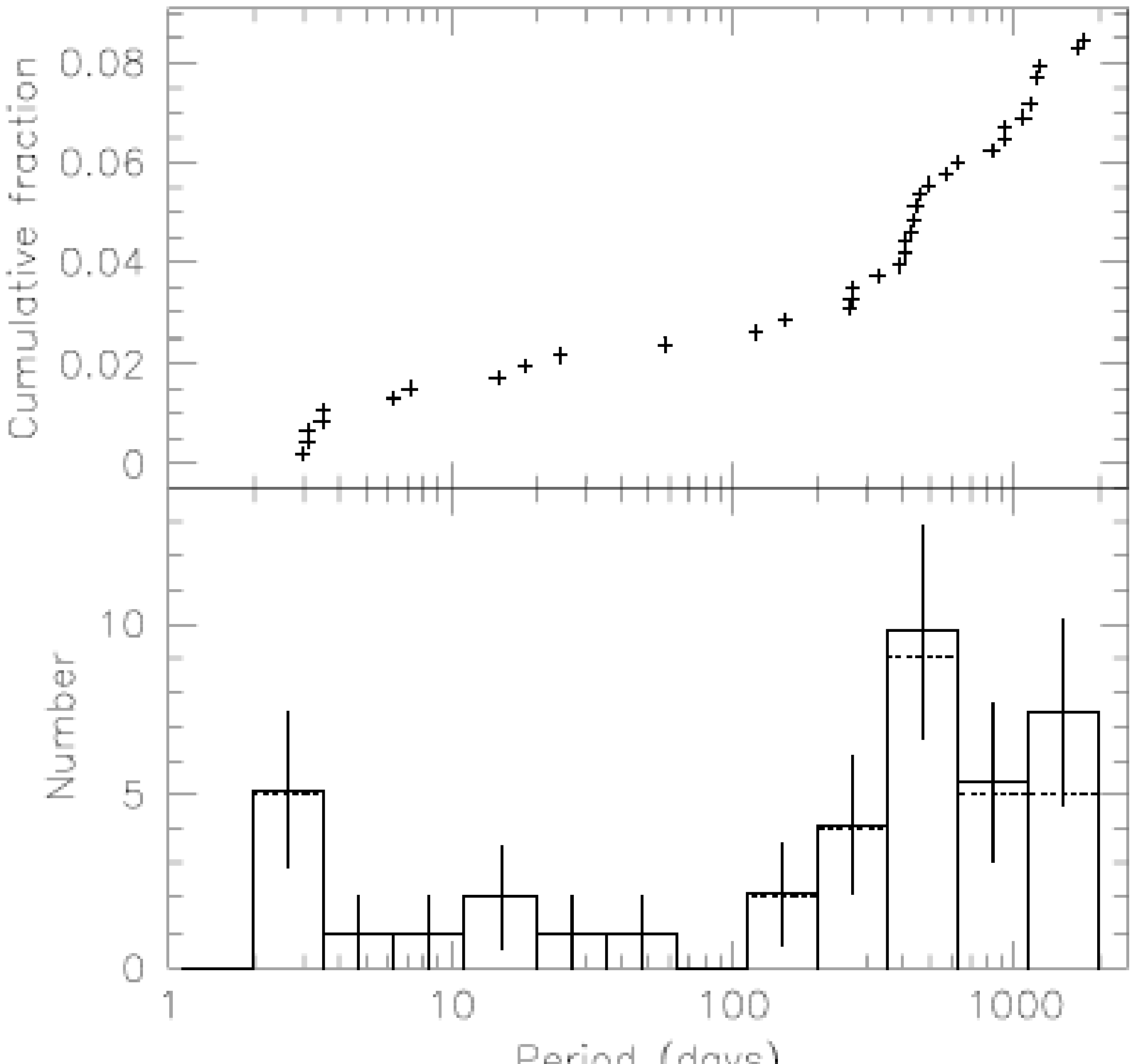
&


Orbit of Binary
Kuiper Belt Object
1998 WW31
Pluto's
orbit
Kuiper Belt and outer
Solar System planetary orbits
The Oort Cloud
(comprising many
billions of comets)



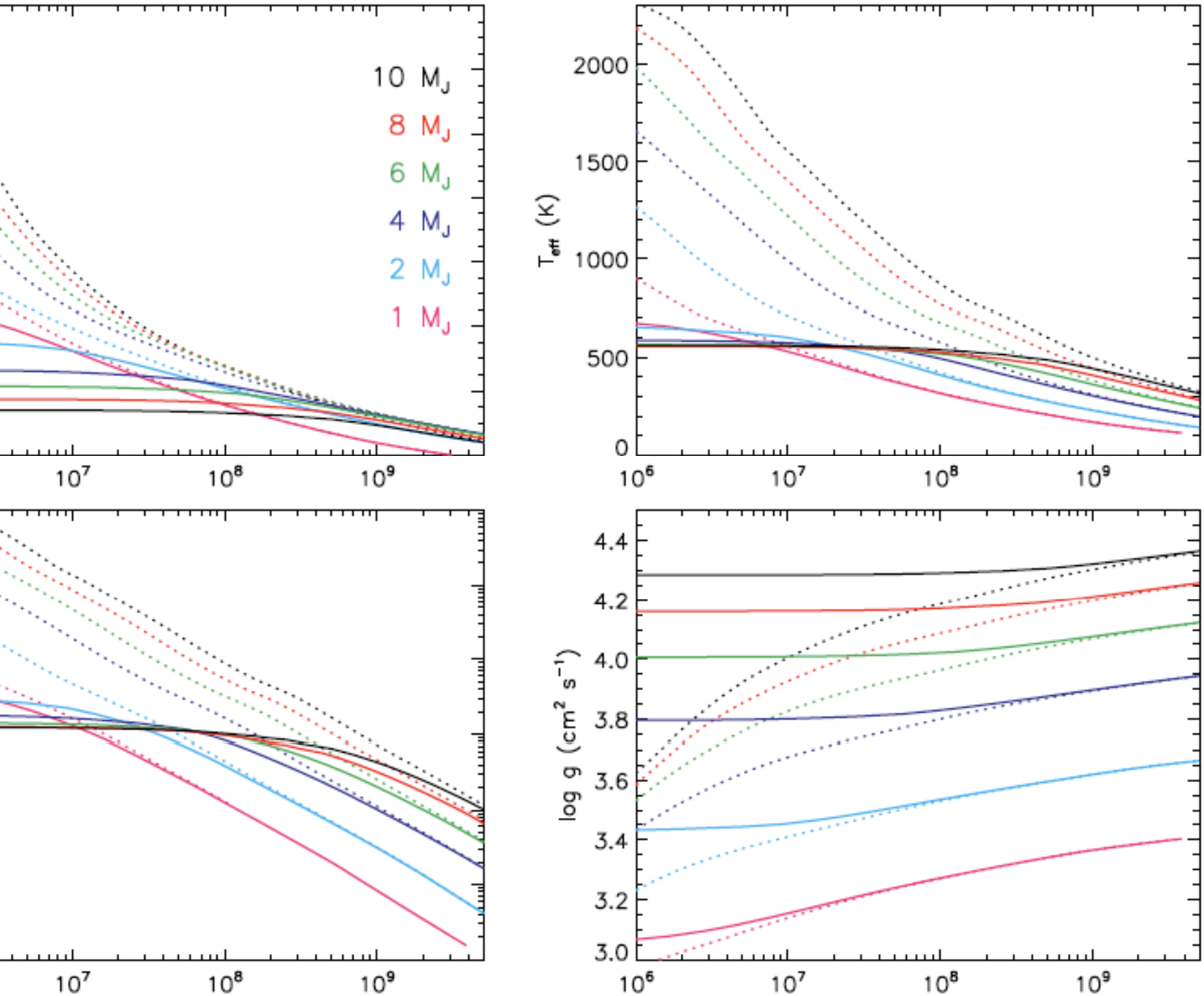
Ida & Lin formation model.


62
its
6
1
7
95 1996 1997 199
Nur
24
12
.583 5.375 7.1


Cumulative fraction
0.08
0.06
0.04
0.02
0
Number
10
5
0
1
10
100
1000
Period (days)

1.00
[AU]

rs wi
20 A

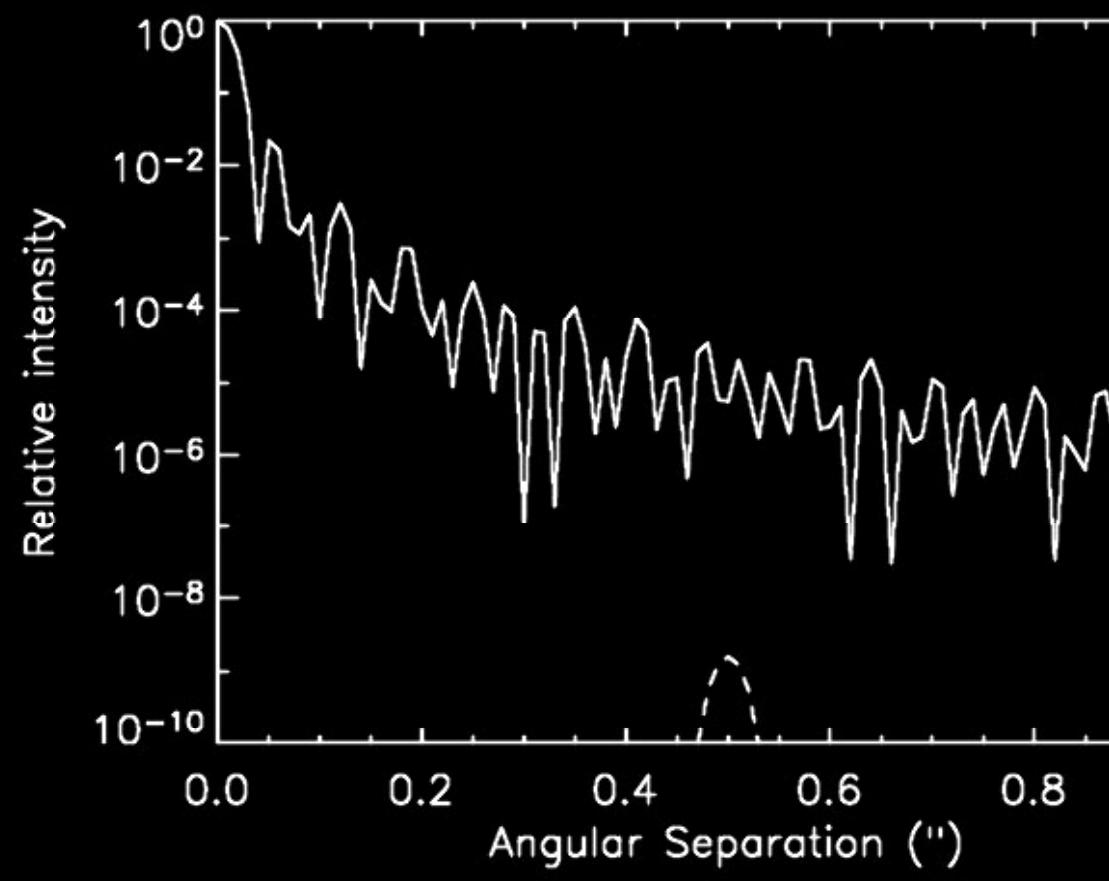


- Stars are bright
are faint
- Planets orbit clo
star
- Planets cool do

Type star, 50 Myr

	H-Band Contrast
MJup	5.9
MJup	7.2
MJup	8.4
MJup	12.4
MJup	17.4

raffe et al. 2003



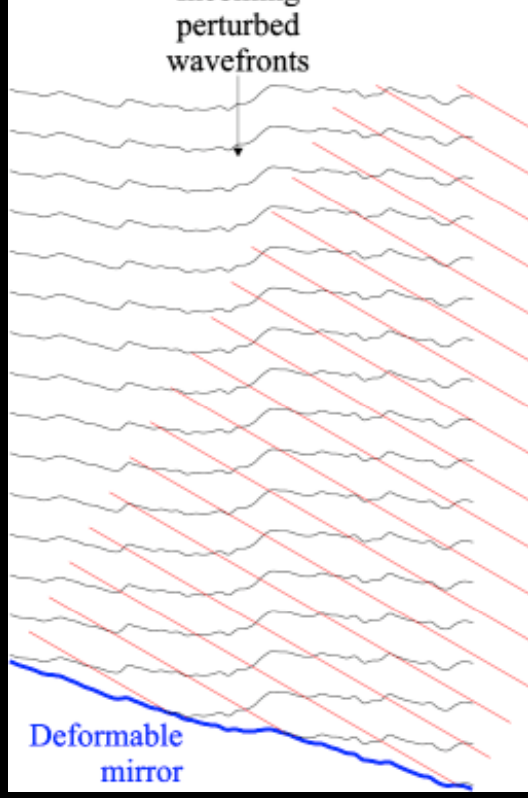
Not as good as in space, but...

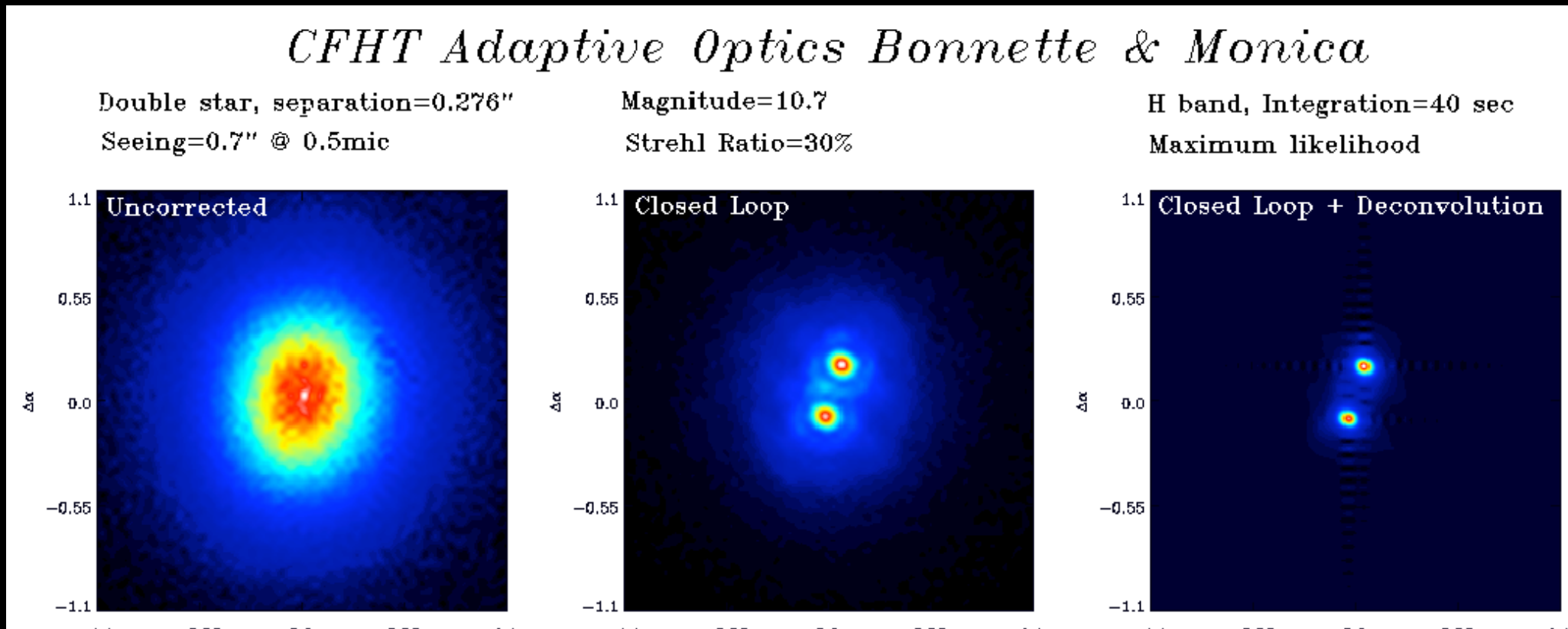
eaper, faster, flexibility, complimentary scien

testbed for new technologies, ...

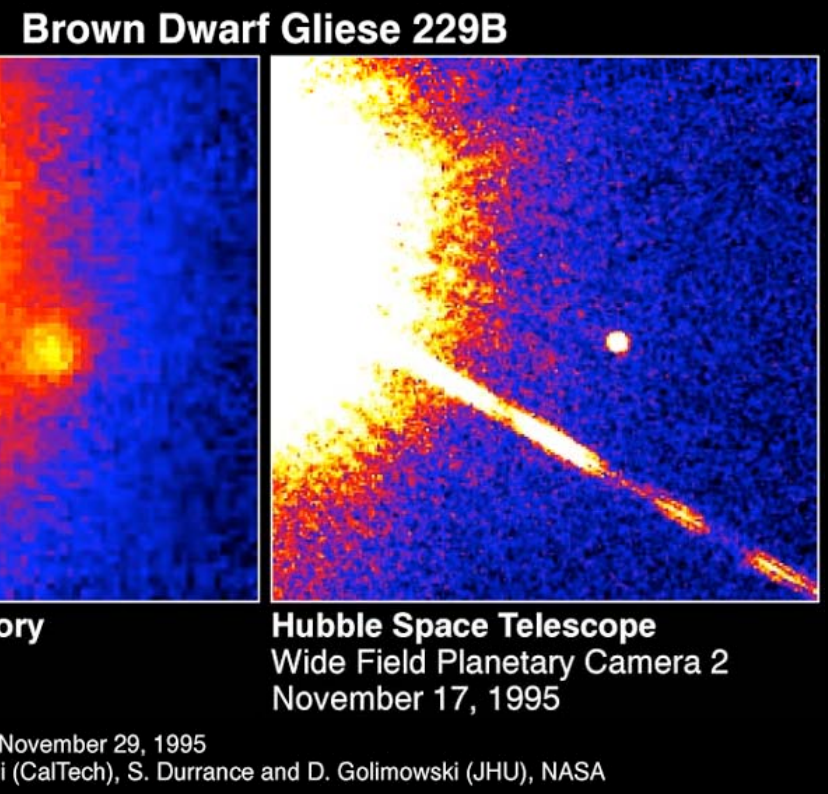
Adaptive Optics

e W. Babcock in 1953
y development for a few
..
oped in 1990s on AGBTs

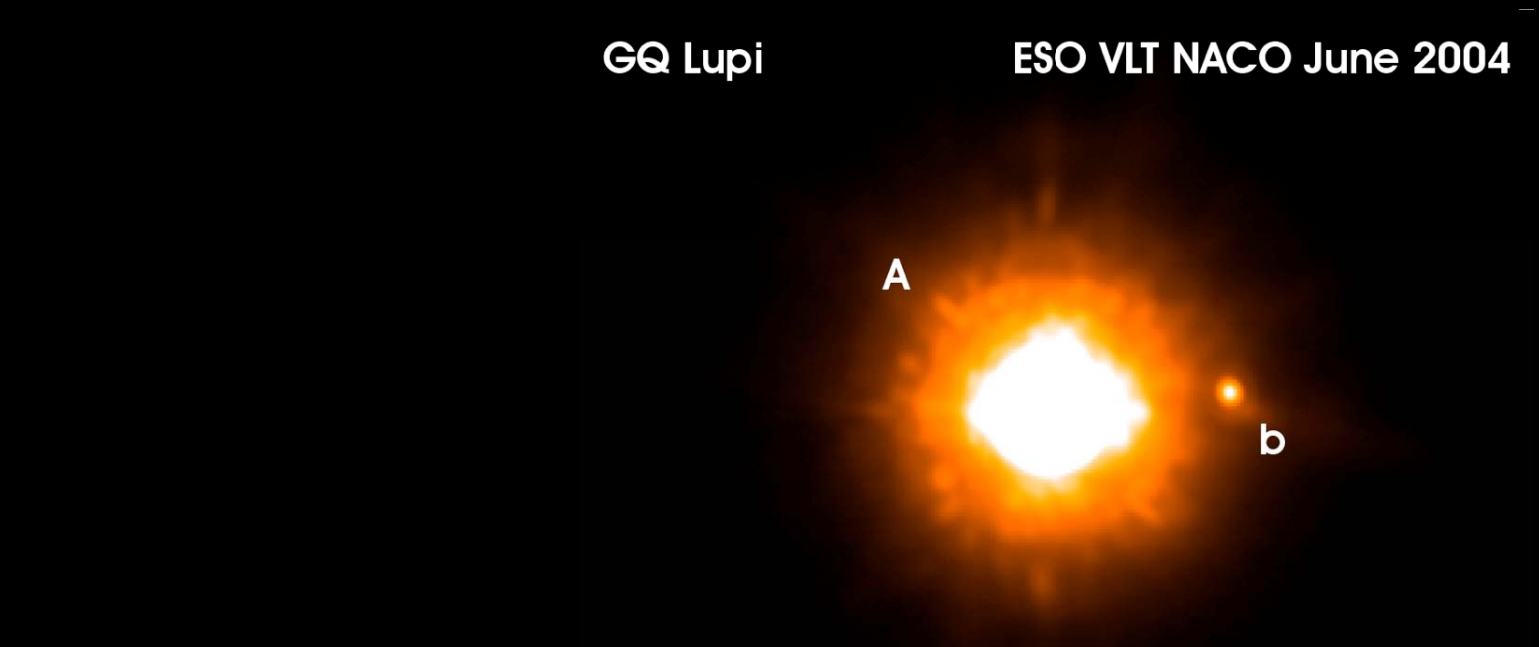




Direct imaging limited success



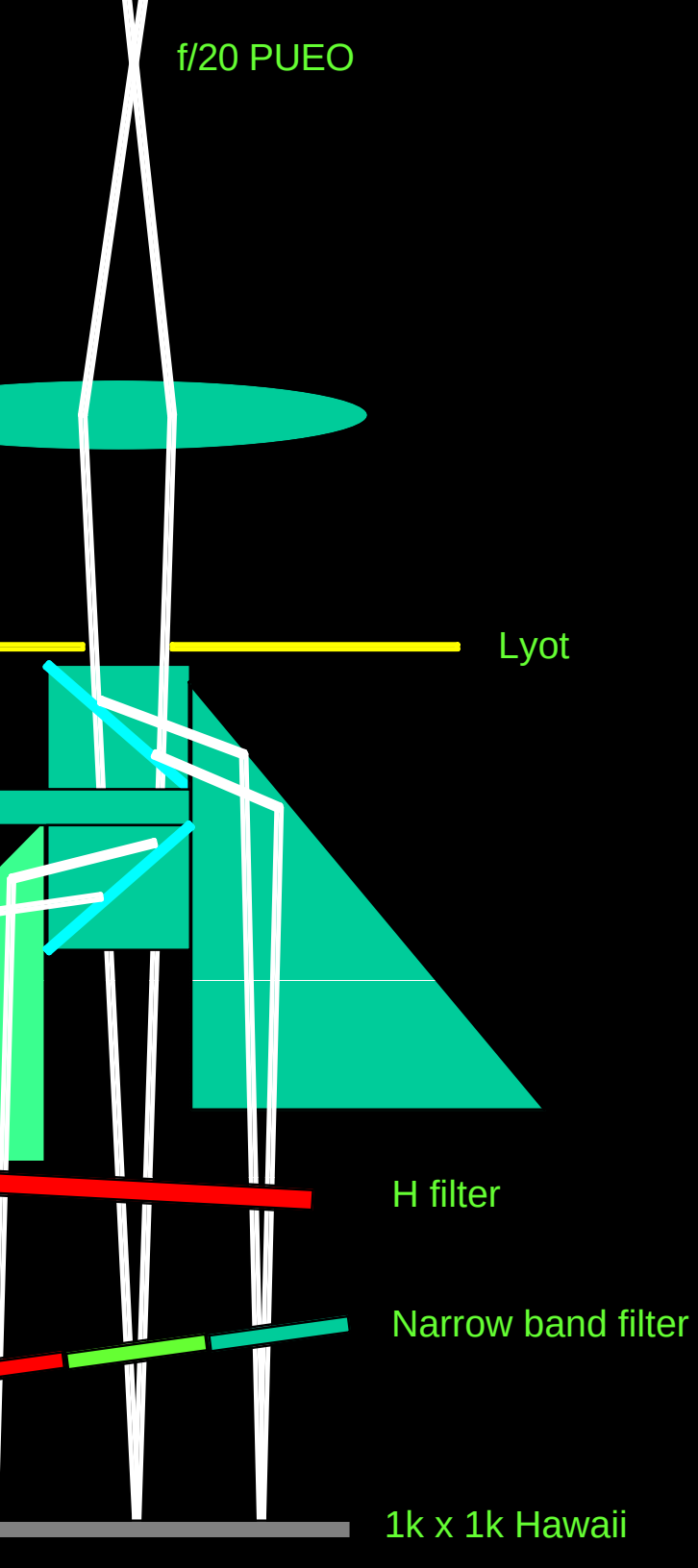
Chauvin et al.

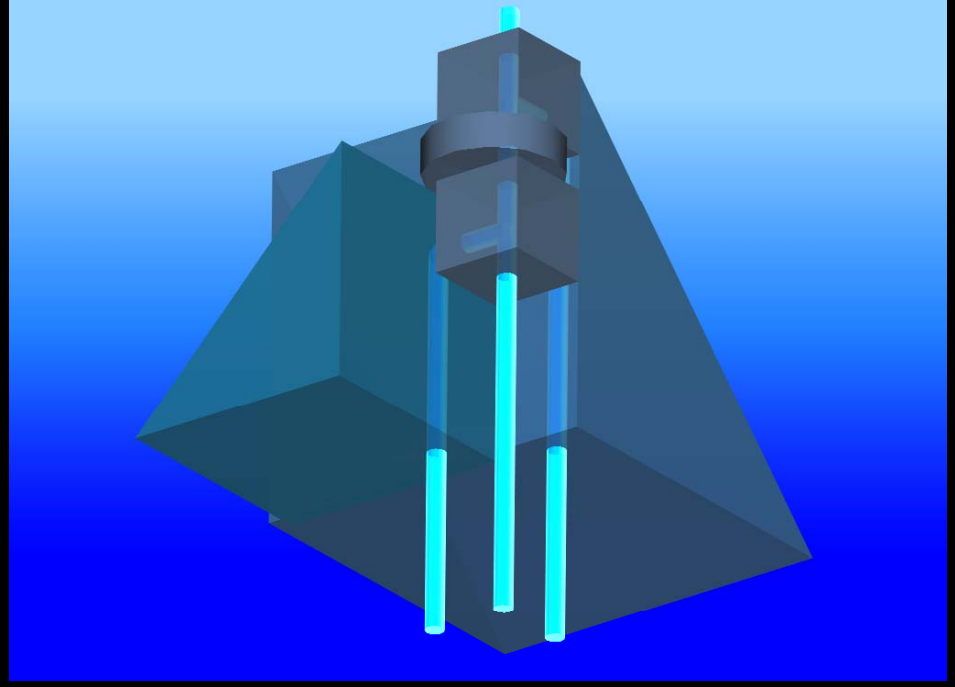


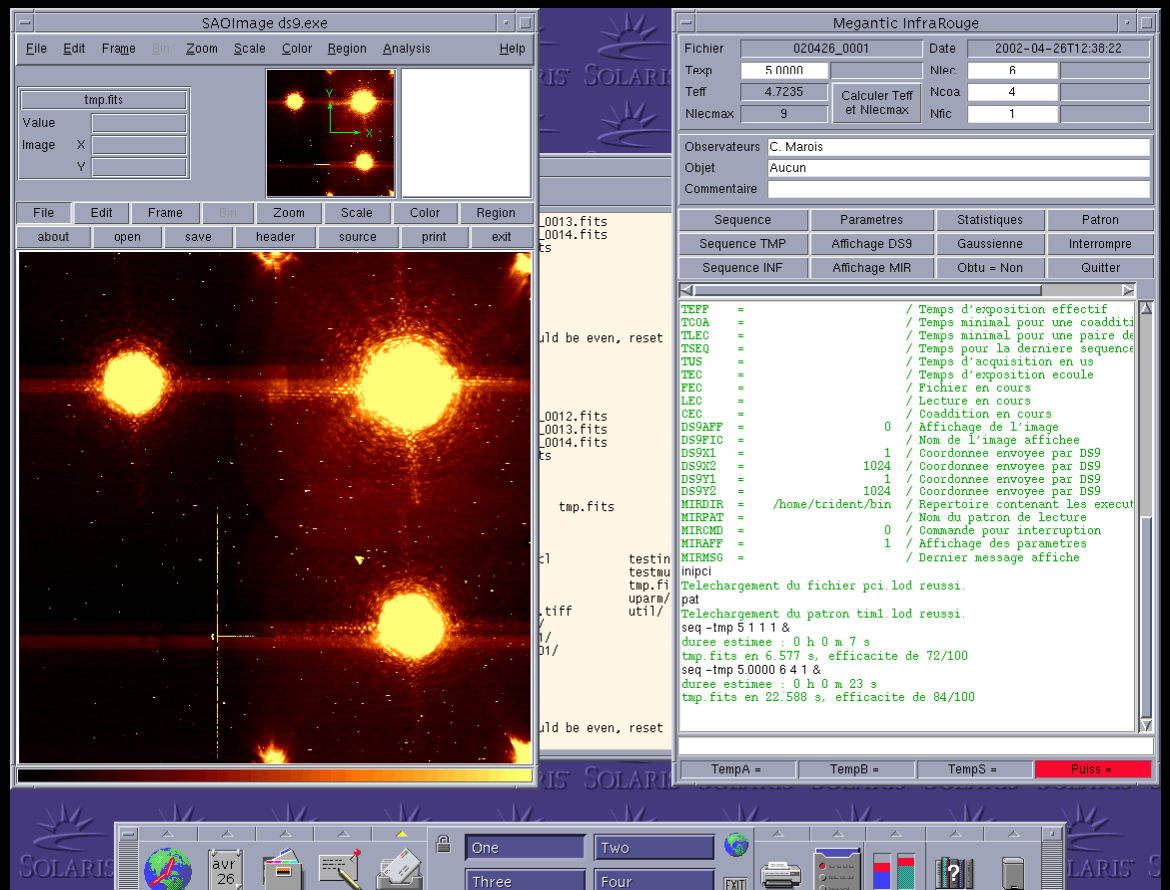
hat is TRIDENT?

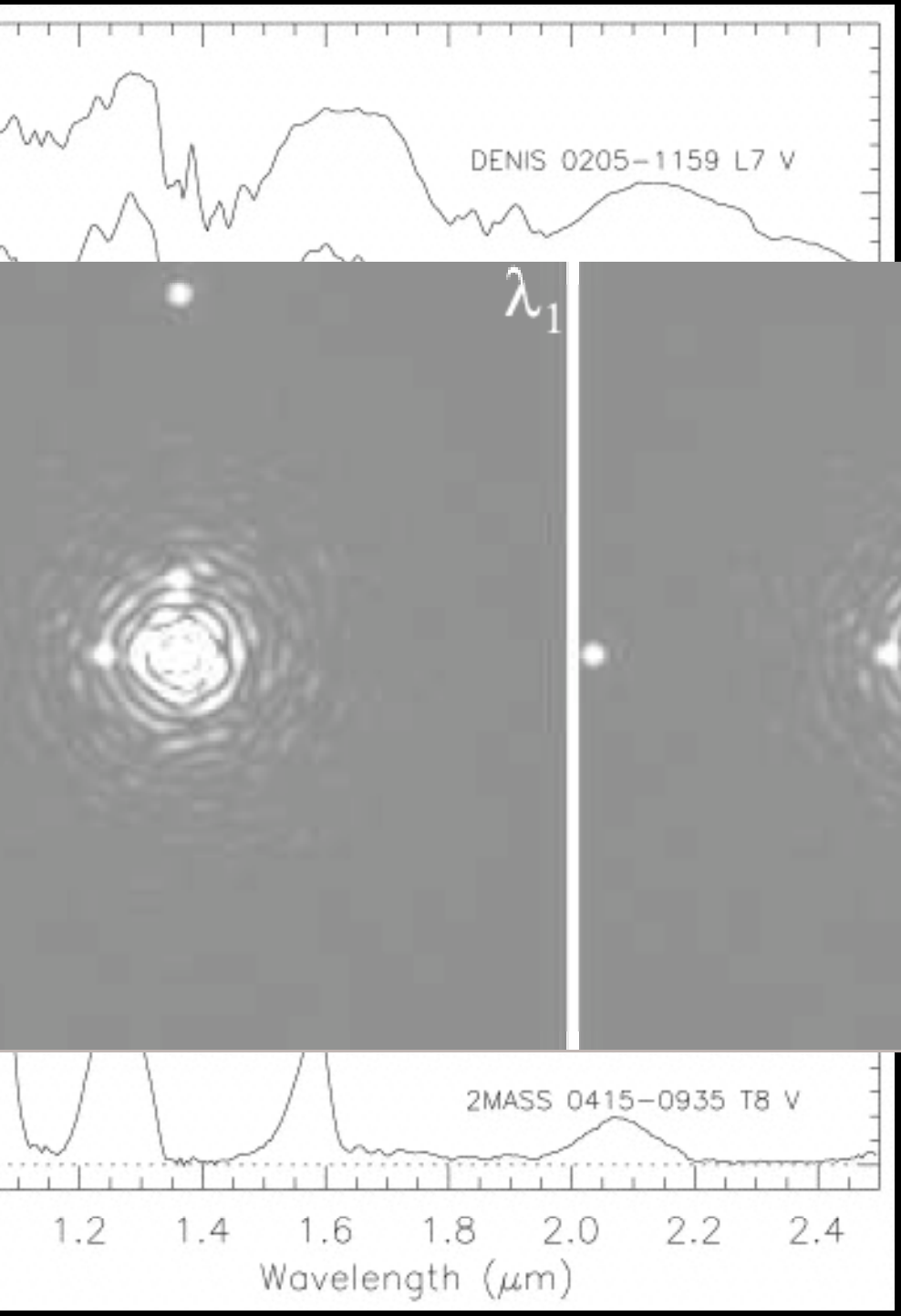
A weapon?

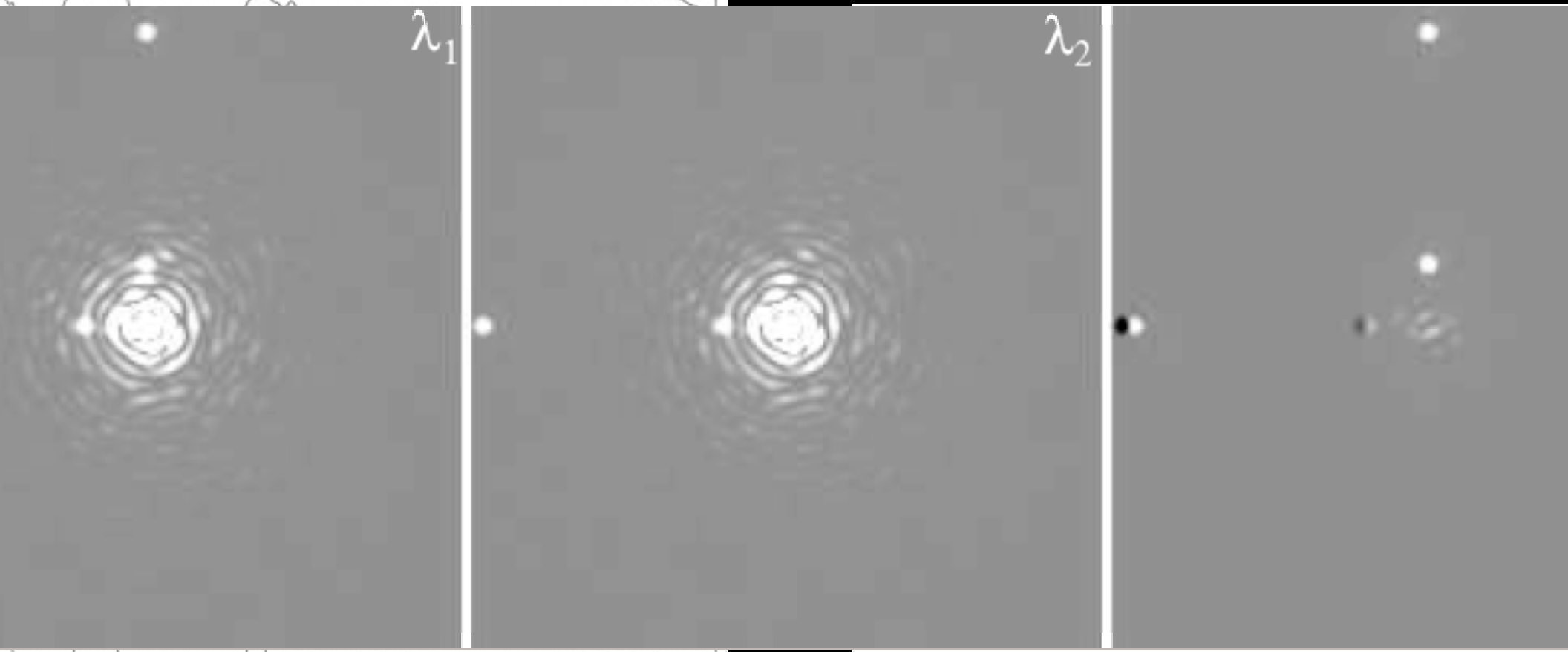
A nuclear missile

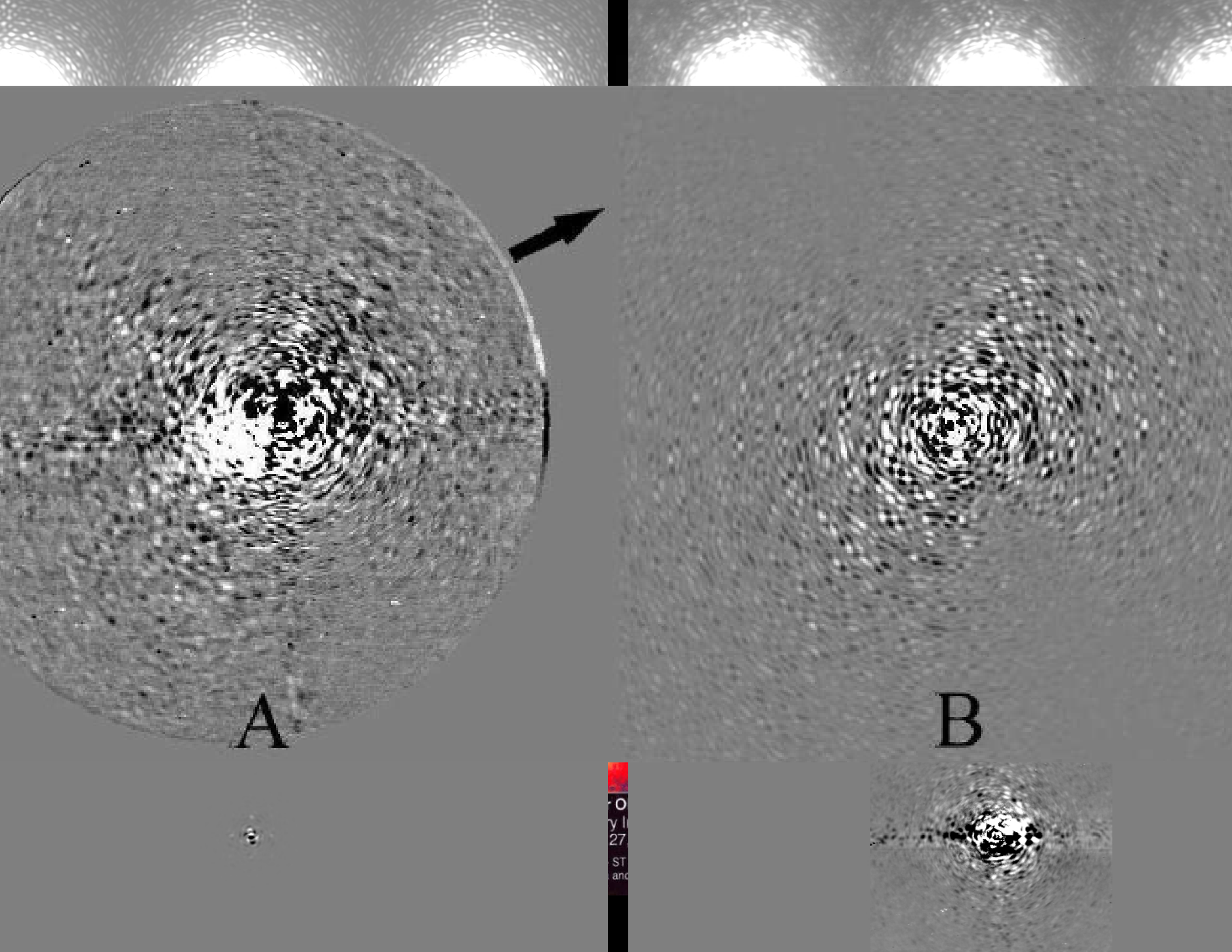

f/20 PUEO
Lyot
H filter
Narrow band filter
1k x 1k Hawaii




SAOImage ds9.exe
File Edit Frame Bin Zoom Scale Color Region Analysis Help
tmp.fits
Value
Image X
Y
File Edit Frame Bin Zoom Scale Color Region
about open save header source print exit
Megantic InfraRouge
Fichier 020426_0001
Date 2002-04-26T12:38:22
Texp 5.0000
Nlec 6
Teff 4.7235
Calculer Teff et Nlecmax
Ncoa 4
Nlecmax 9
Nfic 1
Observateurs C. Marois
Objet Aucun
Commentaire
Sequence
Parametres
Statistiques
Patron
Sequence TMP
Affichage DS9
Gaussienne
Interrompre
Sequence INF
Affichage MIR
Obtu = Non
Quitter
TEFF = / Temps d'exposition effectif
TCOA = / Temps minimal pour une coadditi
TLEC = / Temps minimal pour une paire de
TSEQ = / Temps pour la derniere sequence
TUS = / Temps d'acquisition en us
TEC = / Temps d'exposition ecoule
FEC = / Fichier en cours
LEC = / Lecture en cours
CEC = / Coaddition en cours
DS9AFF = 0 / Affichage de l'image
DS9FIC = / Nom de l'image affichee
DS9X1 = 1 / Coordonnee envoyee par DS9
DS9X2 = 1024 / Coordonnee envoyee par DS9
DS9Y1 = 1 / Coordonnee envoyee par DS9
DS9Y2 = 1024 / Coordonnee envoyee par DS9
MIRDIR = /home/trident/bin / Repertoire contenant les execut
MIRPAT = / Nom du patron de lecture
MIRCMD = 0 / Commande pour interruption
MIRAFF = 1 / Affichage des parametres
MIRMSG = / Dernier message affiche
inipci
Telechargement du fichier pci.lod reussi.
pat
Telechargement du patron tim1.lod reussi.
seq -tmp 5 1 1 1 &
duree estimee : 0 h 0 m 7 s
tmp.fits en 6.577 s, efficacite de 72/100
seq -tmp 5.0000 6 4 1 &
duree estimee : 0 h 0 m 23 s
tmp.fits en 22.588 s, efficacite de 84/100
TempA = TempB = TempS = Puiss =
SOLARIS
One Two Three Four


DENIS 0205−1159 L7 V
2MASS 0415−0935 T8 V
1.2
1.4
1.6
1.8
2.0
2.2
2.4
Wavelength (μm)


λ1
λ2


A
B

Main result for the TRIDENT experiment

atic aberrations are a major limitations on g
d AO to search for exoplanets.

SDI difficult to implement to achieve predict
rmances.

convolution (roll subtraction)

On ground-based alt/az telescopes

Combining images acquired
same wavelength but with
different field angles to subt
quasi-static speckles.

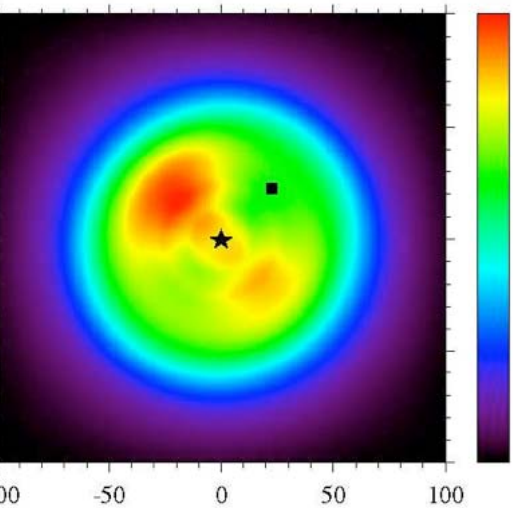
HST: Roll subtraction (0th order ADI).

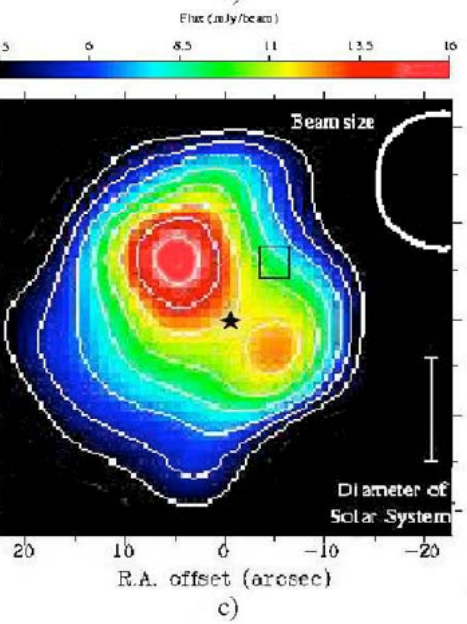
Gemini: Full ADI (many angles, Cass

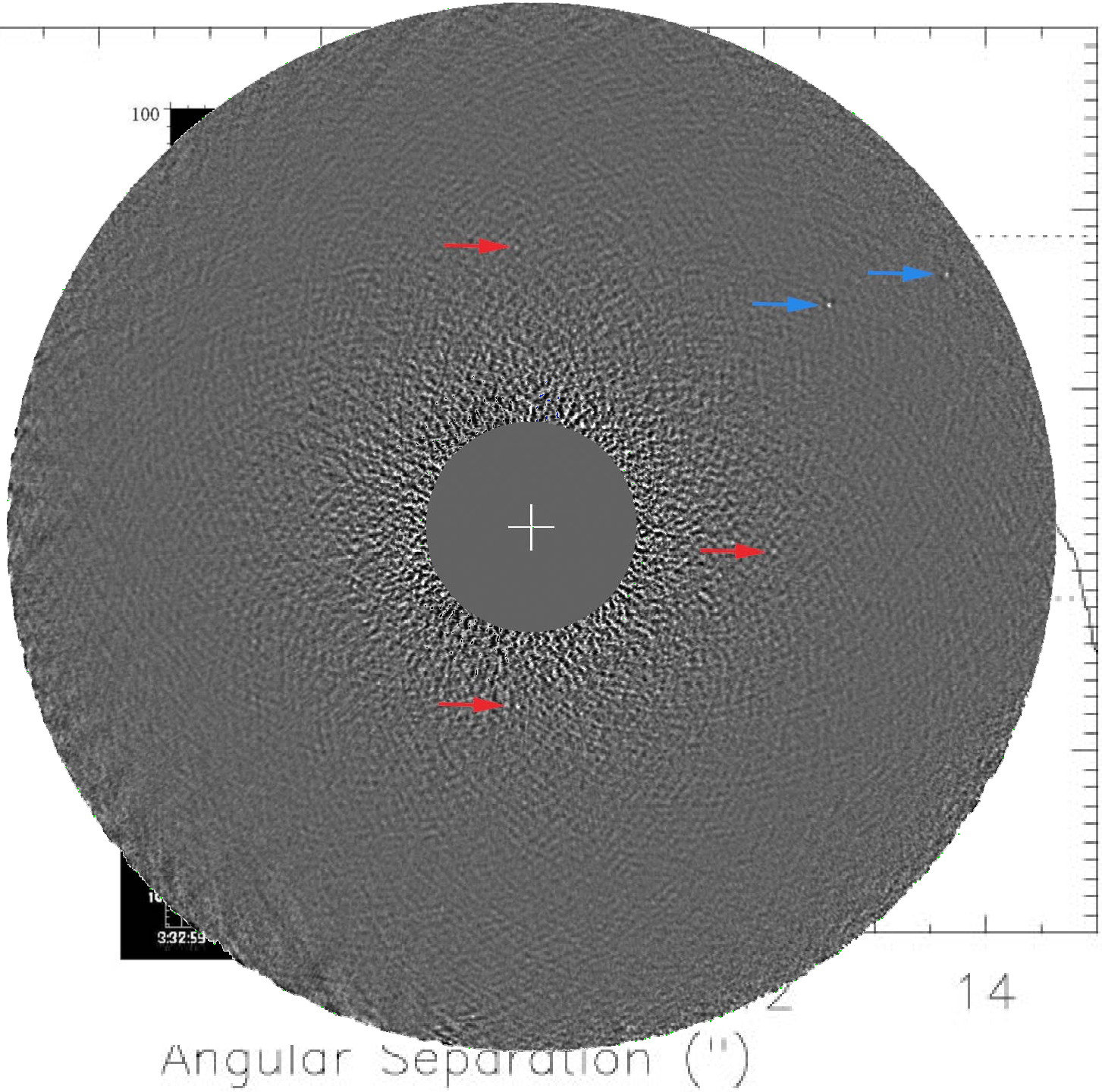
Lyot: Multi-rotation-plane ADI (Nasm
focus).

SDI: partial ADI (Nasmyth focus), sing
subtraction (force instrument rotation leav
interference quasi-static speckle terms), bu
res quasi-static speckle smoothing due to
focus location.

In theory “perfect”, but in practice limited
by quasi-static speckle time evolution


-50
0
50
100
a)


Flux (mJy/beam)
Beam size
Diameter of Solar System
20
10
0
−10
−20
R.A. offset (arcsec)
c)

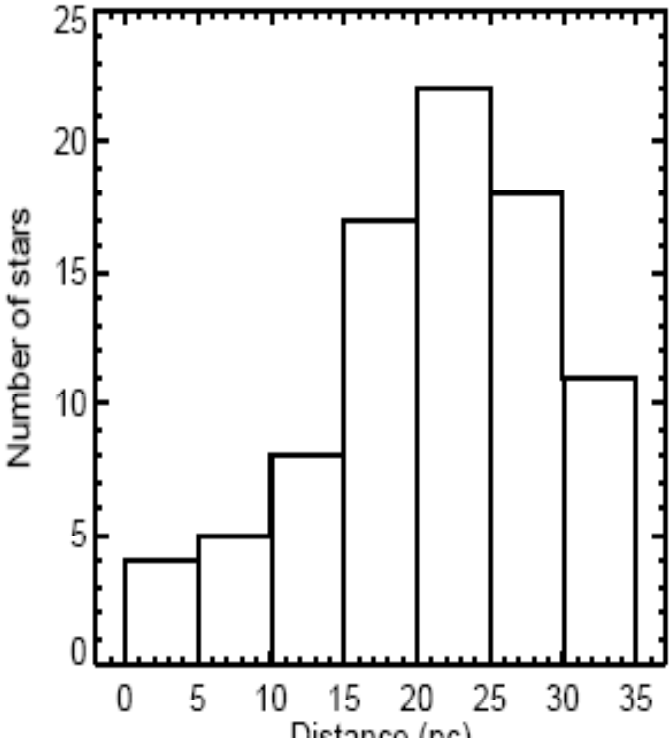

23
100
14
Angular Separation (")

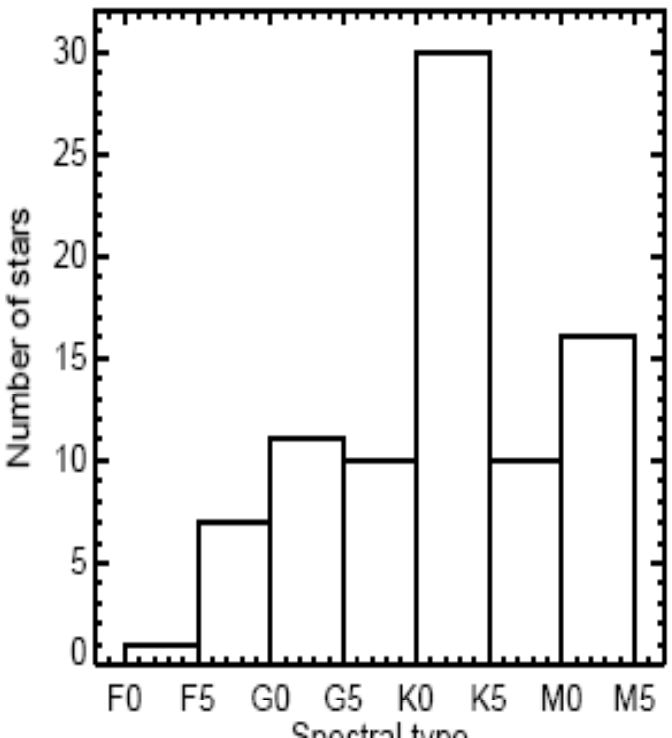
The Gemini Deep Planet Survey (GDPS)

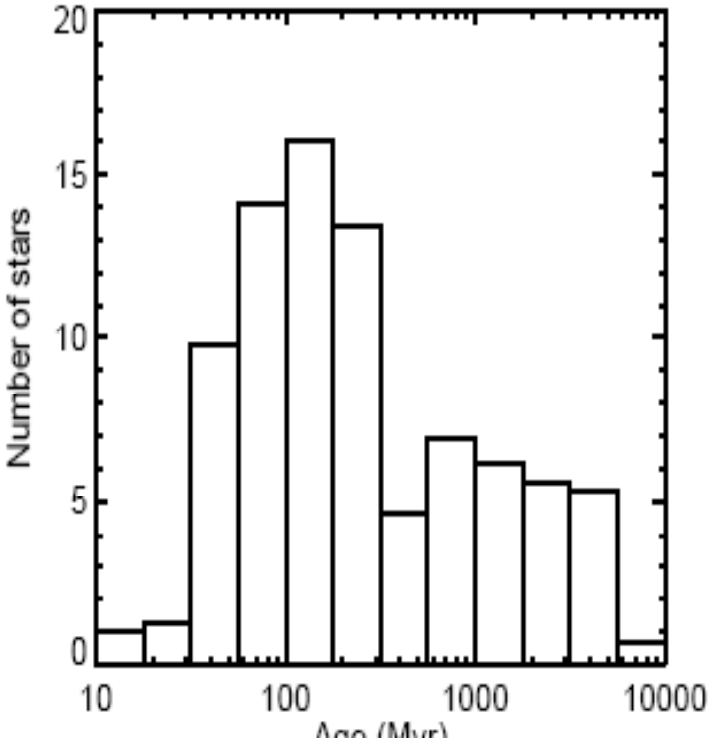
Characterize “massive” exoplanet population >10 A

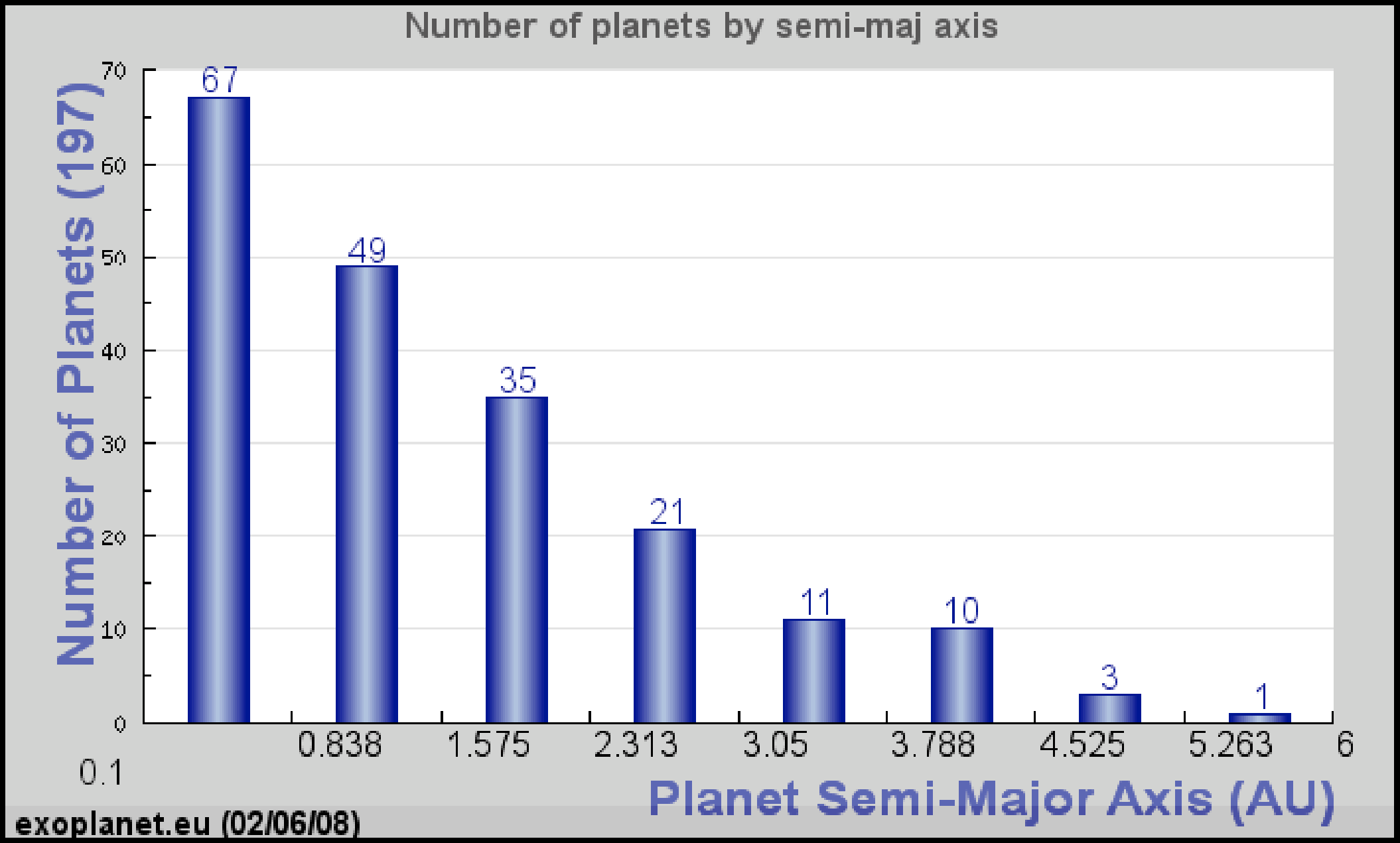
ope: Gemini North (Altair/NIRI)

sample: ~80 young (~100Myr) & close (~20pc) Su





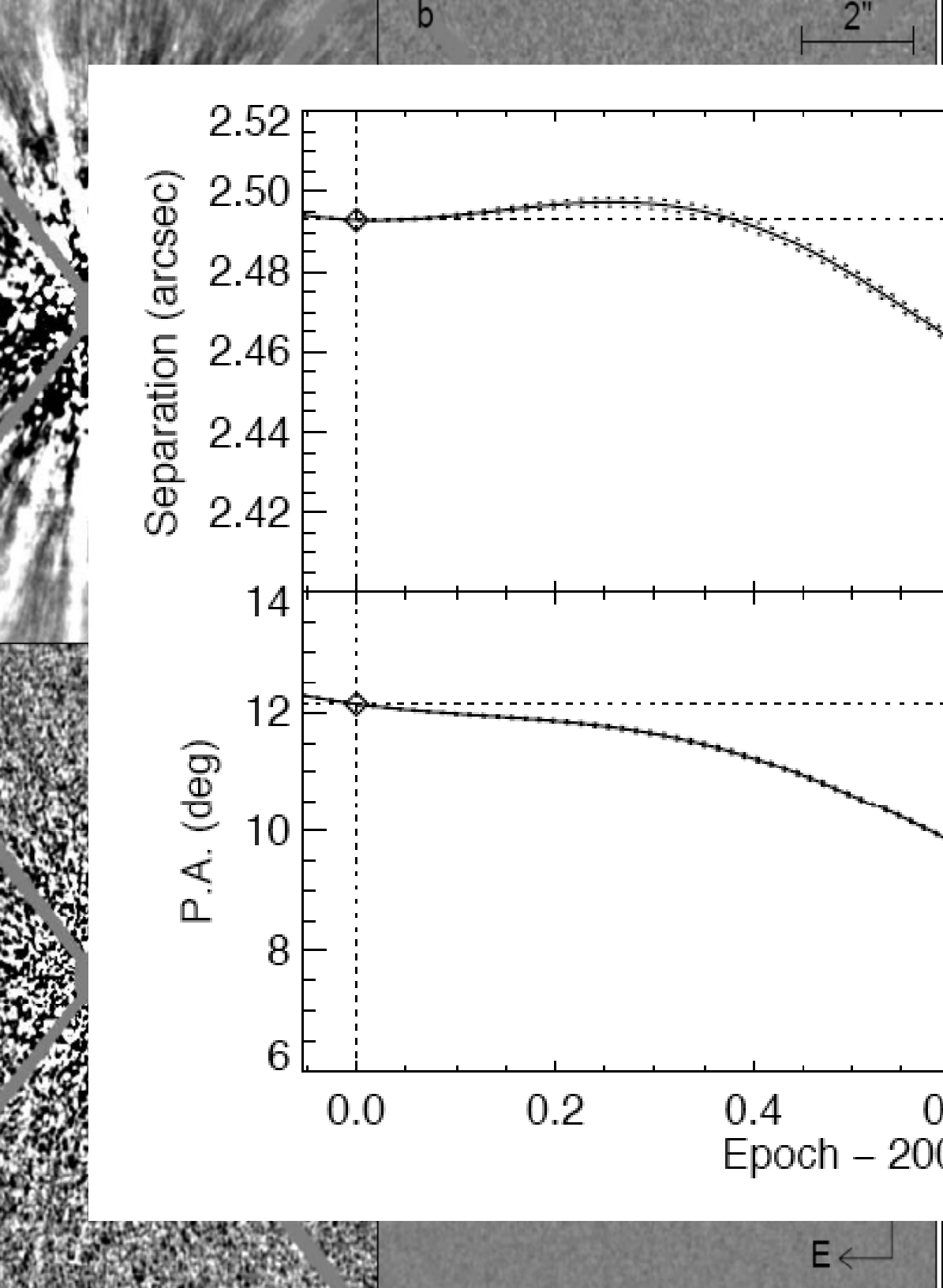




Population of planets >5 AU?

Planet formation outer scale?

Speckle attenuatio



. 2

all

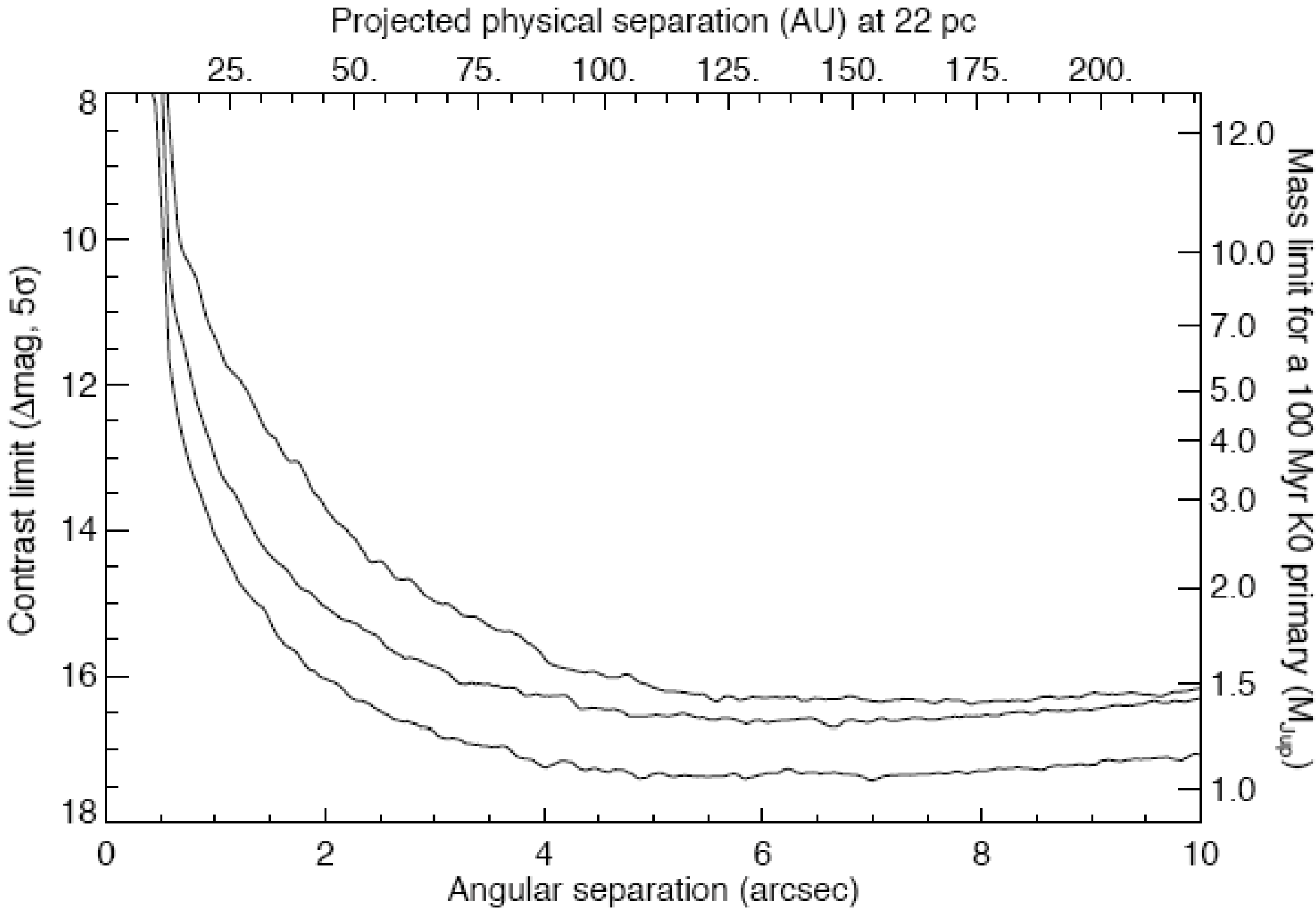
eac

ion

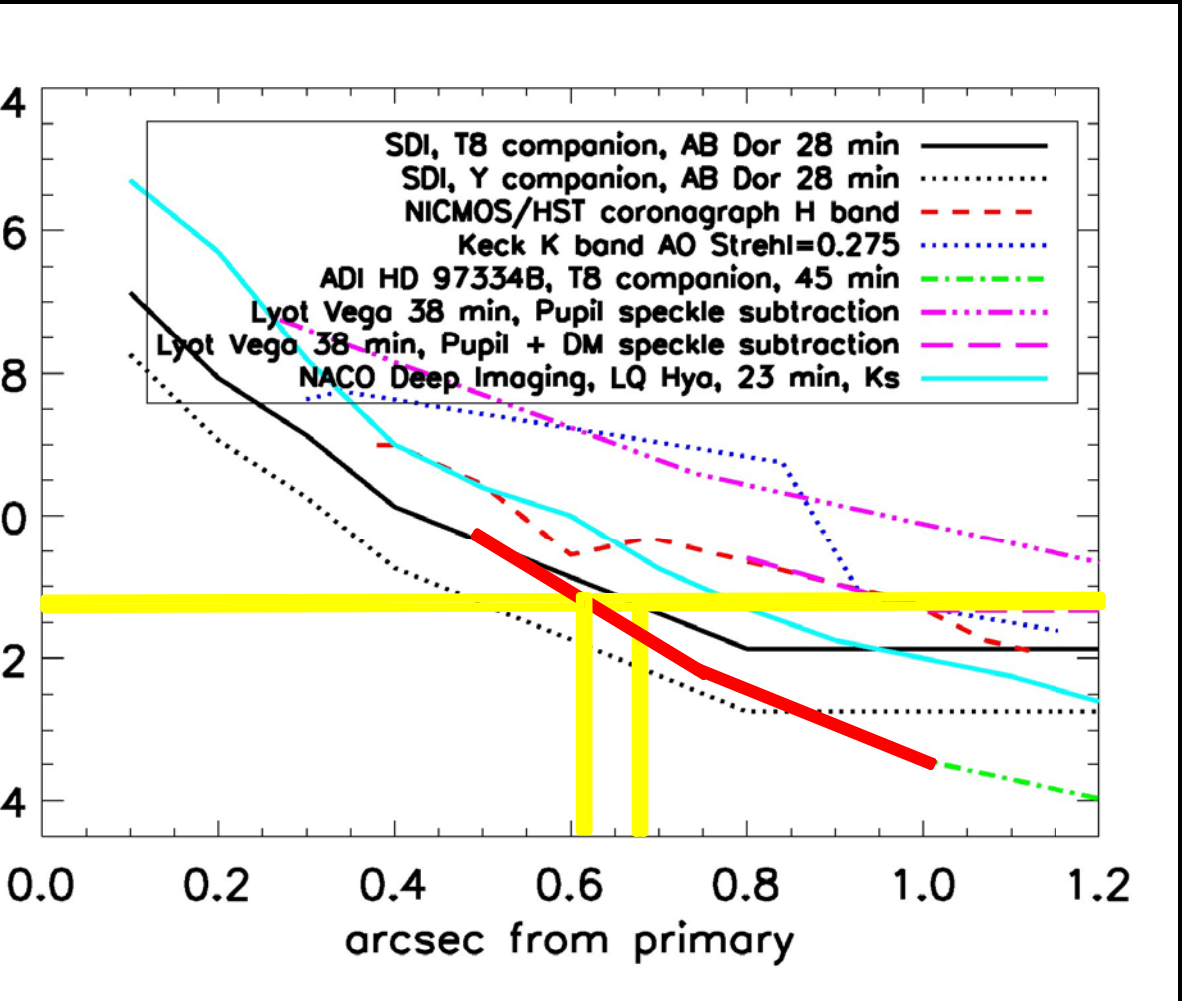
ise

en

PSF subtraction.

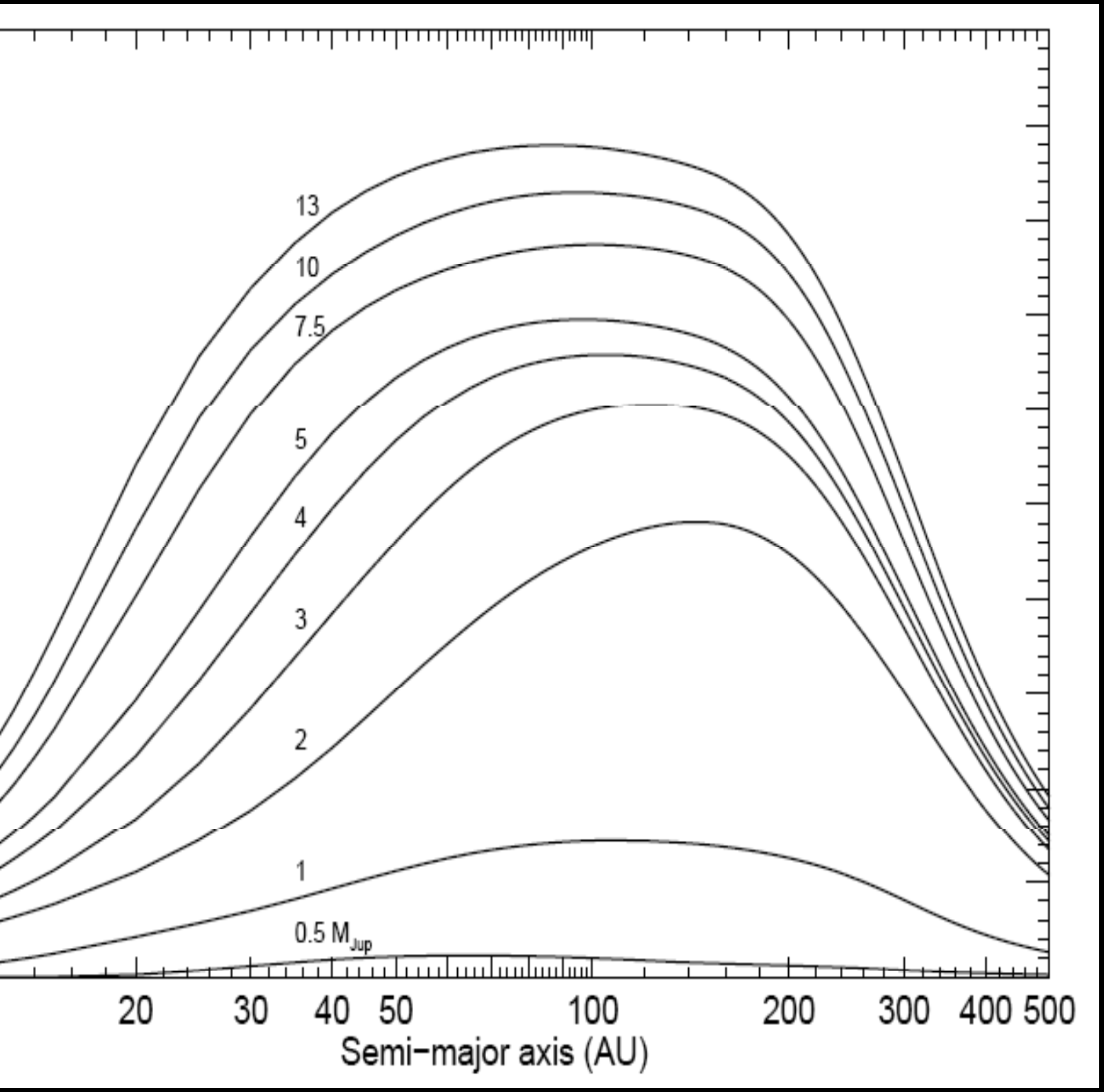

Projected physical separation (AU) at 22 pc
25.
50.
75.
100.
125.
150.
175.
200.
Contrast limit (Δmag, 5σ)
8
10
12
14
16
18
Mass limit for a 100 Myr K0 primary (M_{Jup})
12.0
10.0
7.0
5.0
4.0
3.0
2.0
1.5
1.0
0
2
4
6
8
10
Angular separation (arcsec)

/ HST / SDI - VLT&MMT / MMT-CLIO / Sub
HICIAO / Aperture Masking / Palomar / Lyot

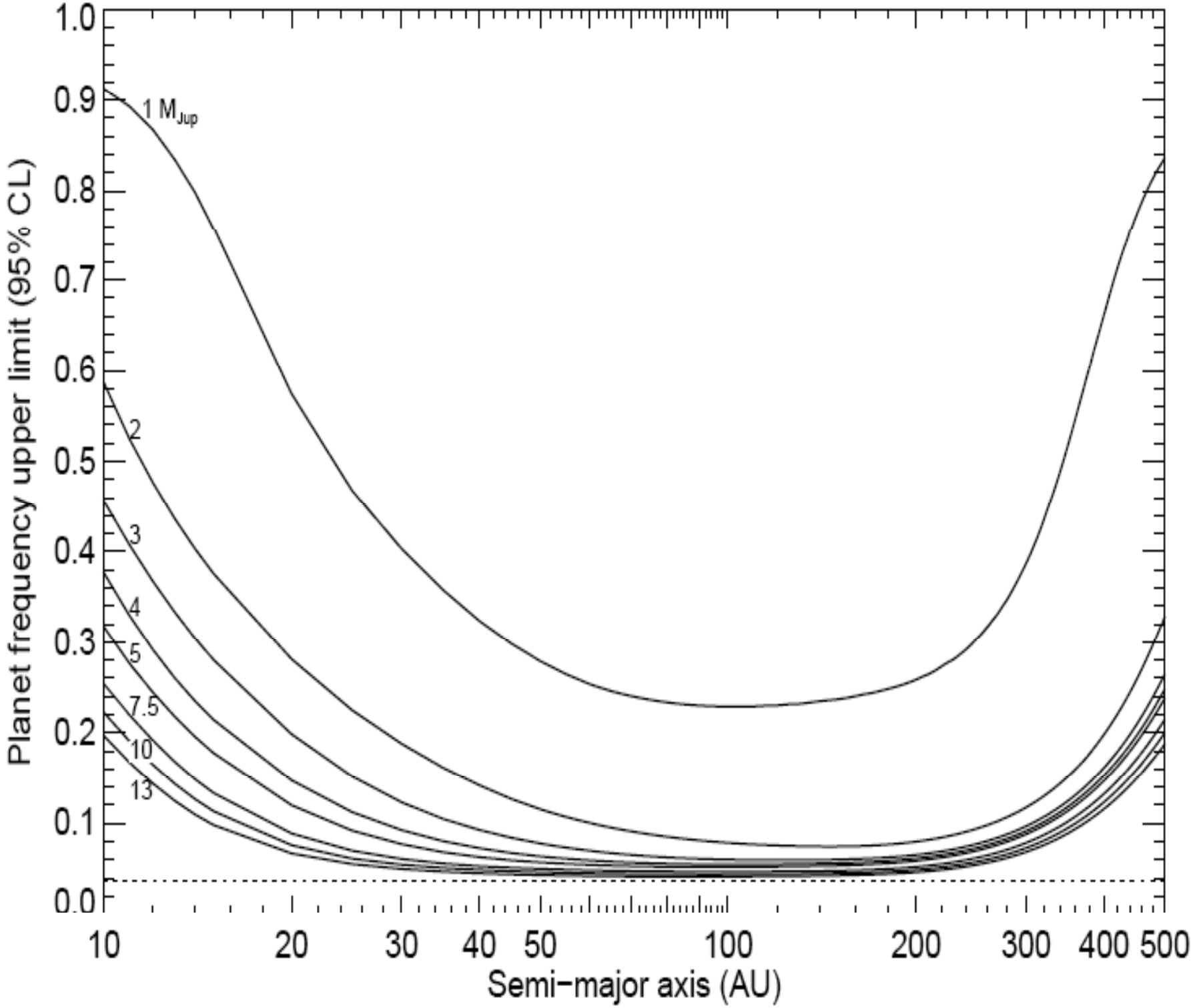


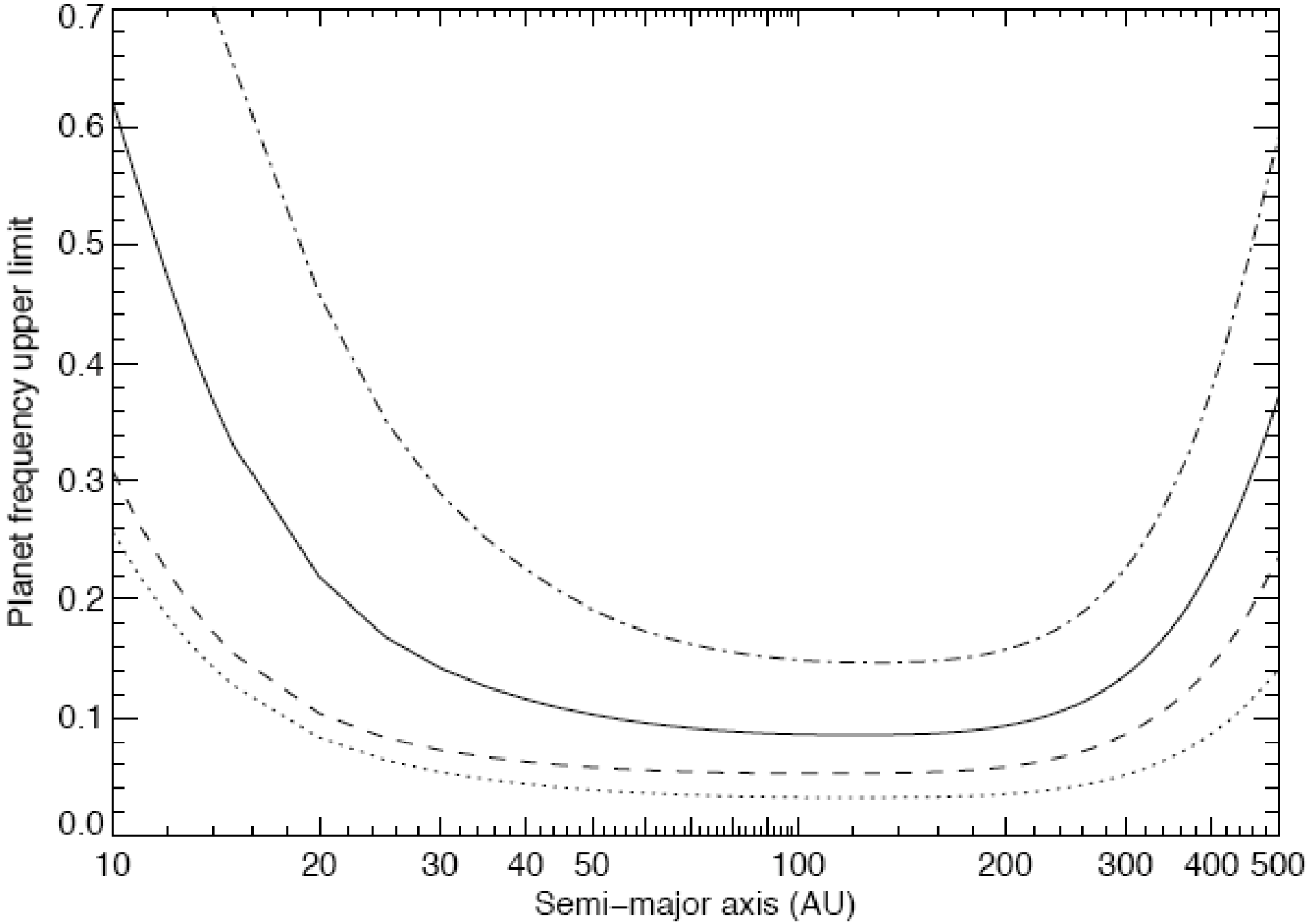
T8 corrected (1.8x) ADI (from GDPS survey).

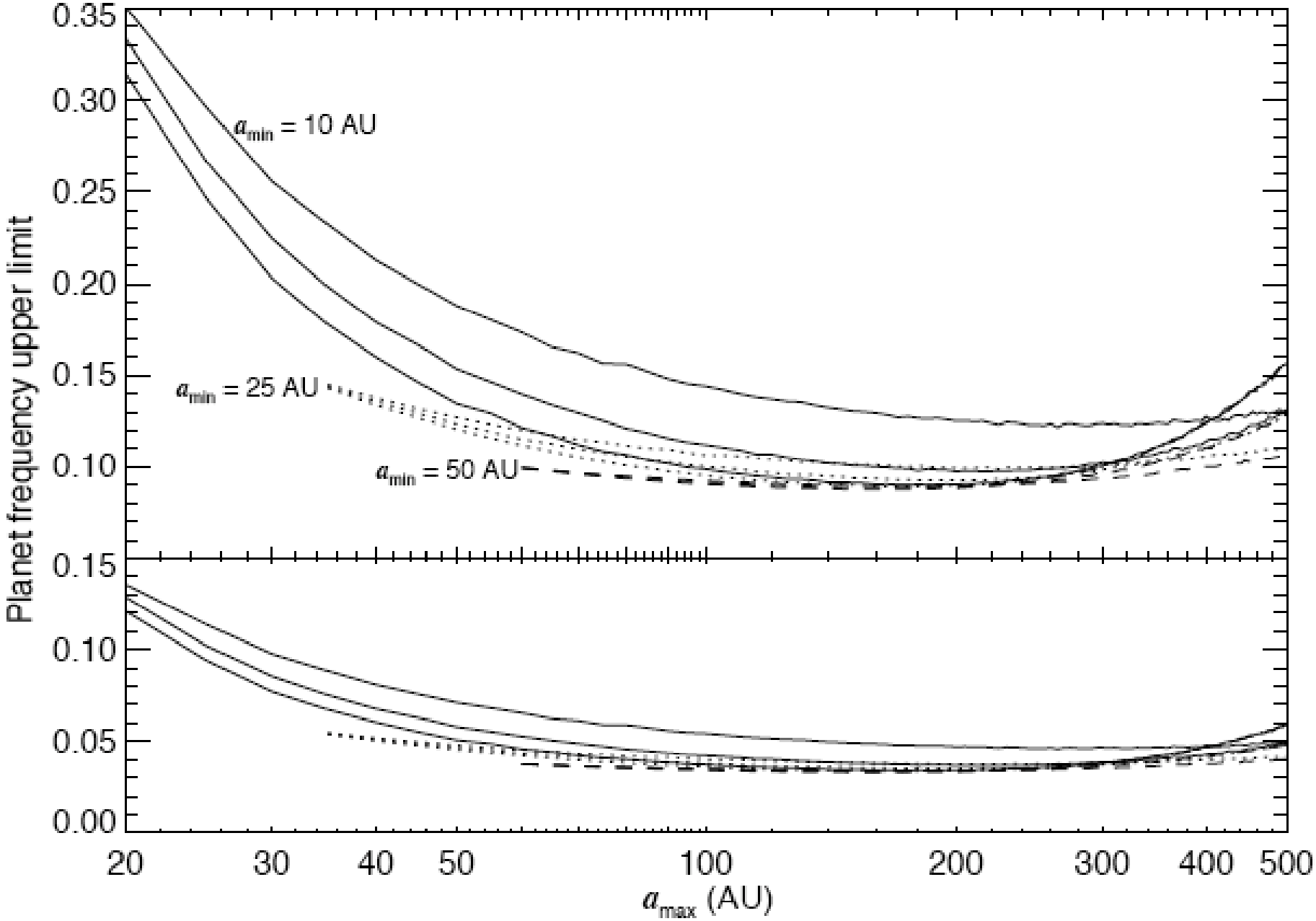
ed from Billers et al. 2007



- Gaussian ec
- For each ma semi-major axis
- Random orbi orientations
- Baraffe mode (contrast to dete mass)
- Include age & errors
- 10,000 plane


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Planet frequency upper limit (95% CL)
1 M_Jup
2
3
4
5
7.5
10
13
10
20
30
40
50
100
200
300
400
500
Semi−major axis (AU)

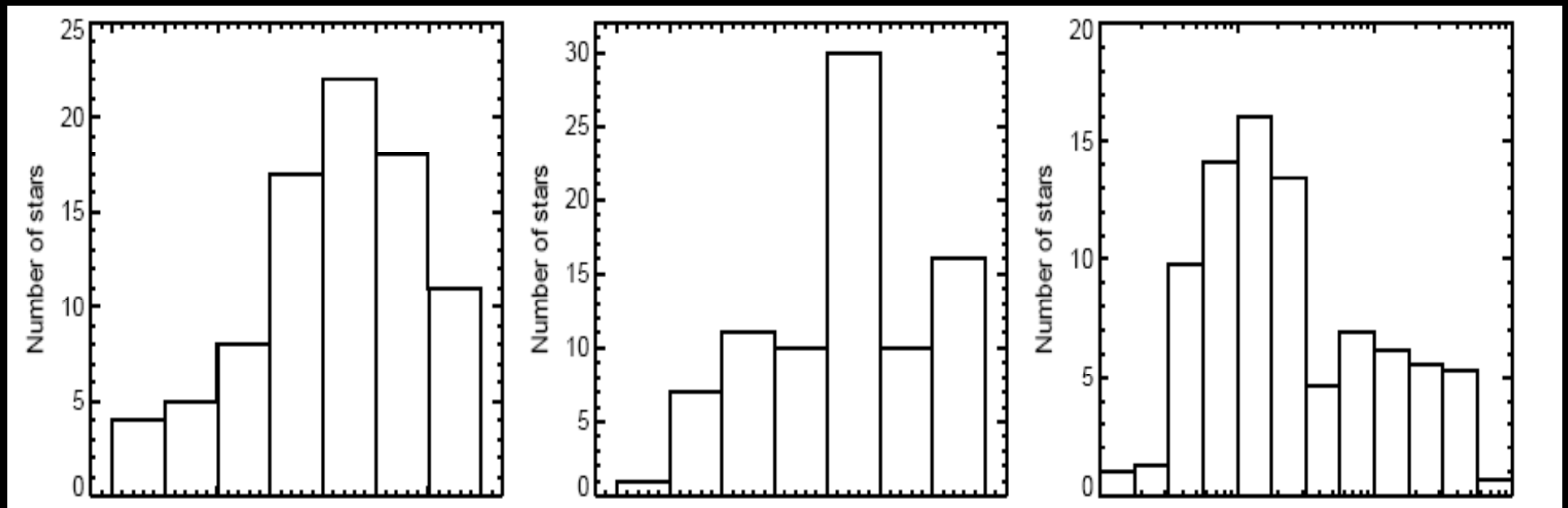

Planet frequency upper limit
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
10
20
30
40
50
100
200
300
400
500
Semi−major axis (AU)

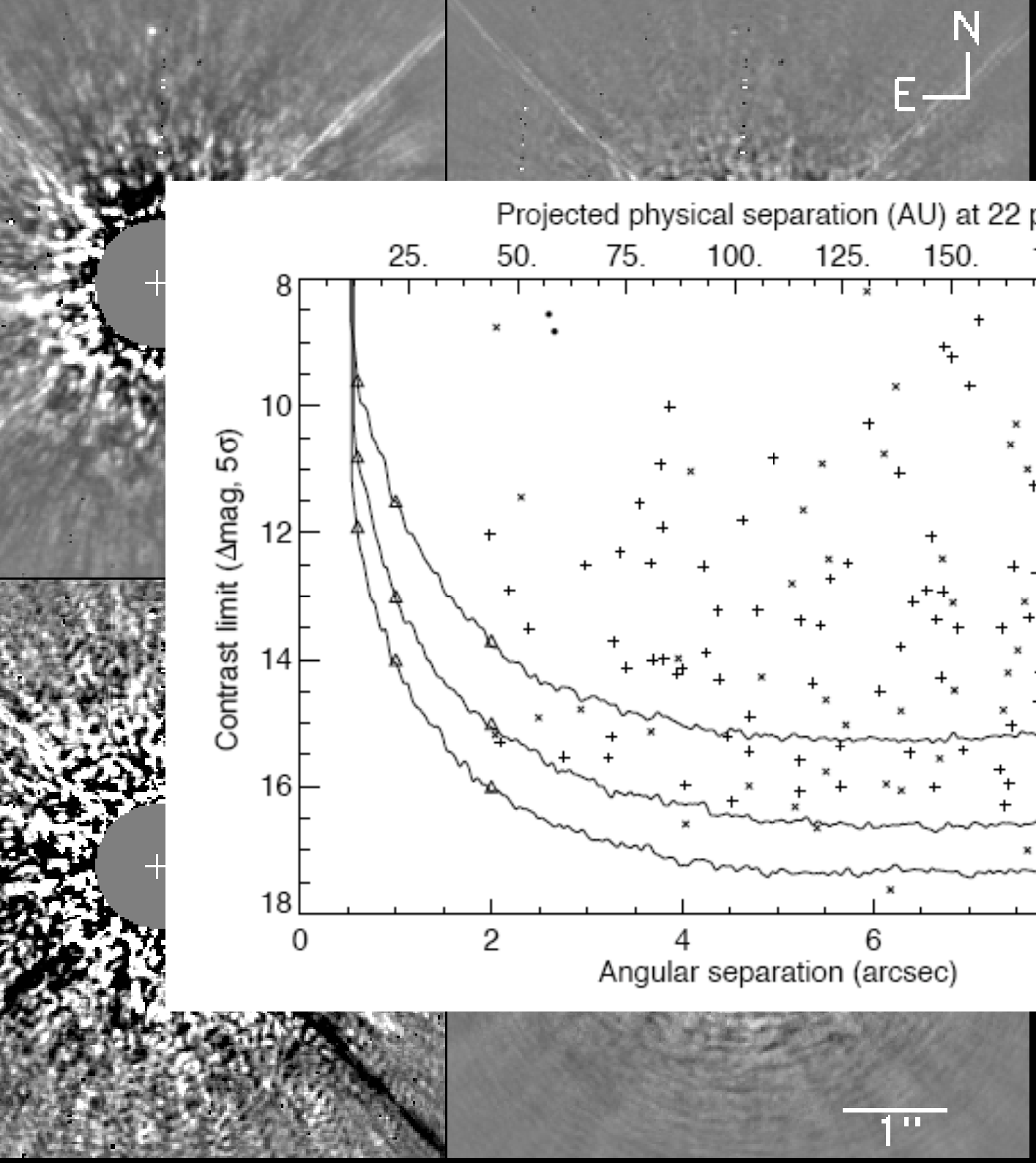

0.35
0.30
0.25
0.20
0.15
0.10
0.15
0.10
0.05
0.00
Planet frequency upper limit
a_{min} = 10 AU
a_{min} = 25 AU
a_{min} = 50 AU
20
30
40
50
100
200
300
400
500
a_{max} (AU)

al: Characterize “massive” planet population
around “massive” stars (Johnson et al. 200

escopes: Gemini, Keck & VLT

get: ~80 young/dusty (10-100Myr) and clos
0pc) A & F stars.





mag = 13

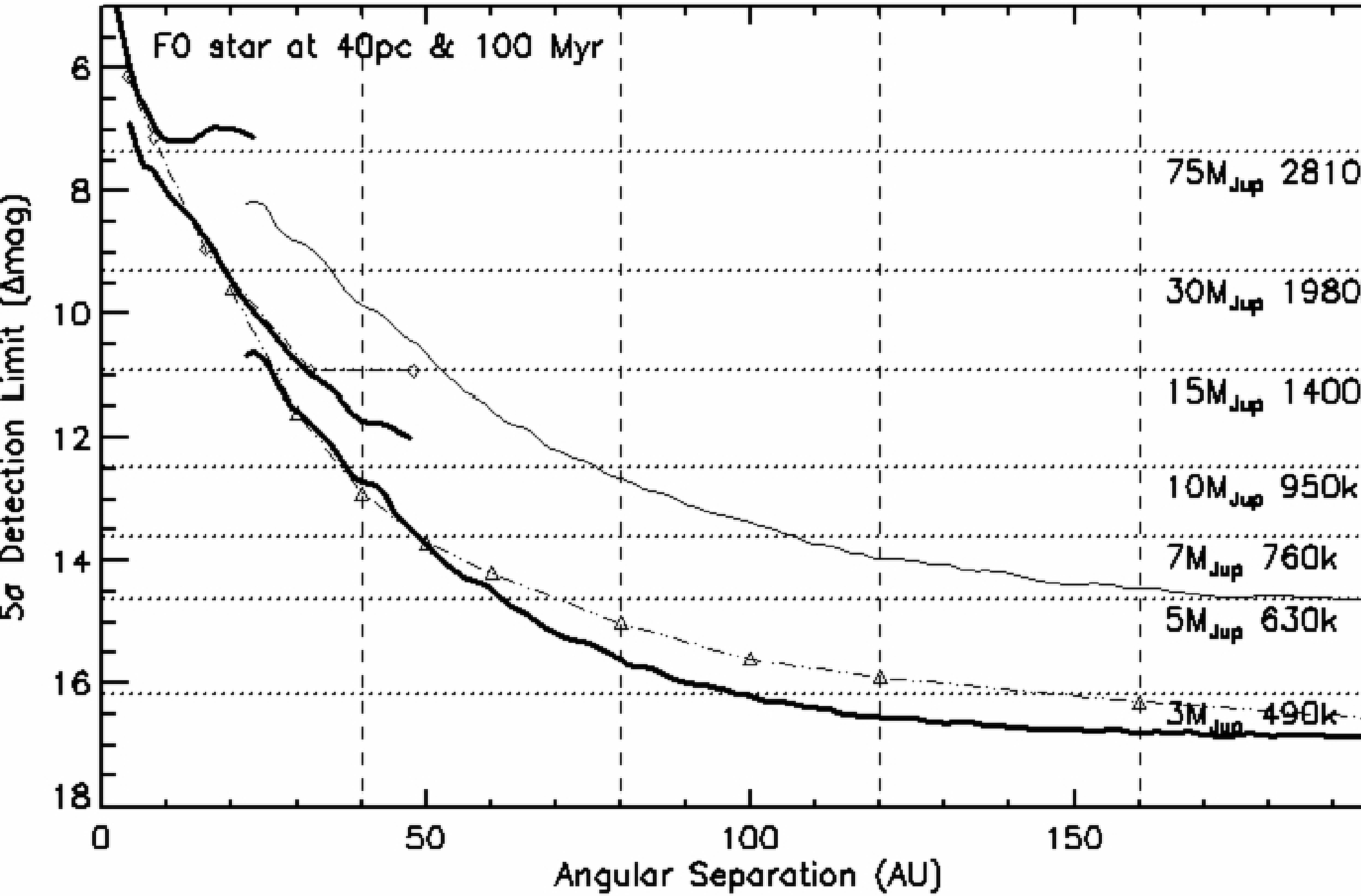
Sep = 1.8" (7

& fai

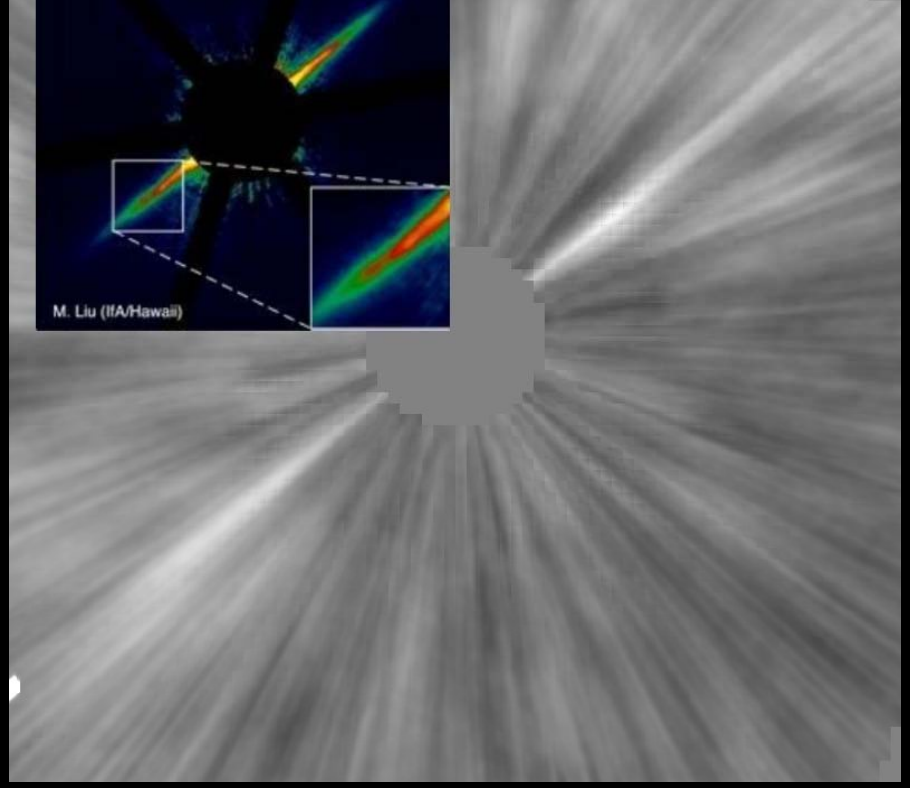
om 1

om ga

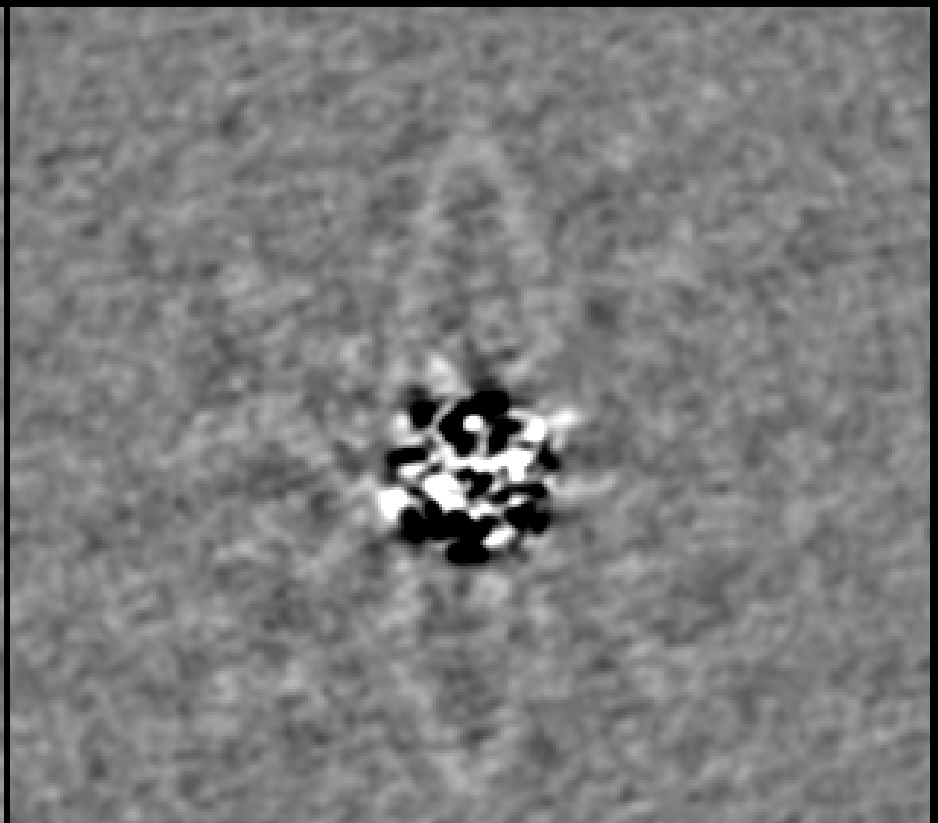
plane & bulge


F0 star at 40pc & 100 Myr
75M$_{Jup}$ 2810
30M$_{Jup}$ 1980
15M$_{Jup}$ 1400
10M$_{Jup}$ 950k
7M$_{Jup}$ 760k
5M$_{Jup}$ 630k
3M$_{Jup}$ 490k
5σ Detection Limit (Δmag)
Angular Separation (AU)
6
8
10
12
14
16
18
0
50
100
150

ck

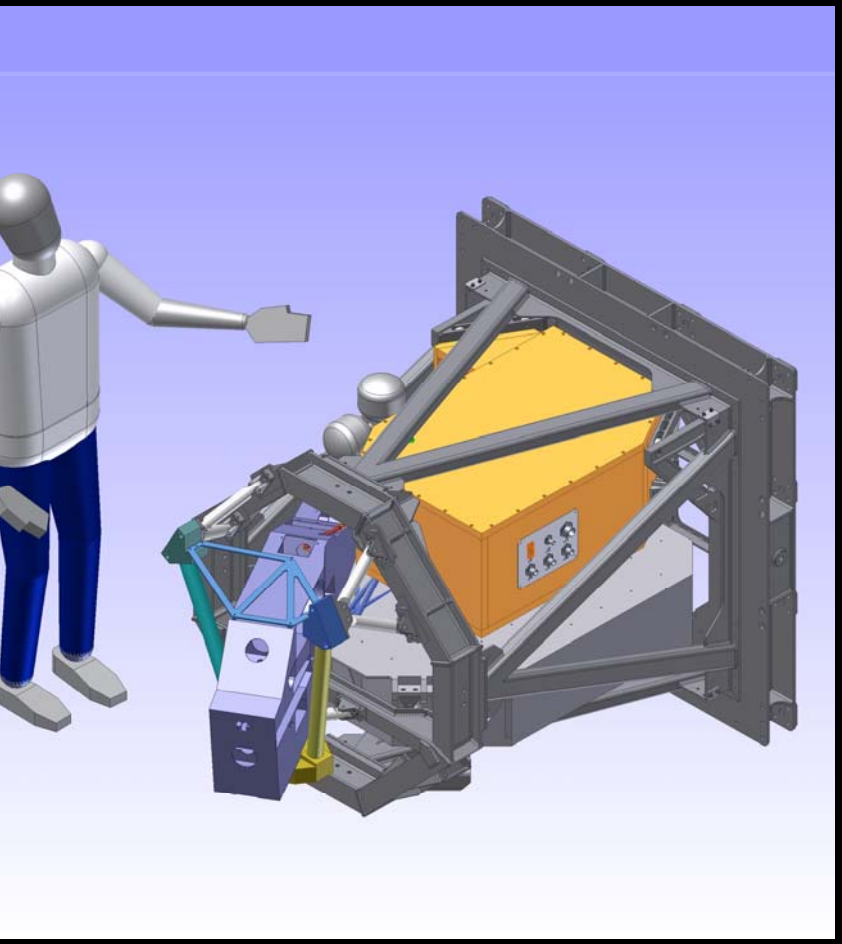


03

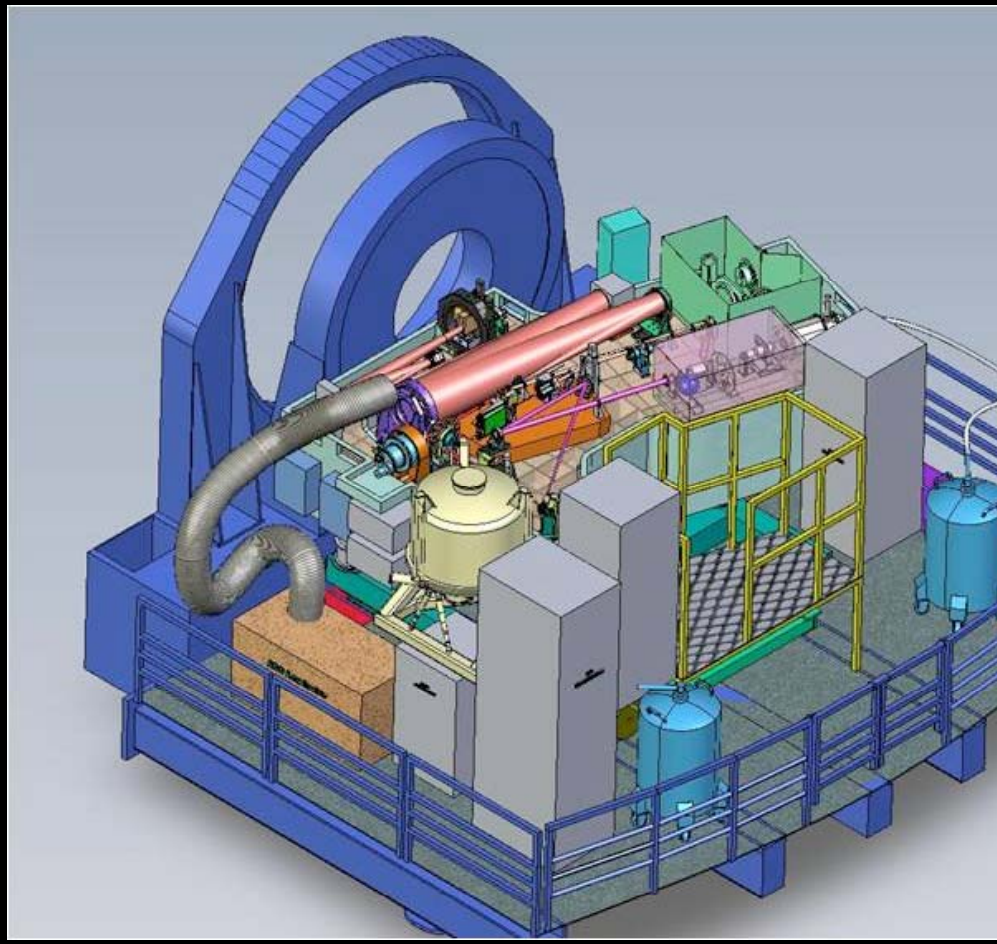


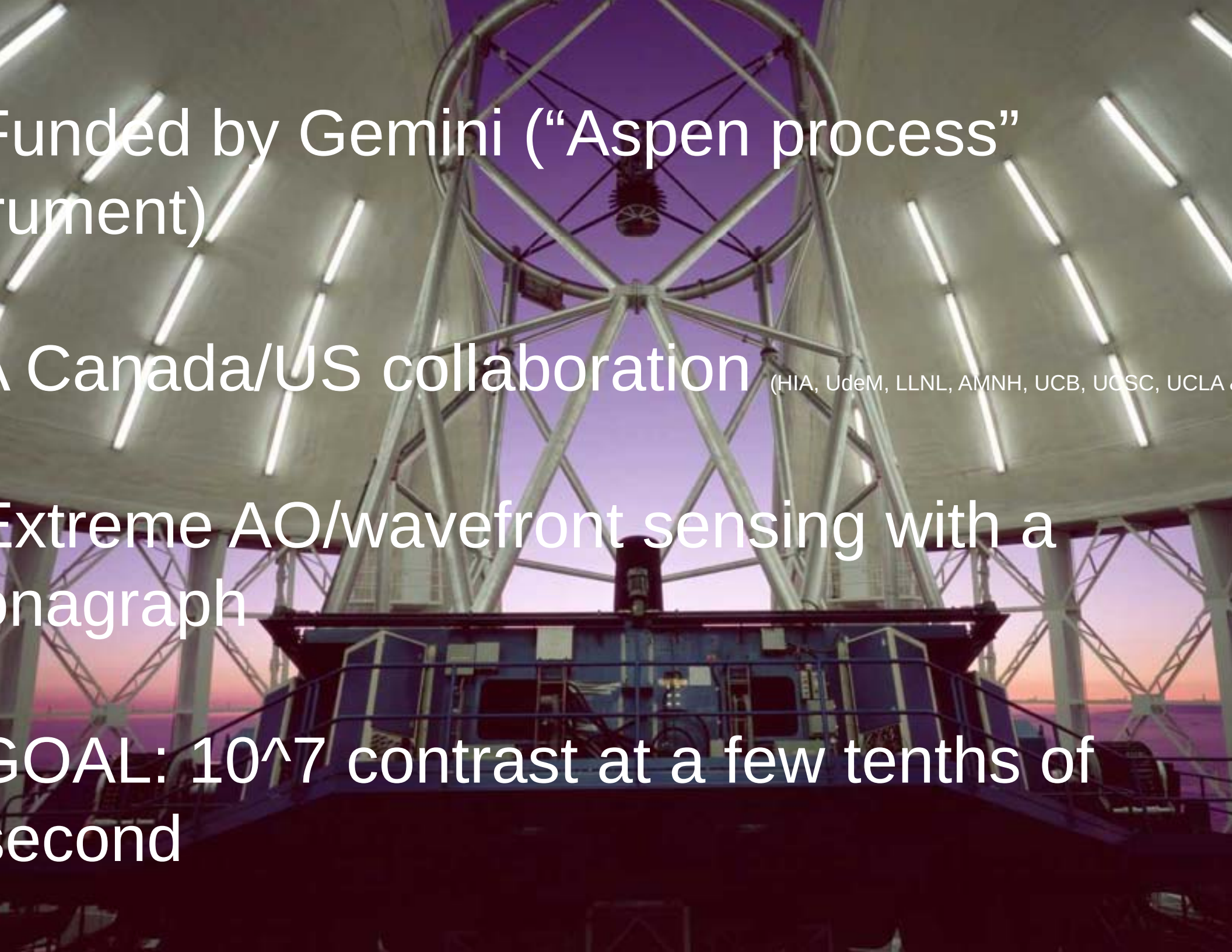
96

Gemini - GPI



VLT - SPHERE



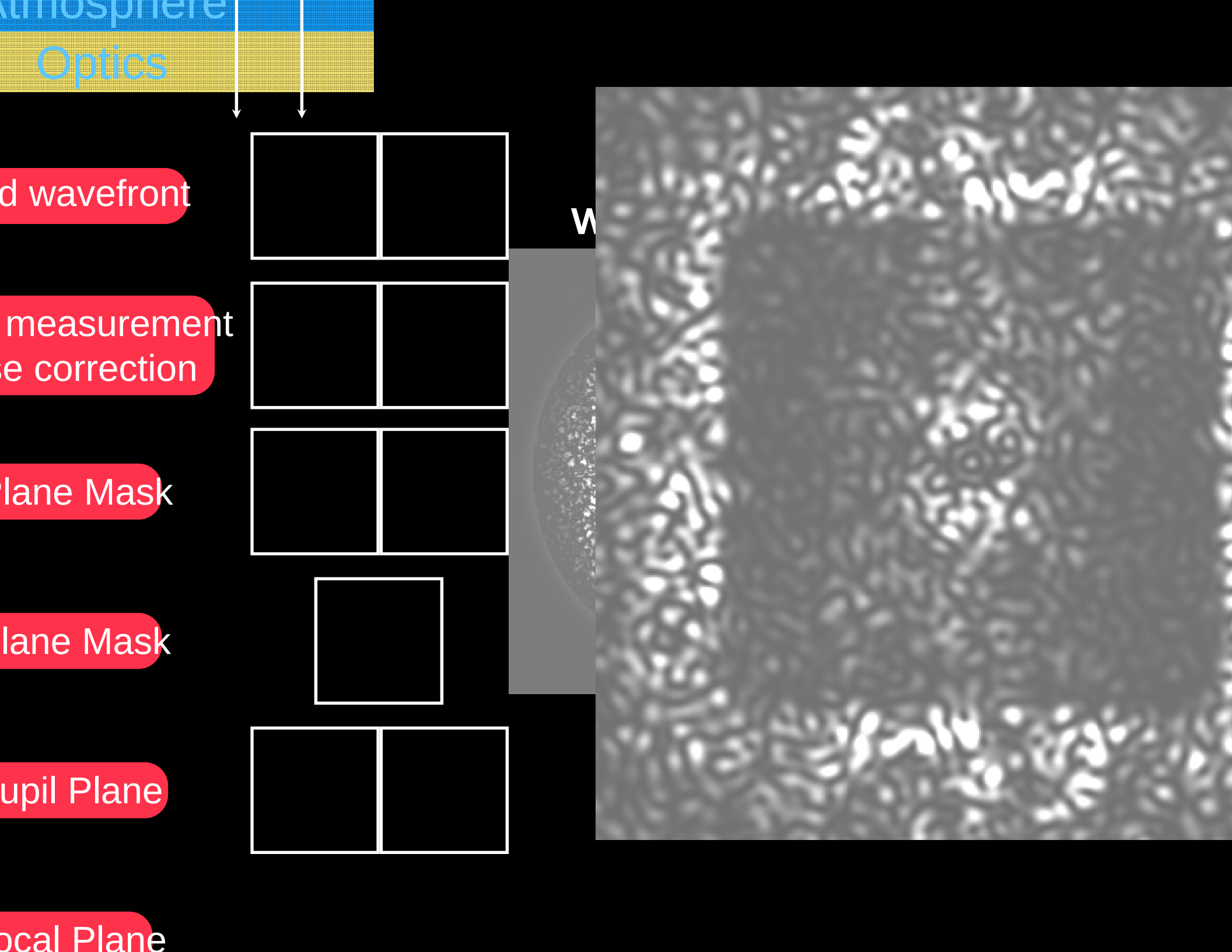


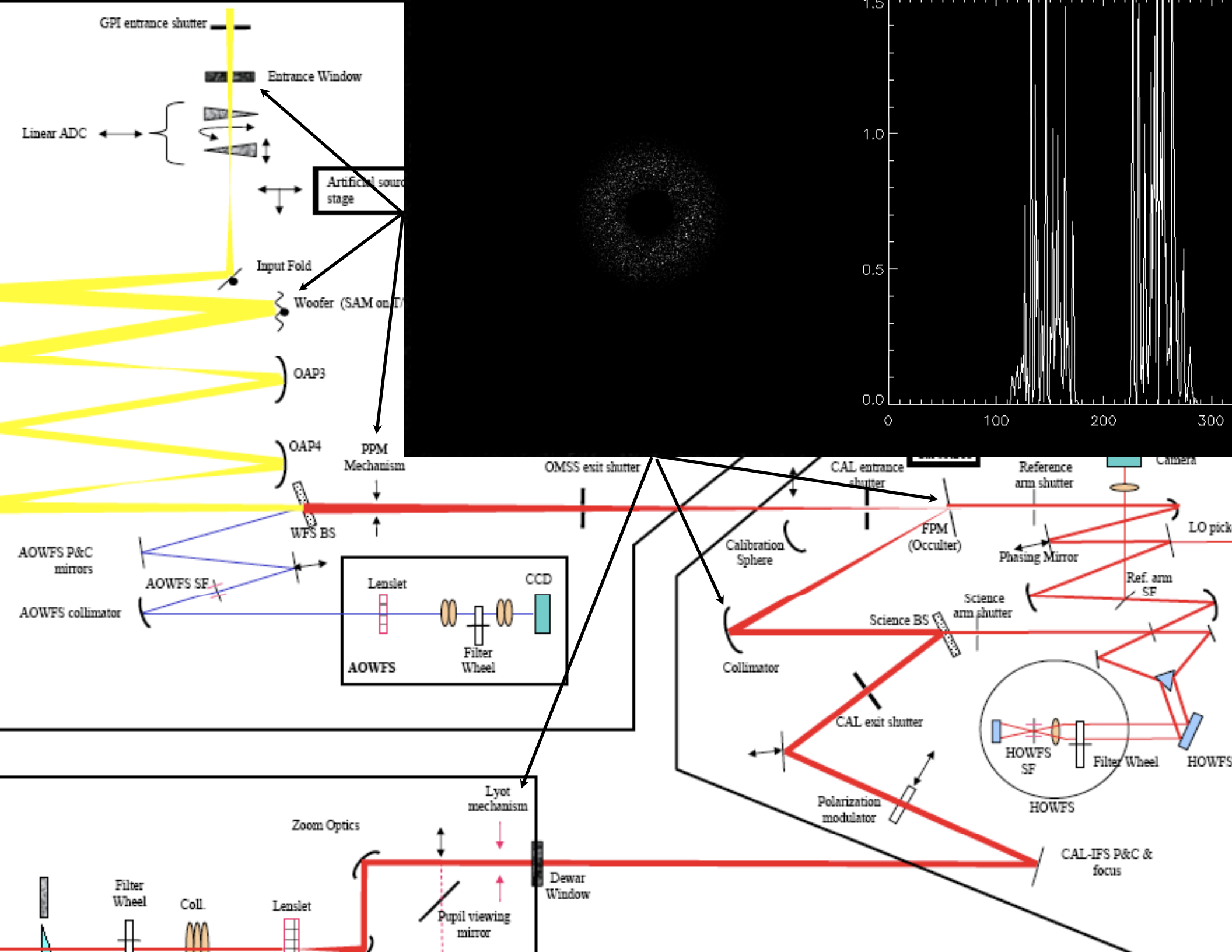
Funded by Gemini (“Aspen process” rument)

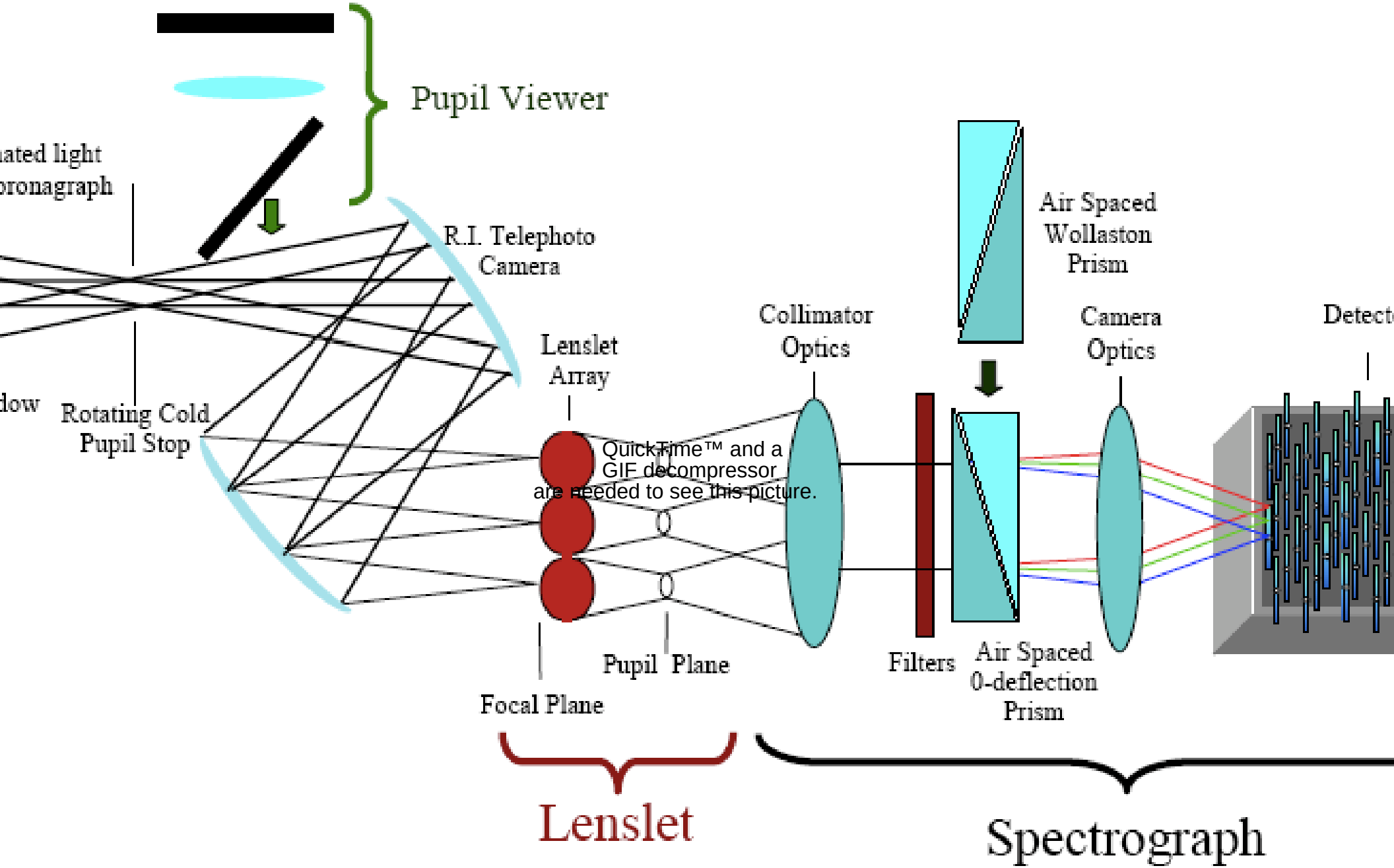
A Canada/US collaboration (HIA, UdeM, LLNL, AMNH, UCB, UCSC, UCLA

Extreme AO/wavefront sensing with a onagraph

GOAL: 10^7 contrast at a few tenths of second


Optics
d wavefront
measurement
se correction
lane Mask
lane Mask
upil Plane
ocal Plane


GPI entrance shutter
Entrance Window
Linear ADC
Artificial sourc
stage
Input Fold
Woofer (SAM on T
OAP3
OAP4
PPM
Mechanism
WFS BS
AOWFS P&C
mirrors
AOWFS SF
AOWFS collimator
Lenslet
CCD
Filter
Wheel
AOWFS
OMSS exit shutter
CAL entrance
shutter
Reference
arm shutter
Camera
LO pick
FPM
(Occulter)
Calibration
Sphere
Phasing Mirror
Ref. arm
SF
Science
arm shutter
Science BS
Collimator
CAL exit shutter
HOWFS
SF
Filter Wheel
HOWFS
HOWFS
Polarization
modulator
CAL-IFS P&C &
focus
Lyot
mechanism
Zoom Optics
Dewar
Window
Filter
Wheel
Coll.
Lenslet
Pupil viewing
mirror
1.5
1.0
0.5
0.0
0
100
200
300


Pupil Viewer
ated light
oronagraph
R.I. Telephoto
Camera
Air Spaced
Wollaston
Prism
Collimator
Optics
Camera
Optics
Detect
Lenslet
Array
dow
Rotating Cold
Pupil Stop
QuickTime™ and a
GIF decompressor
are needed to see this picture.
Pupil Plane
Filters
Air Spaced
0-deflection
Prism
Focal Plane
Lenslet
Spectrograph

22.5 pixels

g magnitude (for AO): I-mag < 9-10

al bands: Y, J, H, K

al resolution: IFS with R~45 at H (~same at J and K-band)

band polarimetric mode

2.9” x 2.9”

vorking angle: 2.8 lambda/D radius

ole size: 21 x 21 lambda/D

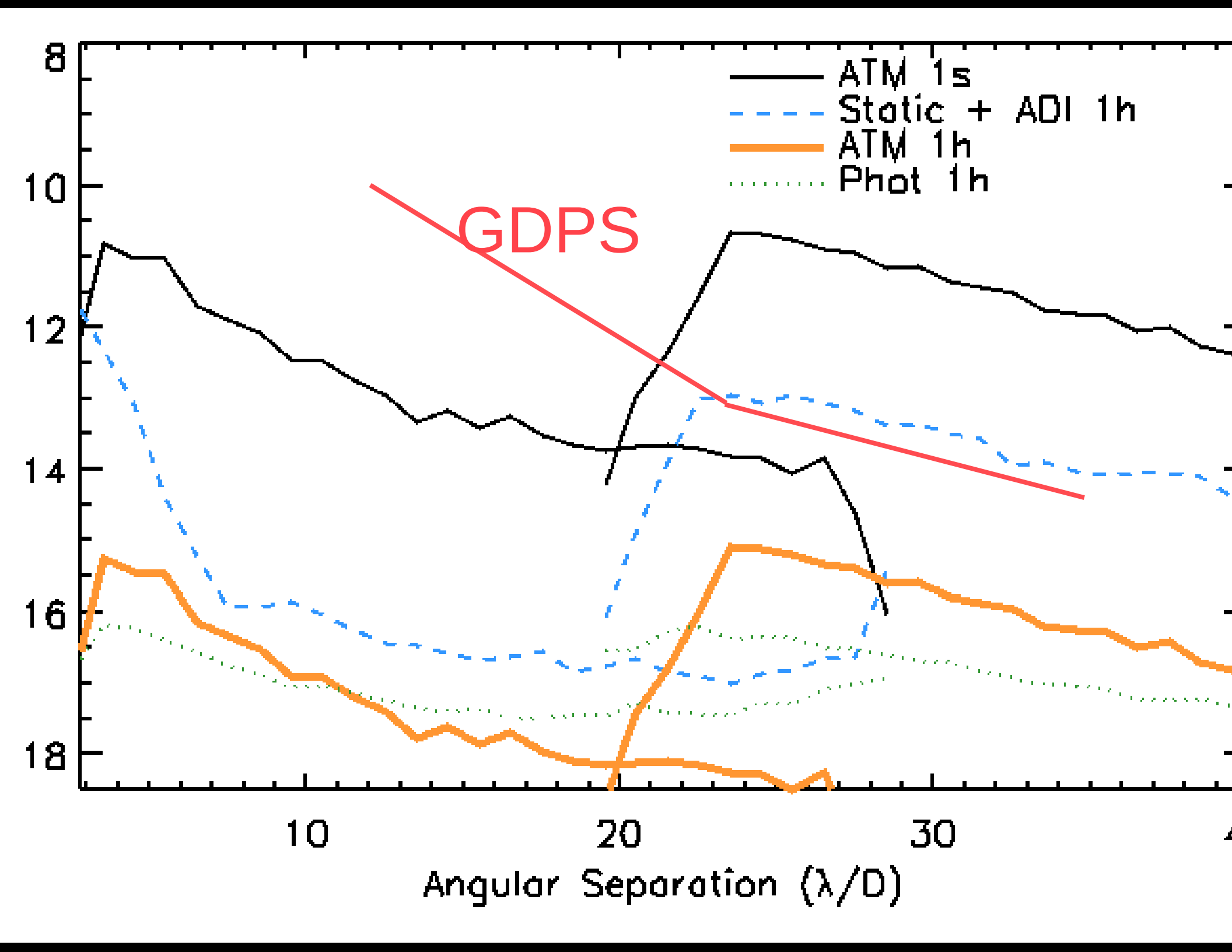
st: up to 10^{-7} from PSF peak intensity

ght: December 2010 at Gemini South

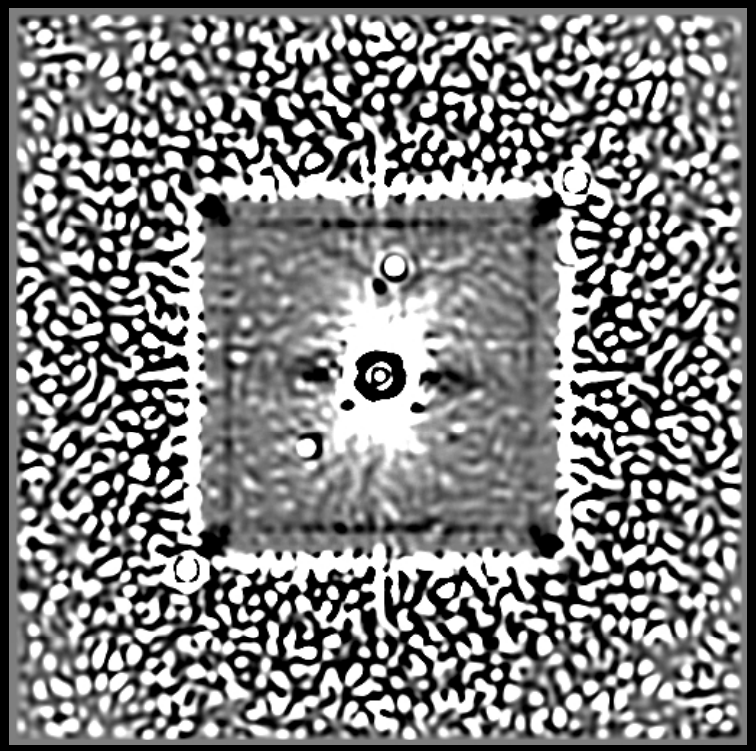
GPI 1 week ago!

I-Band < 10 mag

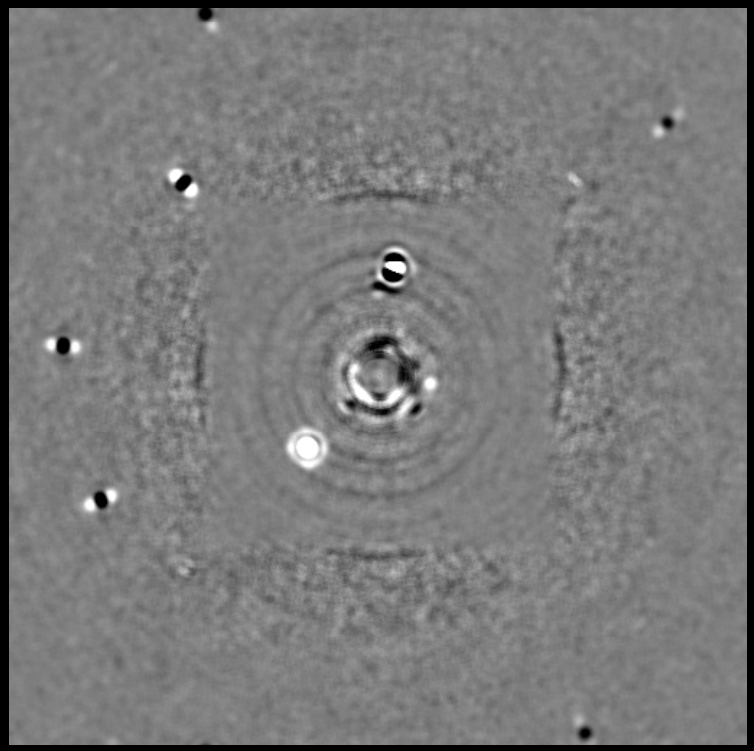
Spectral Type	Distance (pc)	IWA (AU)
O5V	13,200	1,475
B5V	1,750	195
A5V	500	55
F5V	220	25
G5V	115	13
K5V	33	3.7
M5V	12	1.3


ATM 1s
Static + ADI 1h
ATM 1h
Phot 1h
GDPS
8
10
12
14
16
18
10
20
30
Angular Separation (λ/D)

Before



After



ar Differential Imaging: FOV rotation with ti

taneous Spectral Differential Imaging: Spec

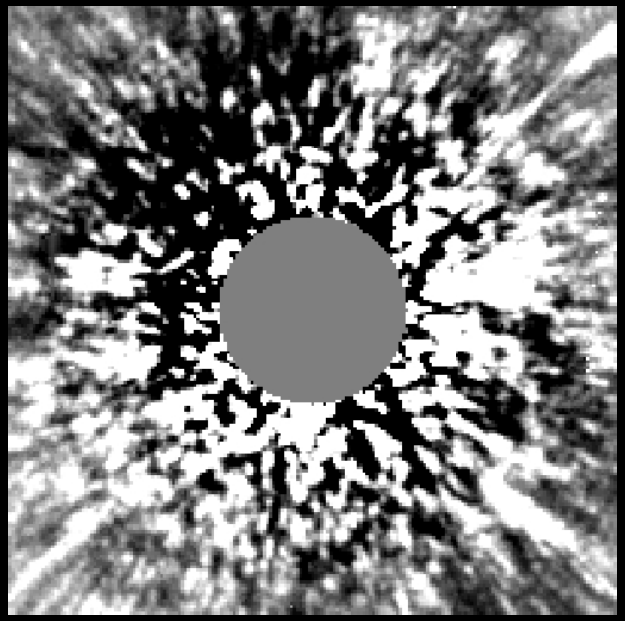
ences between a star and a cool exoplanet.

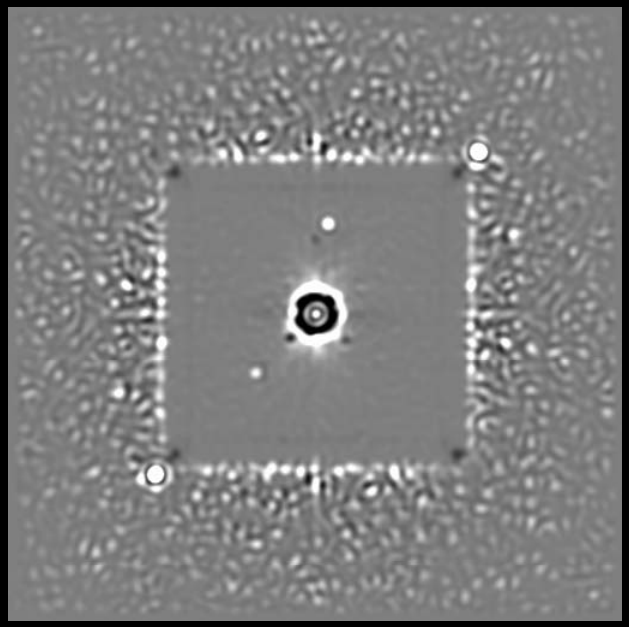
Now

GPI
December 2010

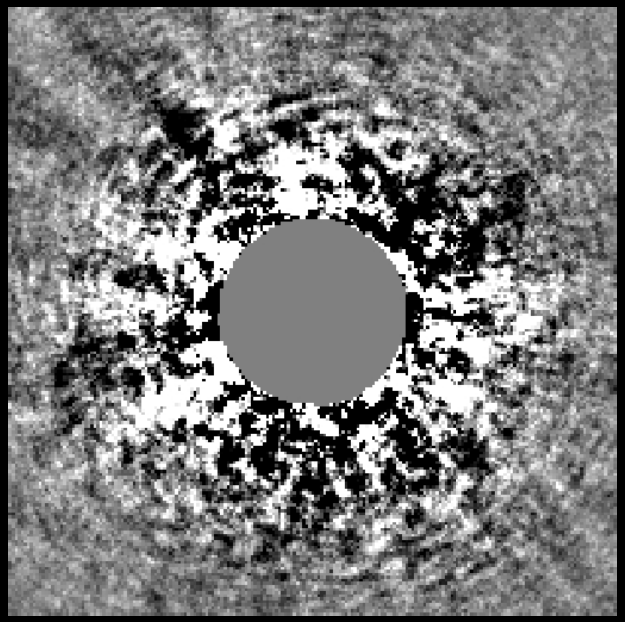
1h

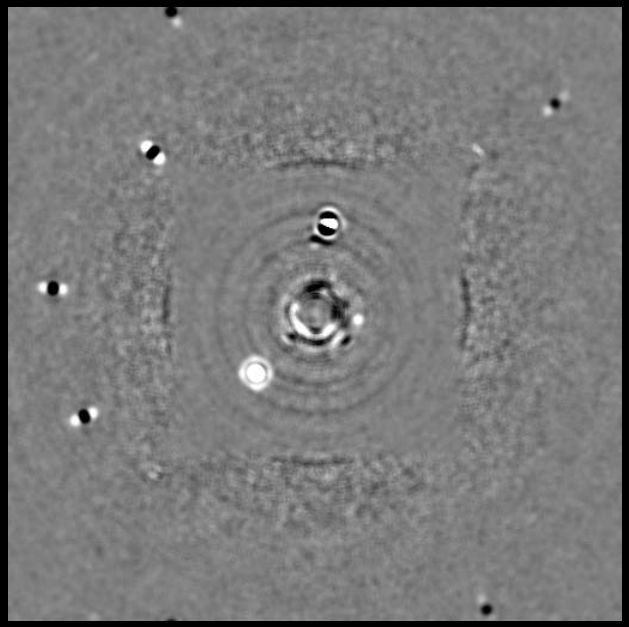
Altair PSF
1.57 microns
CH4 band
4”x4” FOV.
Quasi-static speckle noise limited
Inner region is saturated.
± 1E-5 linear



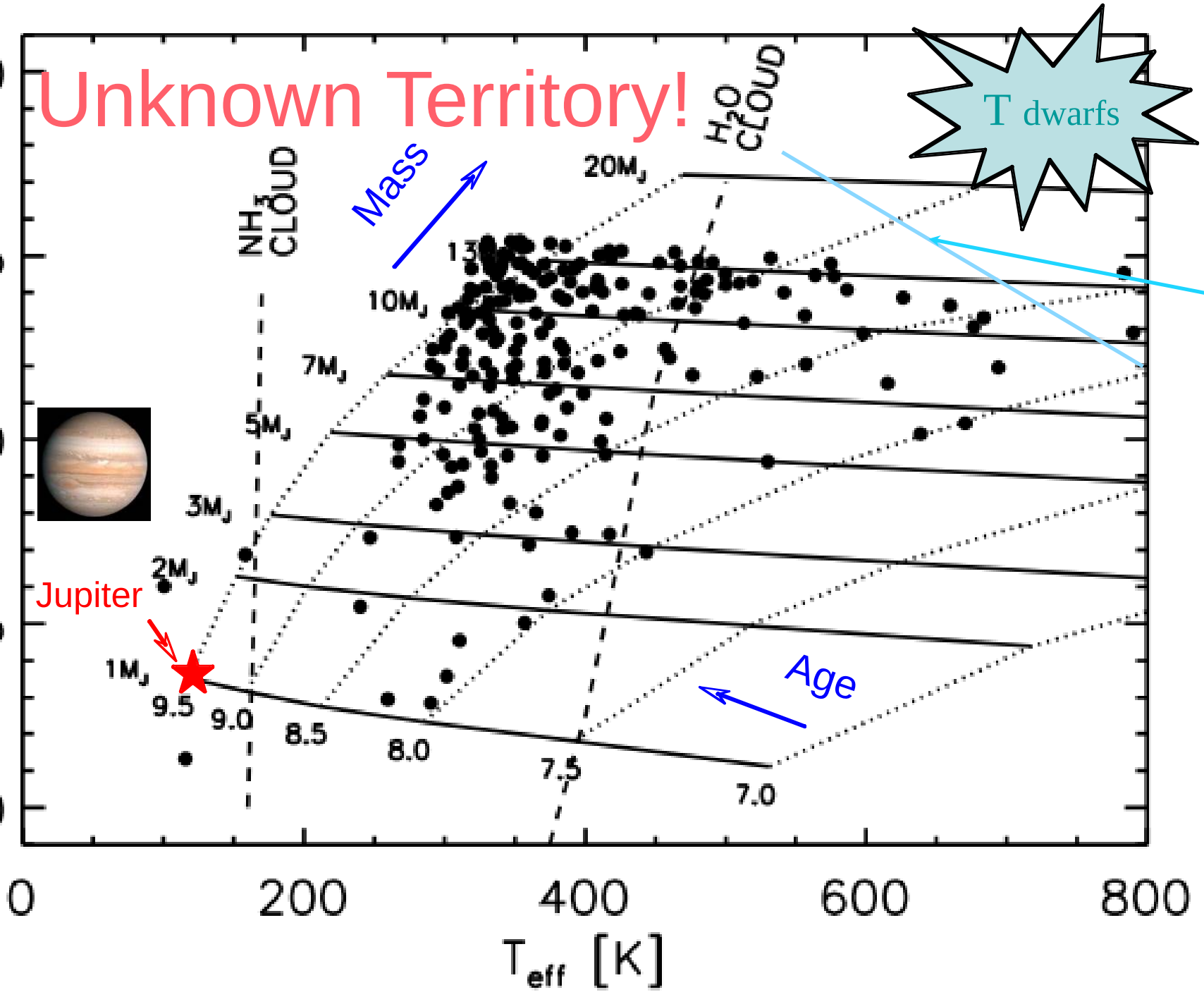


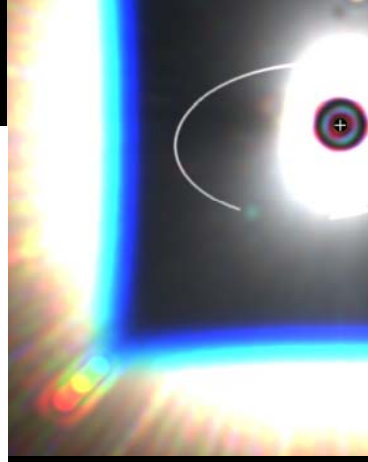
Altair & ADI
45 minutes.
± 5E-7 linear





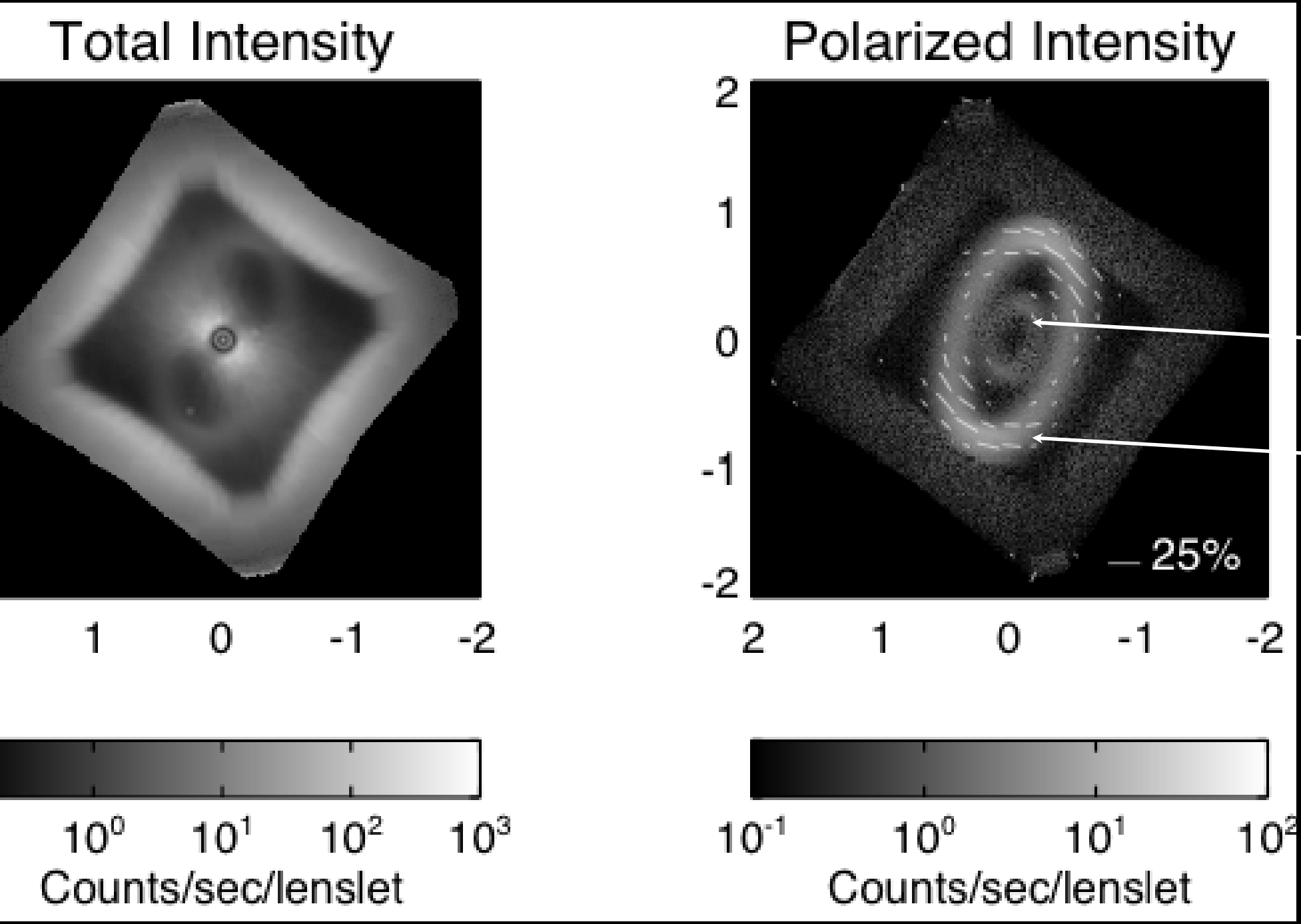
Exoplanets!



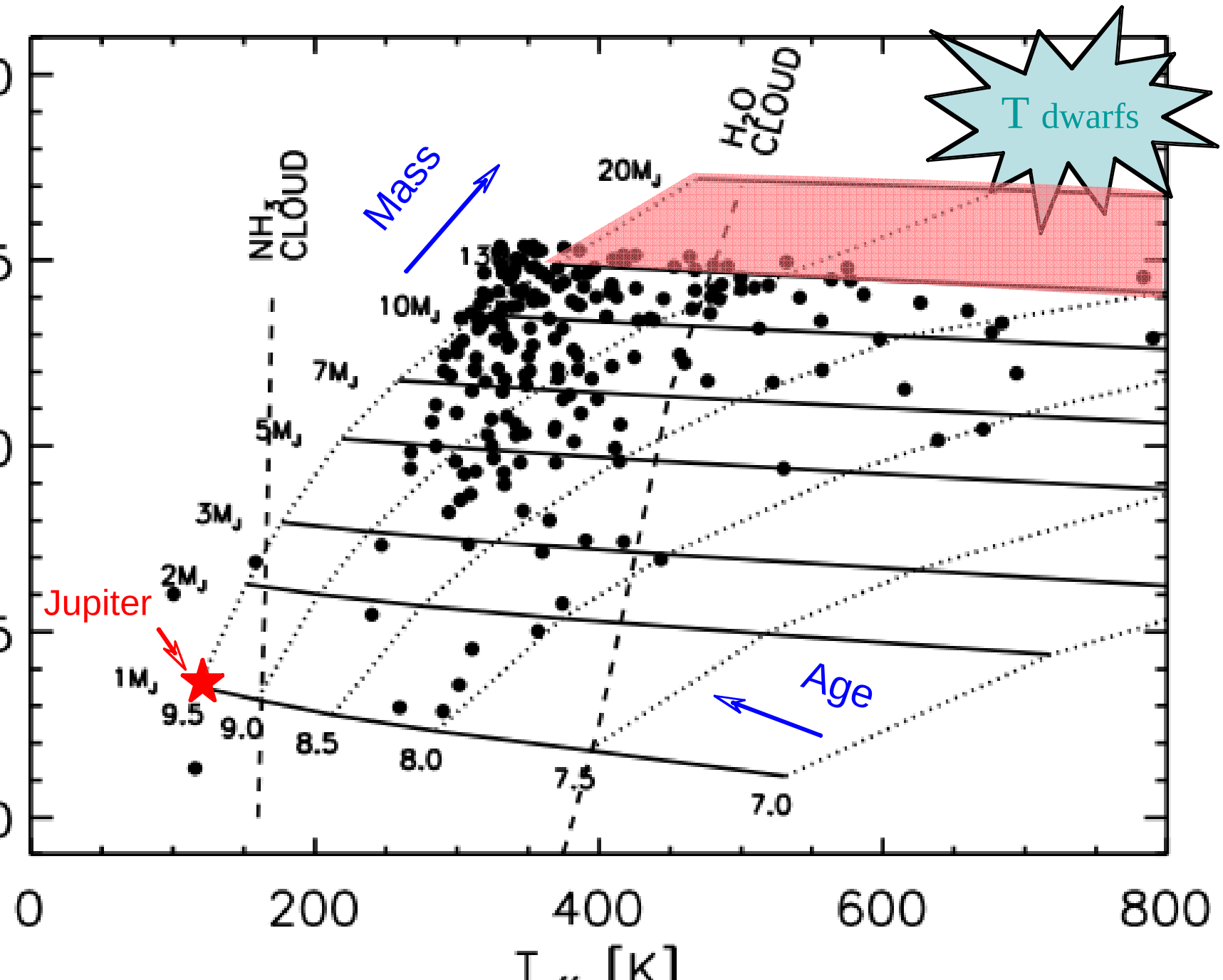


CFHT new

Debris disk!

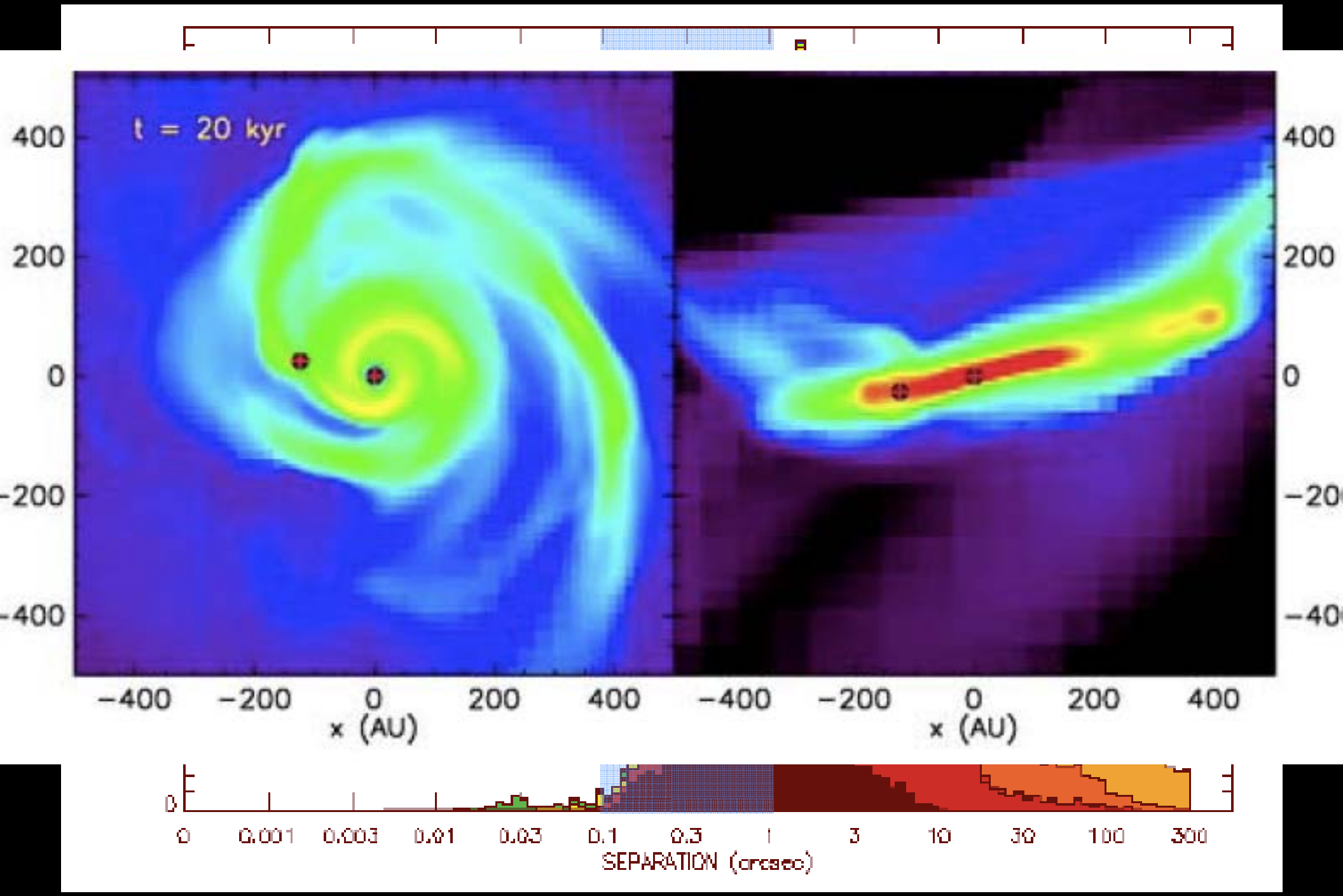

Total Intensity
Polarized Intensity
2
1
0
-1
-2
1
0
-1
-2
2
1
0
-1
-2
— 25%
Aster
(10^
Kuipe
(10^
10^0
10^1
10^2
10^3
Counts/sec/lenslet
10^{-1}
10^0
10^1
10^2
Counts/sec/lenslet

Brown Dwarfs "SNAP SHOT" survey



- Easy to find
- Quick (few integration dow
- Constraint t companion pop BD formation s

Stellar Binary Analysis (from RV trends)



lassive Star Mass Loss

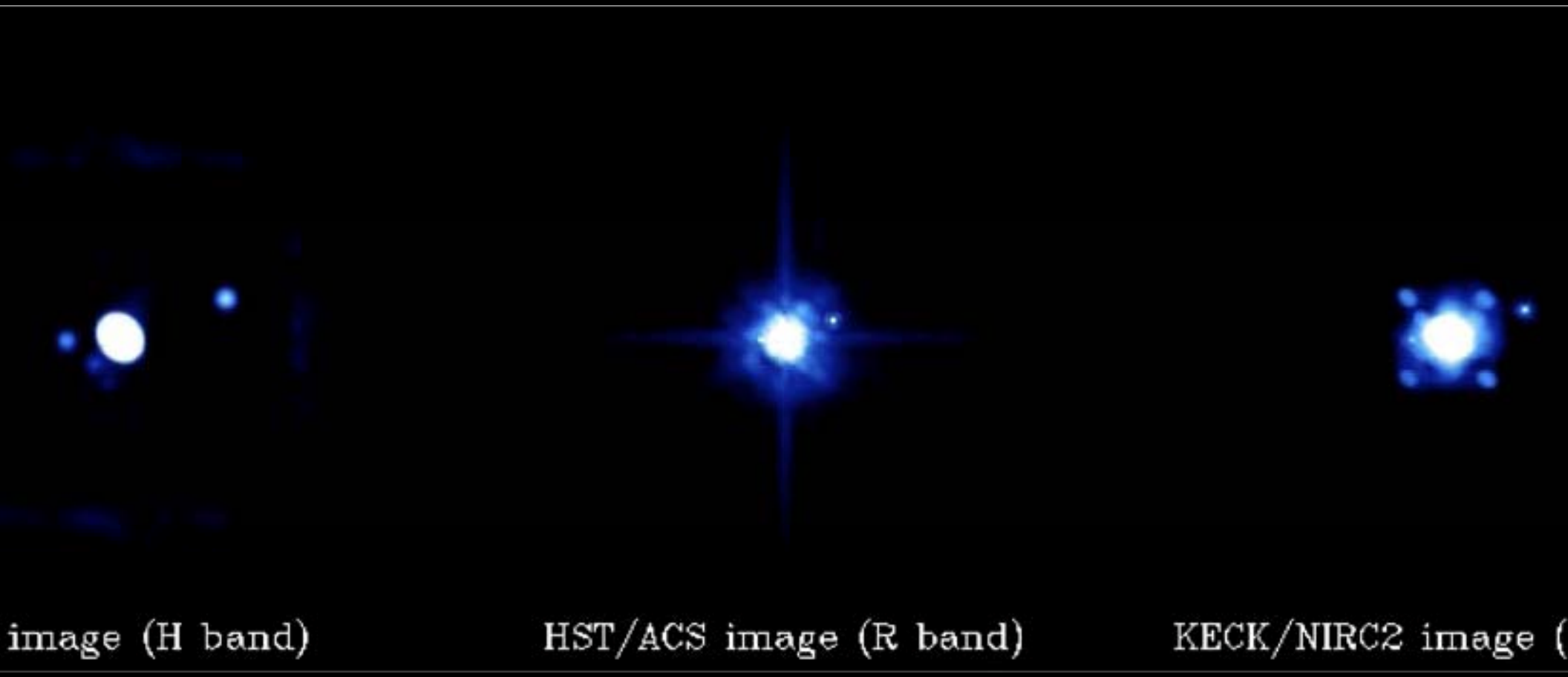
NGC6543

ntric gas shells
high-speed gas
al shock-induced knots of gas

- PNe exhibits unexpected features
- Structure from undetected binary?
- Currently not resolved by

Solar System

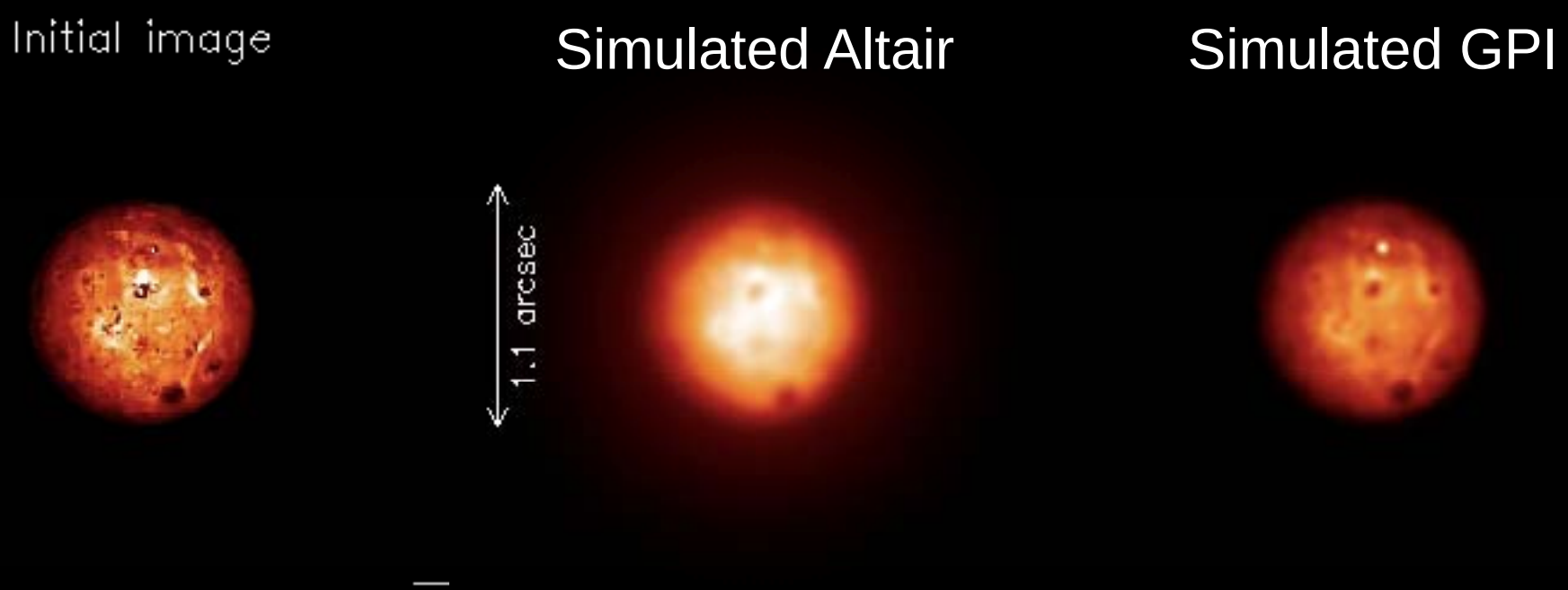
Small solar system bodies



10 brighter than I~9

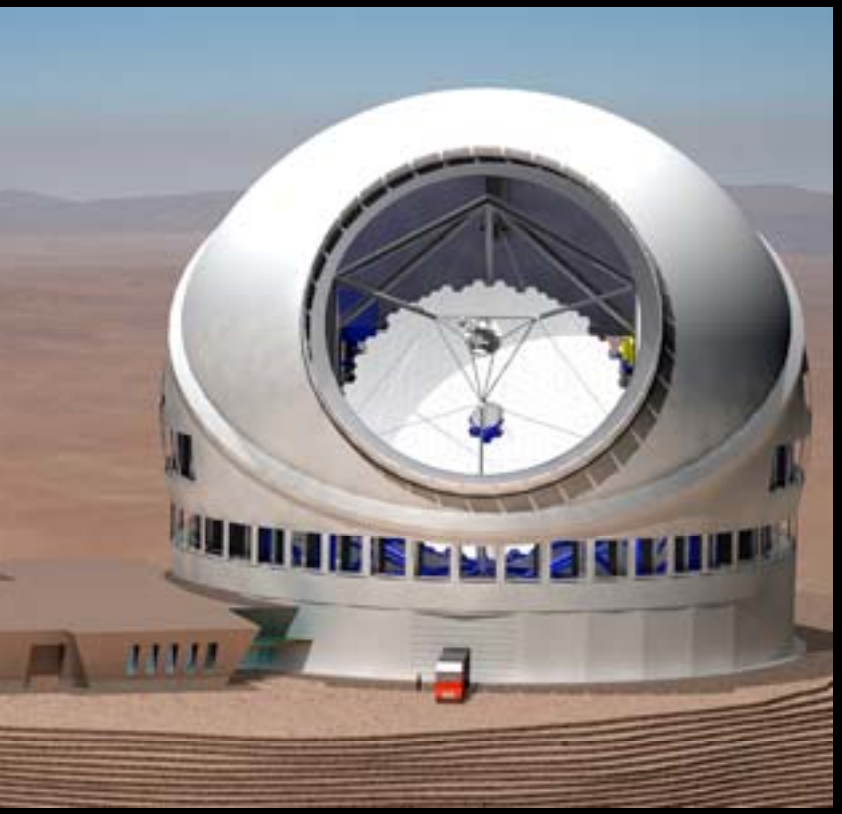
50 brighter than I~10.5

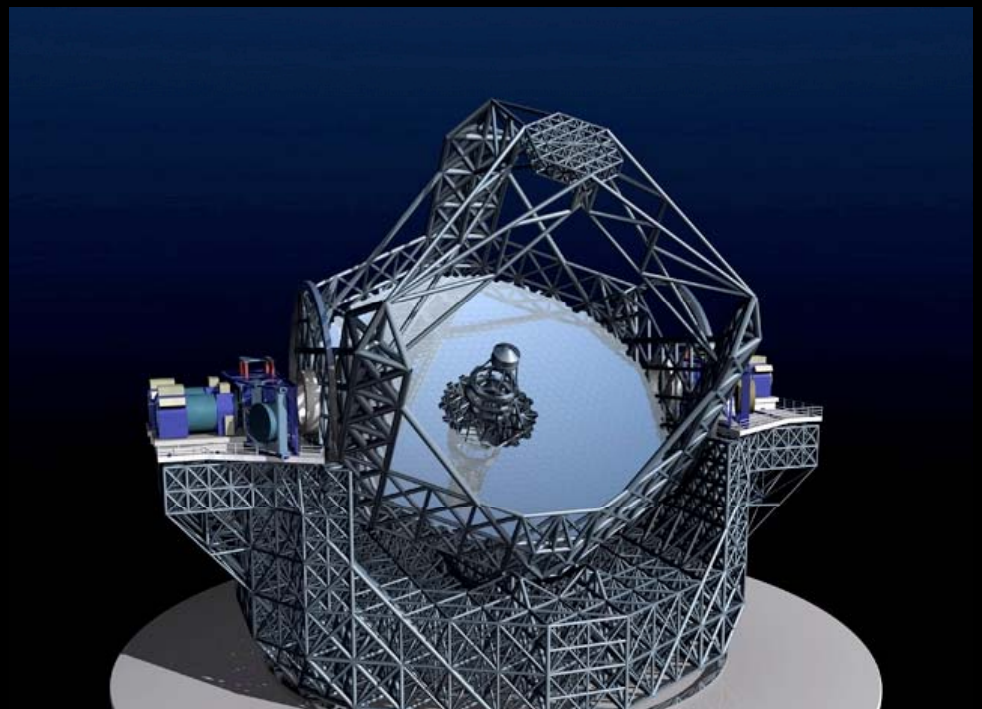
Solar System



No coronagraph
Higher resolution
Find and characterize “hot spots”

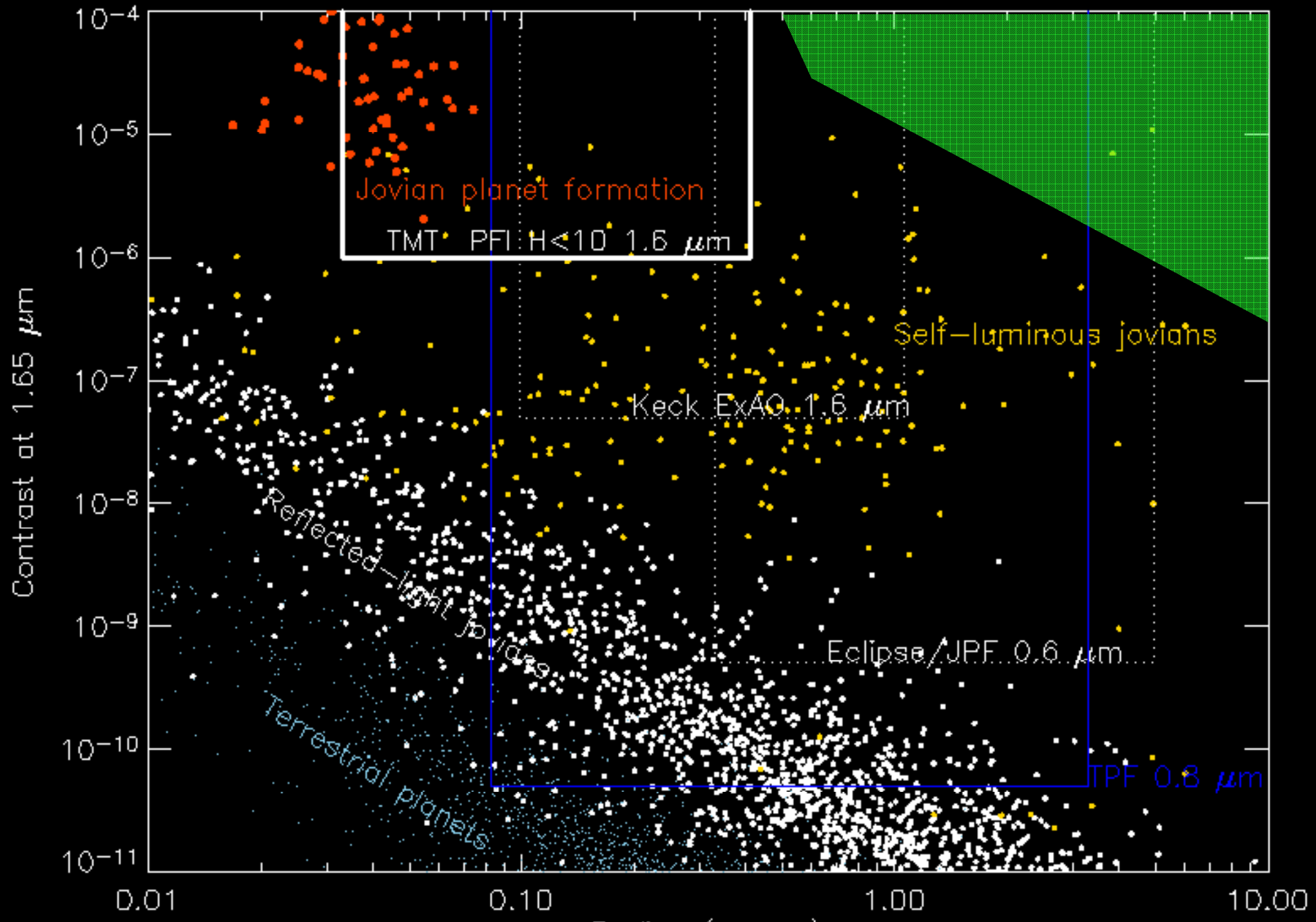
an and other Jovians satellites also interest





In the JWS
&
TPF (2

R < 7, 50 pc sample



round-based imaging offer unique opportun
omplement space-based research.

ground-based ADI survey of NY stars start
training planet formation >10 AU around AF
s.

uture “optimized” ground-based imaging sh
young SS analogs.

0+ meter telescopes mainly aimed at plane
ation studies due to smaller IWA