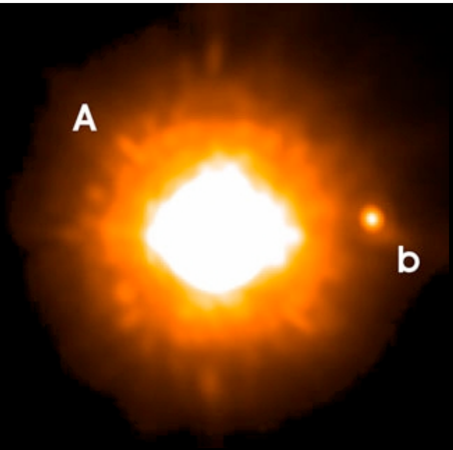
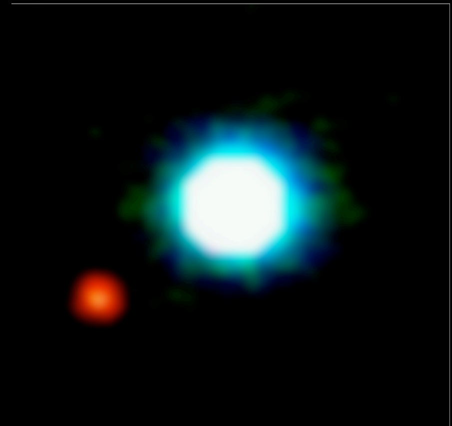


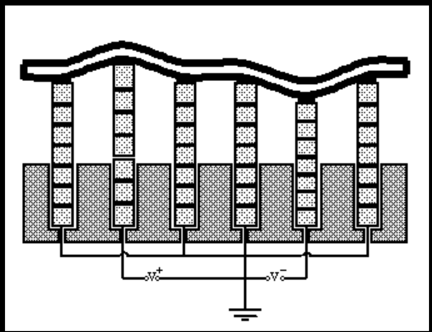


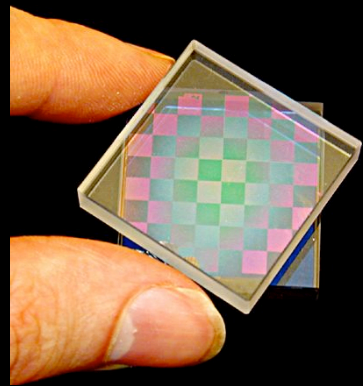
Planetary and Extrasolar Planetary Science with Adaptive Optics

J.-L. Beuzit[1], G. Chauvin[1], A.-M. Lagrange[1], F. Marchis[2], D. Mouillet[1]

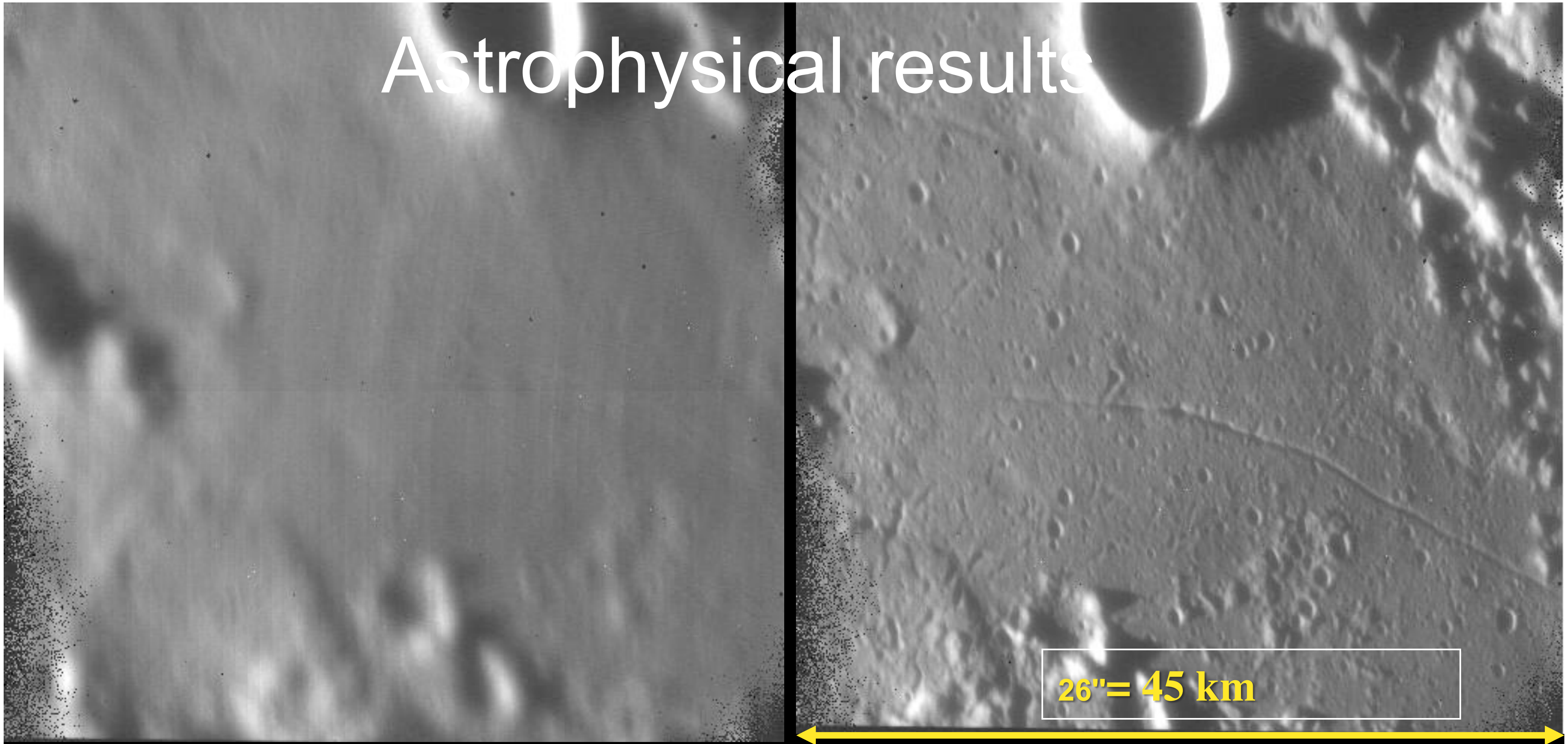
1) LAOG

2) UC Berkeley





Astrophysical results

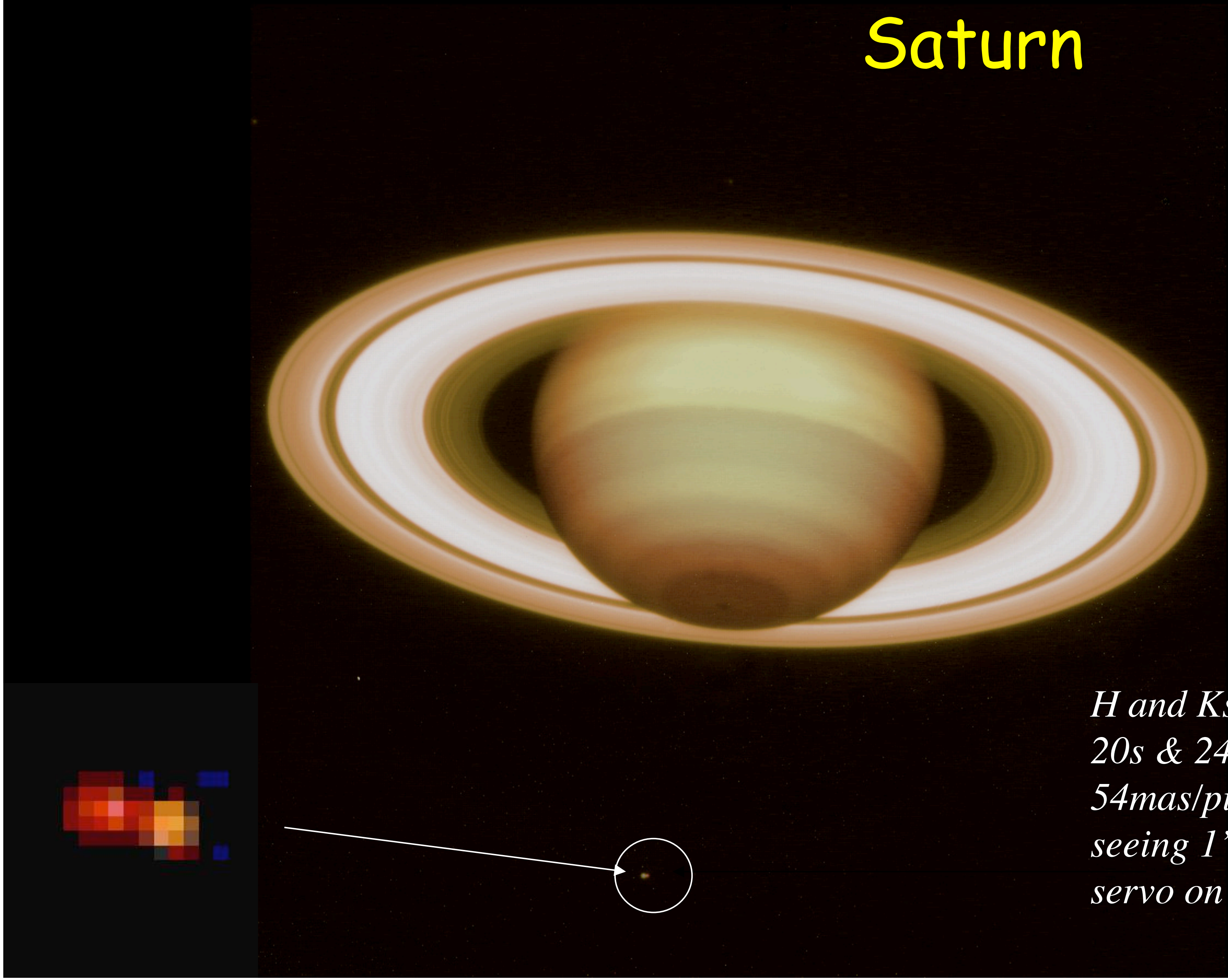


Open loop
2.3 microns

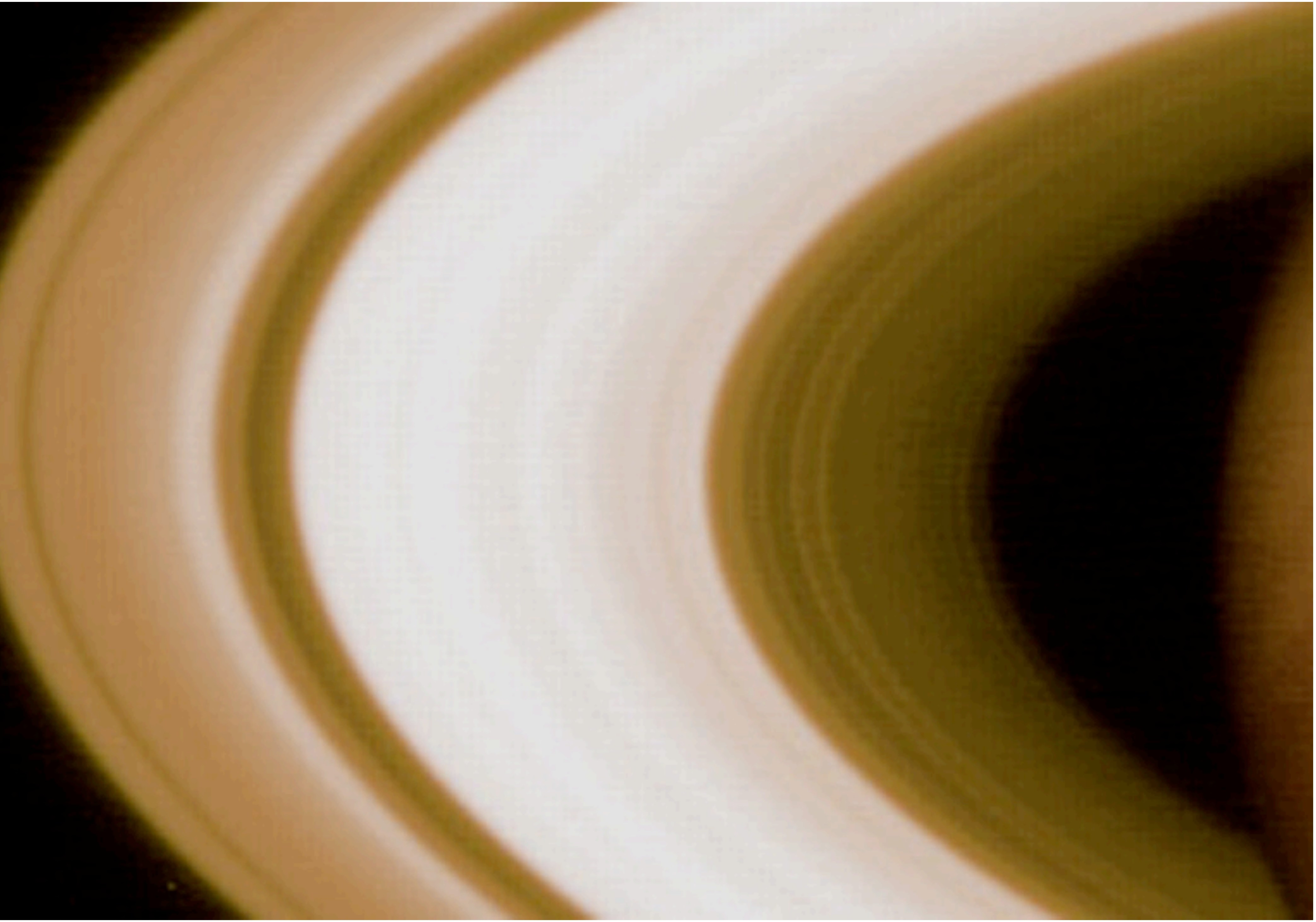
Closed loop
2.3 microns

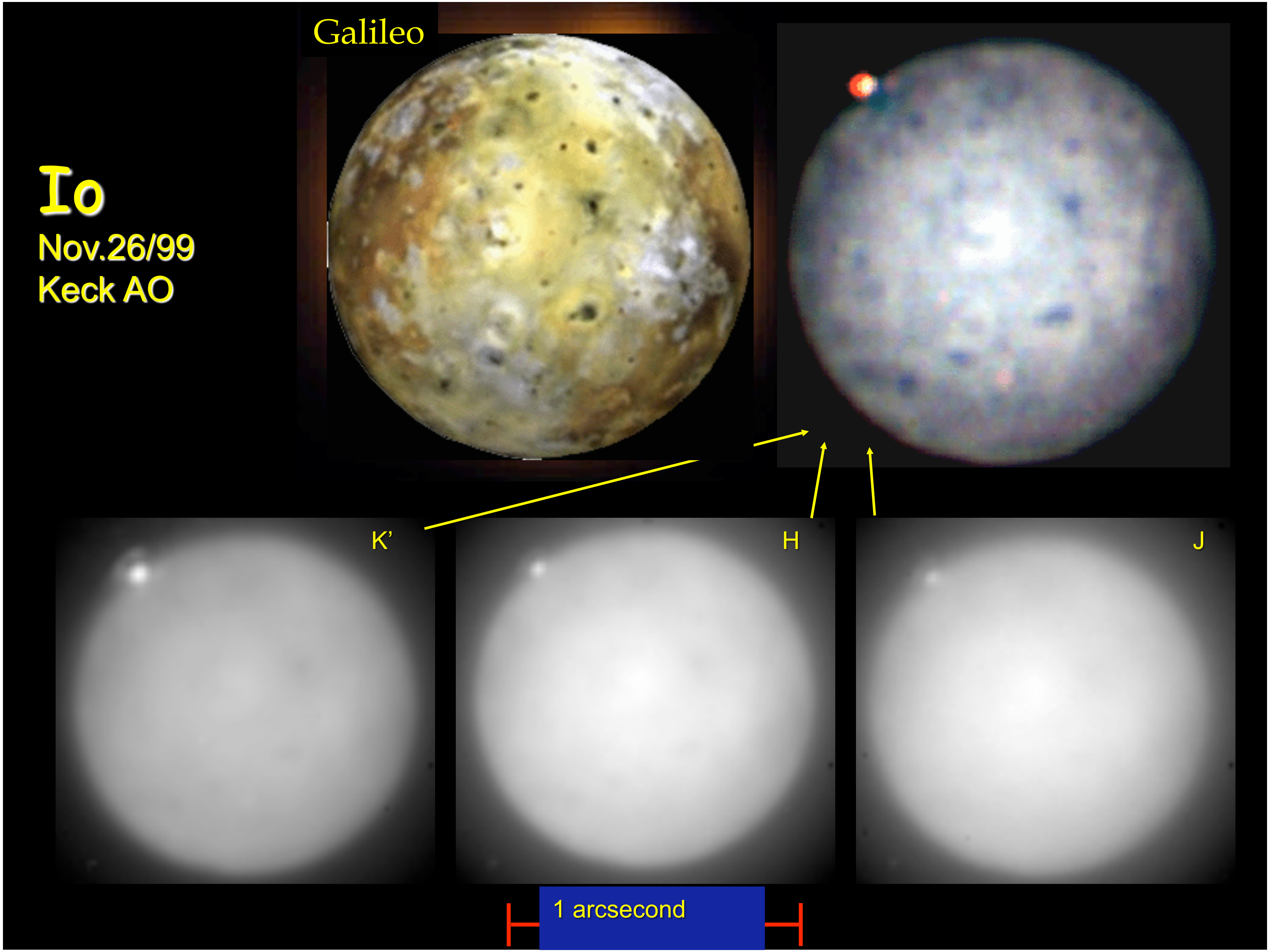
WF sensing on bright lunar peak 20" south of FoV center (3" to 4” diam)

Saturn



H and Ks
20s & 24s
54mas/pix
seeing 1”
servo on Thetys

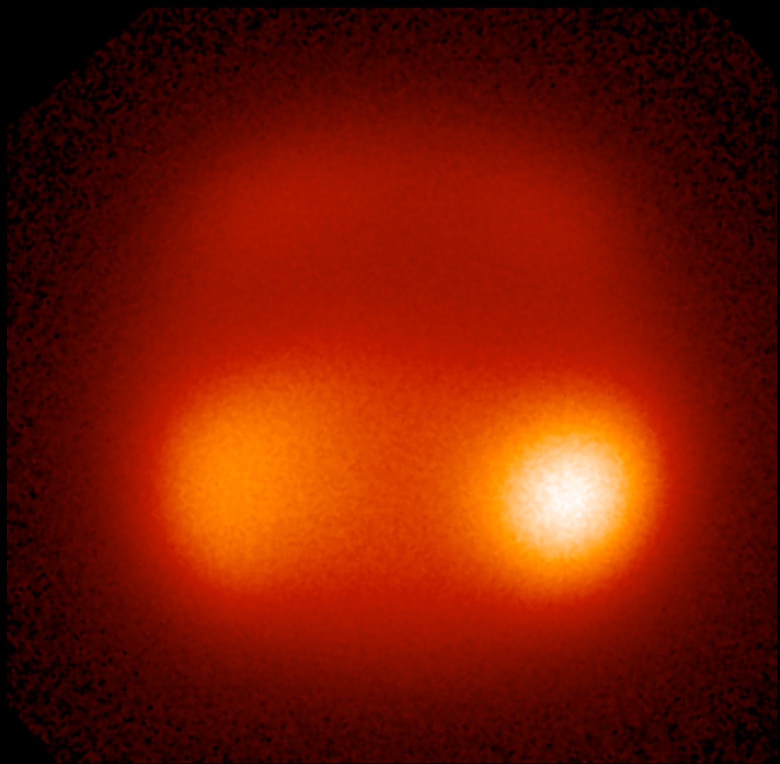




Io
Nov.26/99
Keck AO
Galileo
K'
H
J
1 arcsecond

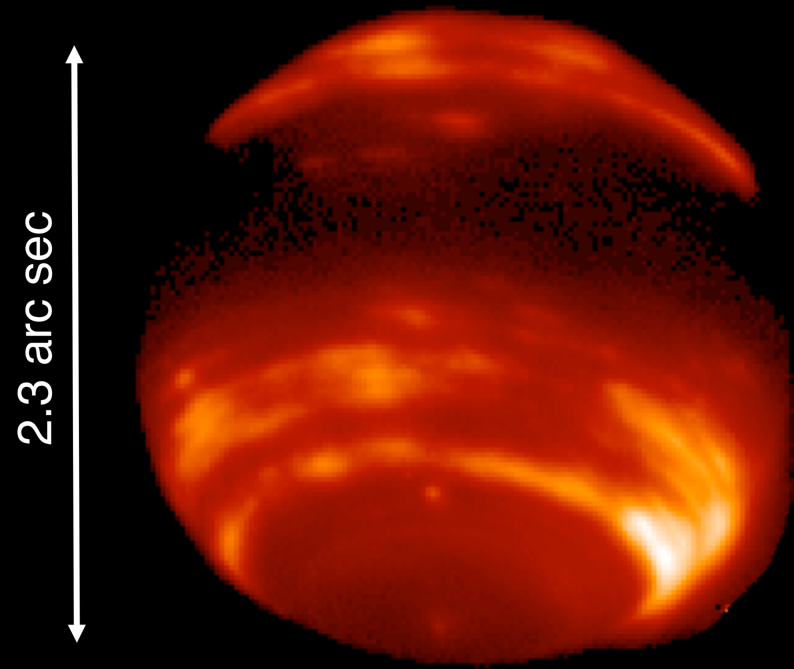
Neptune in infra-red light (1.65 microns)

Without adaptive optics



May 24, 1999

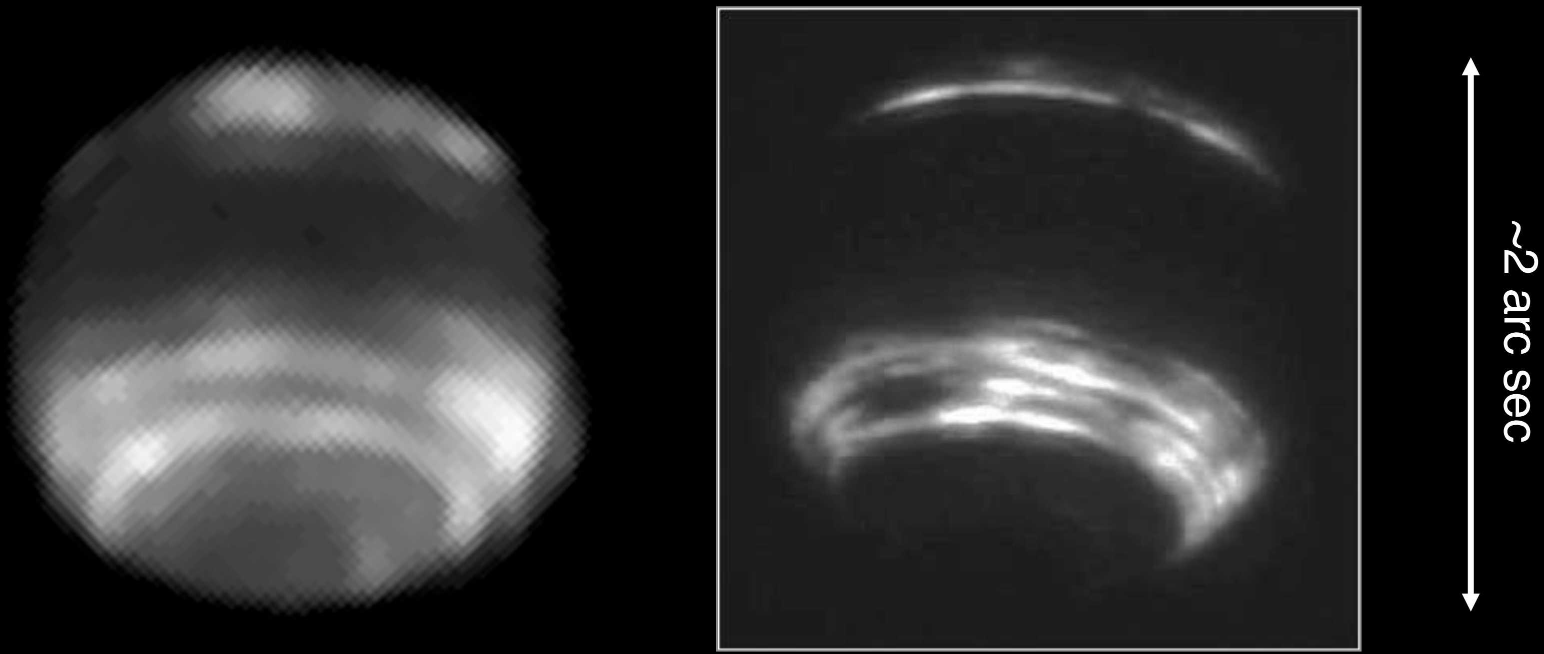
With Keck adaptive optics



June 27, 1999

Neptune at 1.6 μm: Keck AO exceeds resolution of Hubble Space Telescope

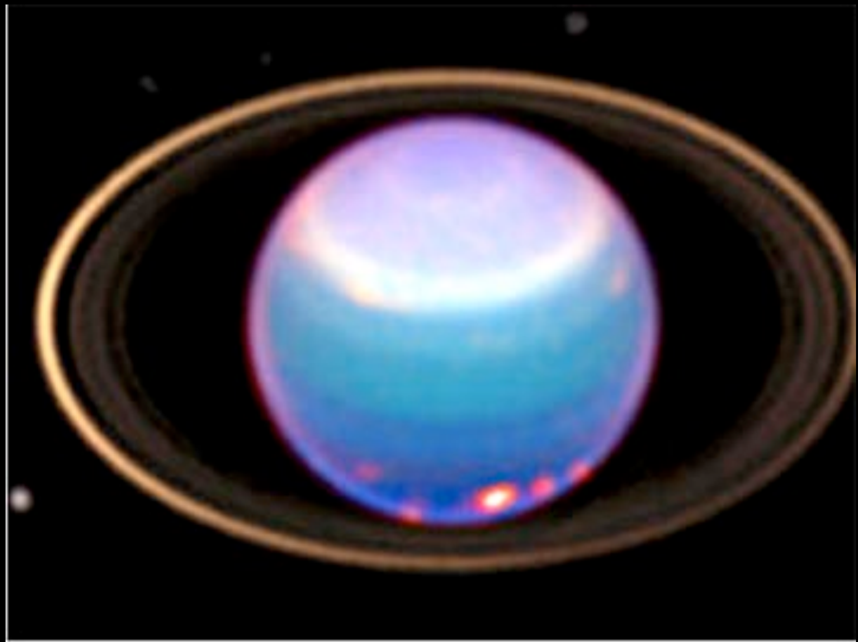
HST - NICMOS Keck AO



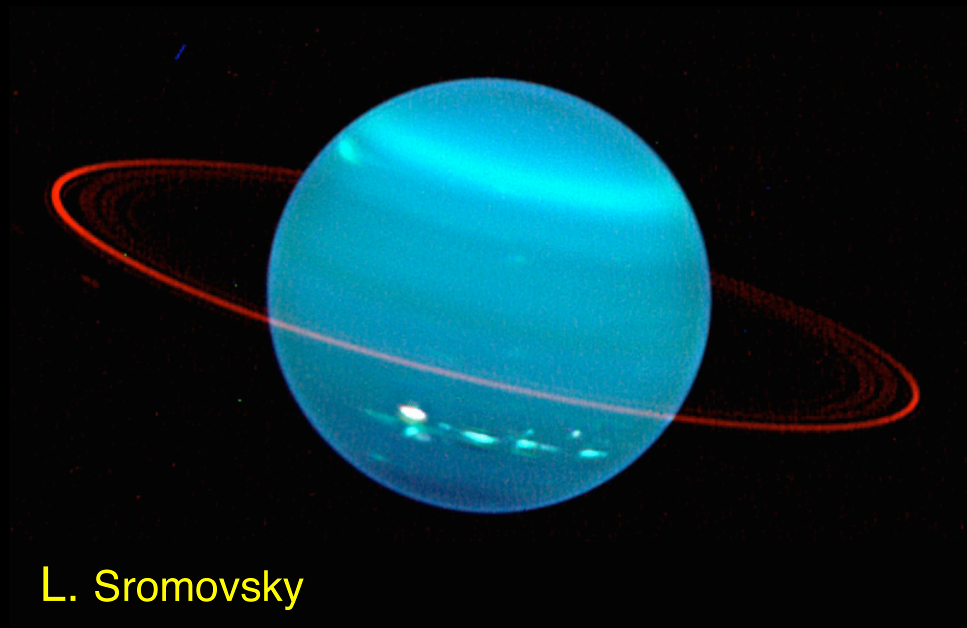
2.4 meter telescope 10 meter telescope

(Two different dates and times)

Uranus with Hubble Space Telescope and Keck AO



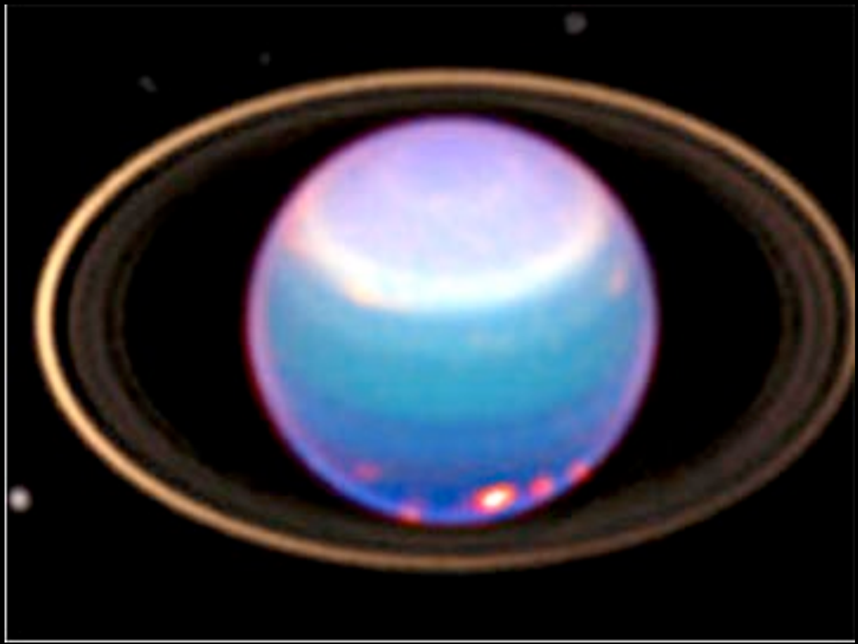
HST, Visible



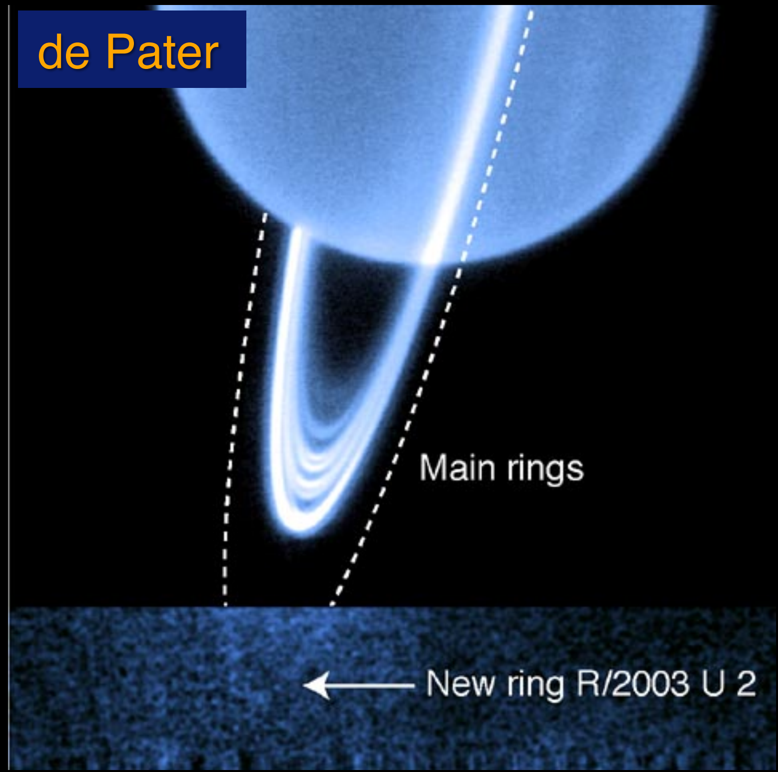
Keck AO, IR

Lesson: Keck in near IR has ~ same resolution as Hubble in visible

Uranus with Hubble Space Telescope and Keck AO

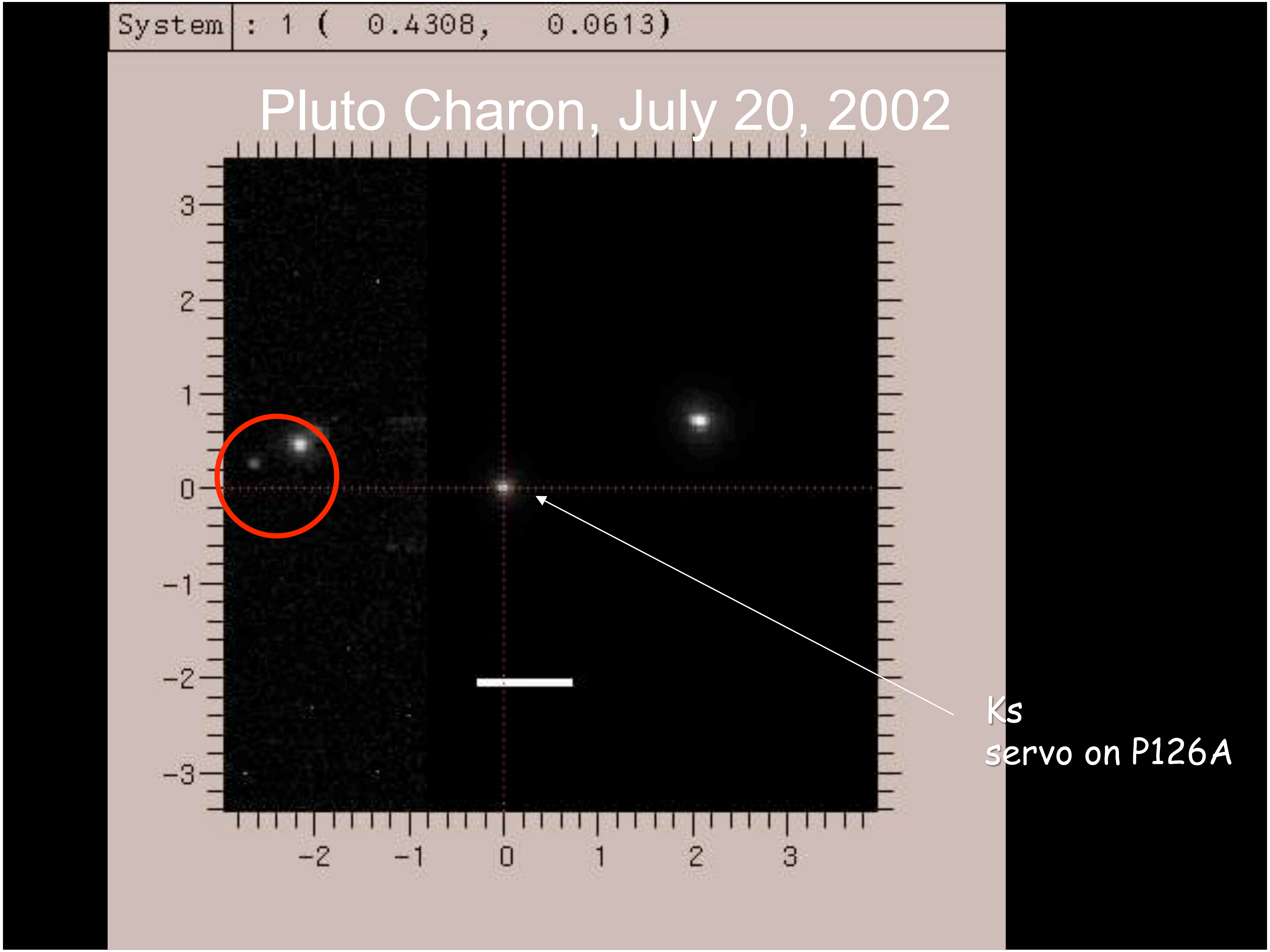


HST, Visible

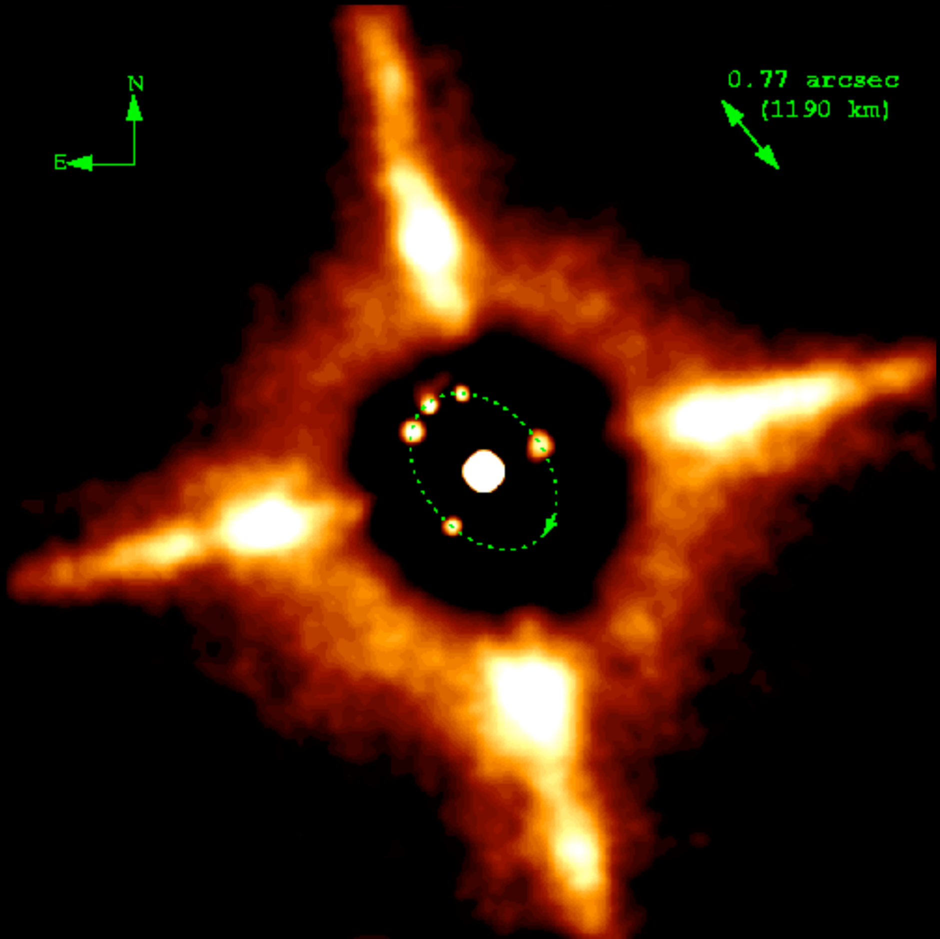


Keck AO, IR

Lesson: Keck in near IR has ~ same resolution as Hubble in visible


System : 1 (0.4308, 0.0613)
Pluto Charon, July 20, 2002
3
2
1
0
−1
−2
−3
−2
−1
0
1
2
3
Ks
servo on P126A

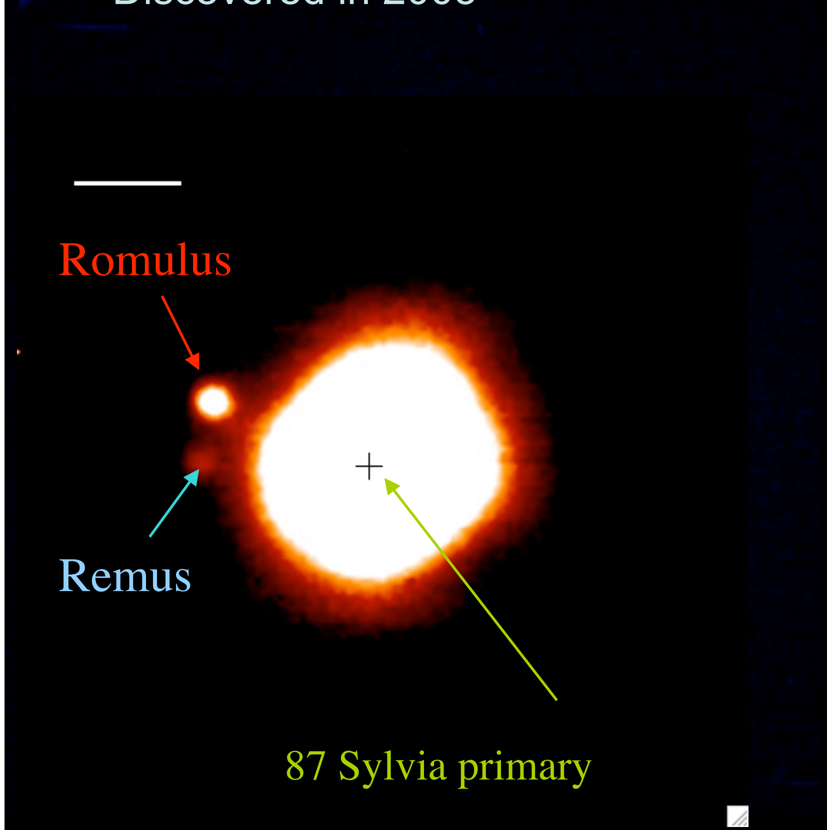
Multiple asteroids



Double asteroid, PUEO, Merline et al. (2000)

The First triple asteroid System: 87 Sylvia

(87) Sylvia
Discovered in 2005



S/2001 (87)1 - Romulus

- D_1=18 ±4 km
- a_1 = 1356 ± 5 km = 1/50 x R_{hill}
- P_1 = 3.6496 ± 0.0007 days

S/2004 (87)1 - Remus

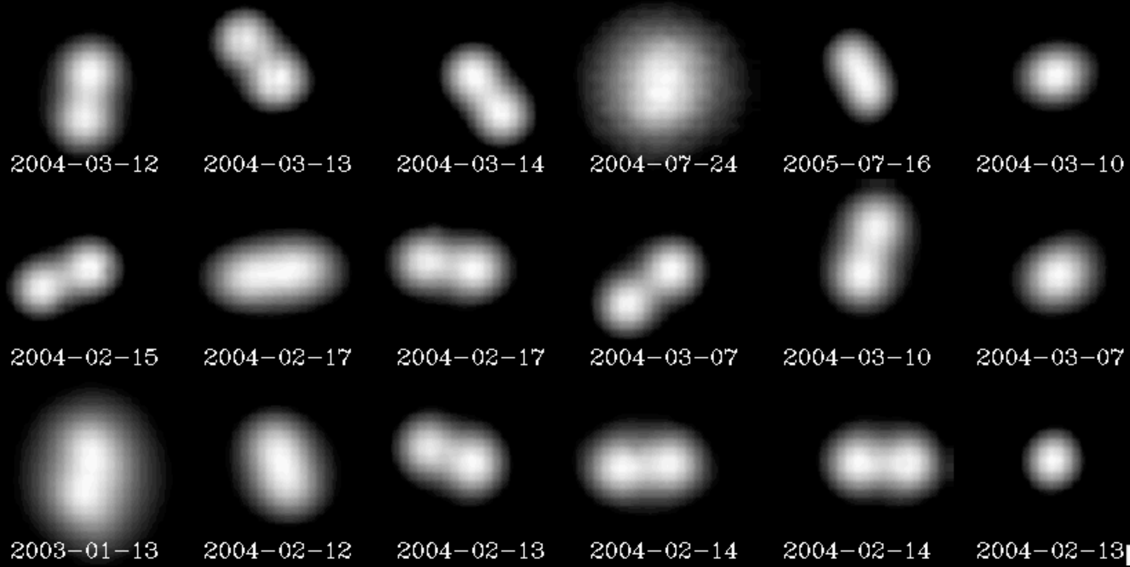
- D_2= 7 ± 2 km
- a_2 = 706 ± 5 km = 0.52 x a_1
- P_2 = 1.3788 ± 0.0007 days

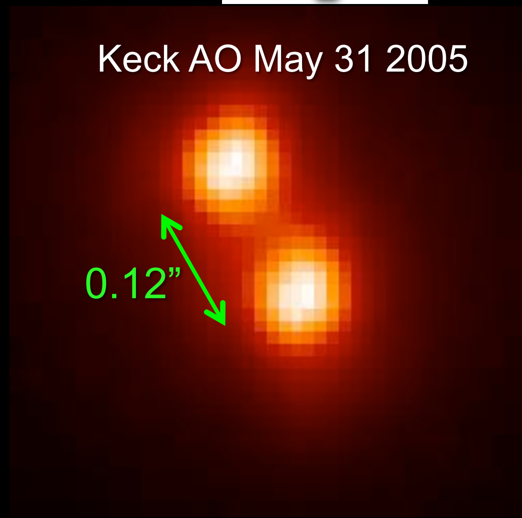
-> coplanar, prograde and equatorial orbits
-> damped by tidal effect
-> precession of the inner moon observed due to oblateness (elongated shape) of the primary

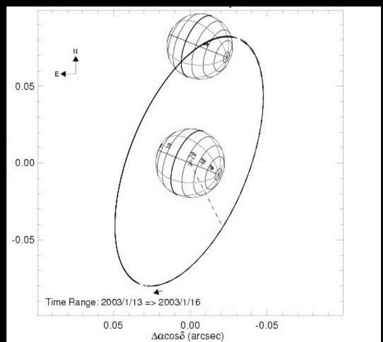
- 5-body numerical simulation showed that the system is stable because of the oblateness of the primary (Winter et al., 2009)
- We discovered new triple systems (45 Eugenia in 2006 with NACO , 216 Kleopatra in 2008 with Keck AO, 93 Minerva in 2009 with Keck AO)
- reference: Marchis et al, Nature, 2005

Double System 90 Antiope

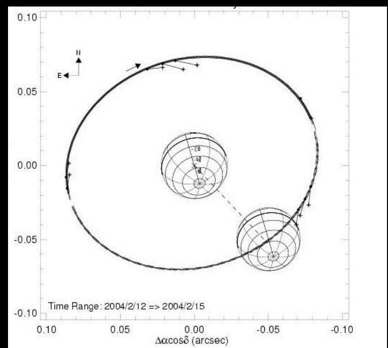
- Discovered in 2001 by Merline et al. (IAU, 2001)
- 17 AO Observations since 2003 with VLT/NACO & Keck AO
- Estimated orbit P=16.505 h, a=171 km = a_{synch}, e=0 (3 mas rms error)



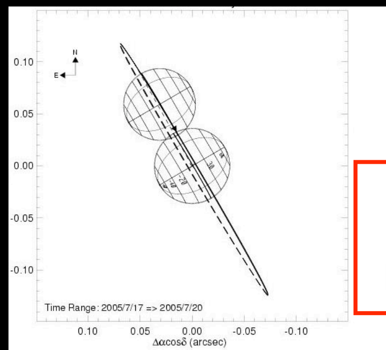




January 2003



Feb-March 2004



July 2005

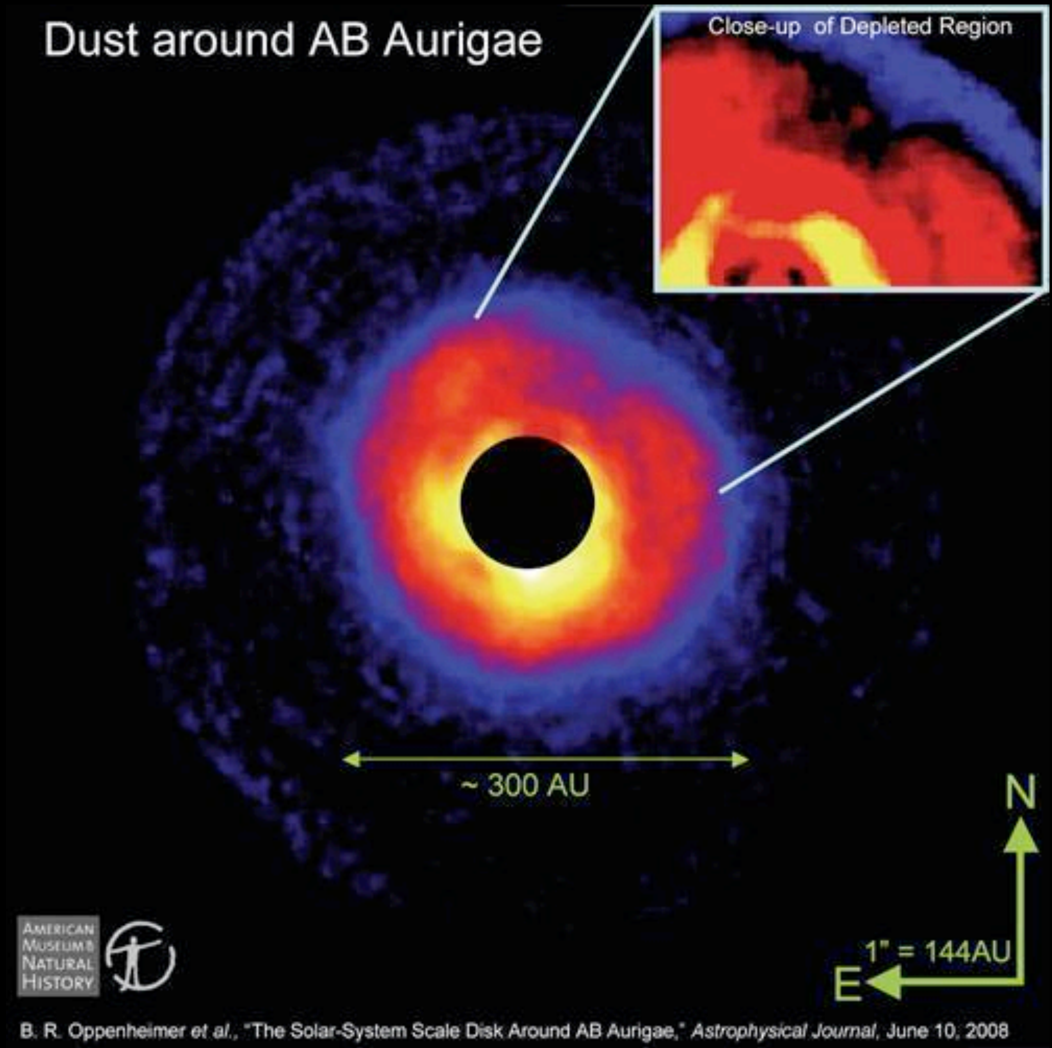
Predicted mutual events!

Planetary disks

- Debris disks *discovered* from space and AO assisted ground based telescopes
- Best images of the disks in the > 1” range obtained with HST
  - PSF stability
- AO on 10 m class
  - Inner parts of the disks (<1”) : new coronagraphs / XAO
  - Search for planets
    - Indirect search:
      - structures at high spatial resolution in the inner disks
    - Direct search
      - high angular resolution, high contrast near IR imaging
      - high angular resolution thermal IR images

Signatures of planets in disks

Disk structures at high spatial resolution



AB Aur (~145 pc; ~4 Myr)

Disk detected down to 43AU

Depleted region at ~0.8" (110AU)

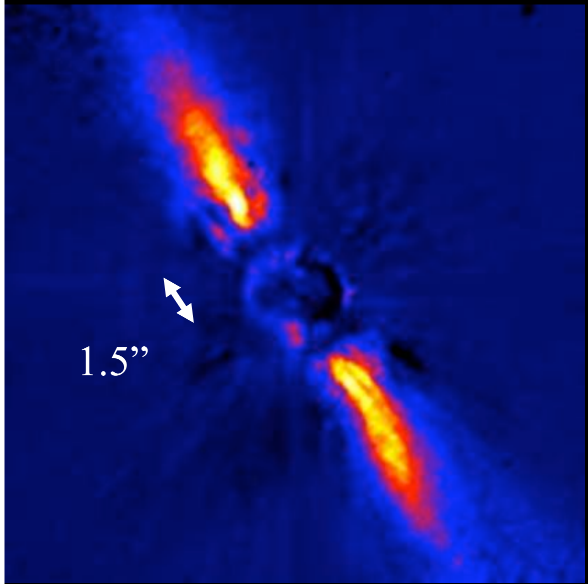
5-37 MJup

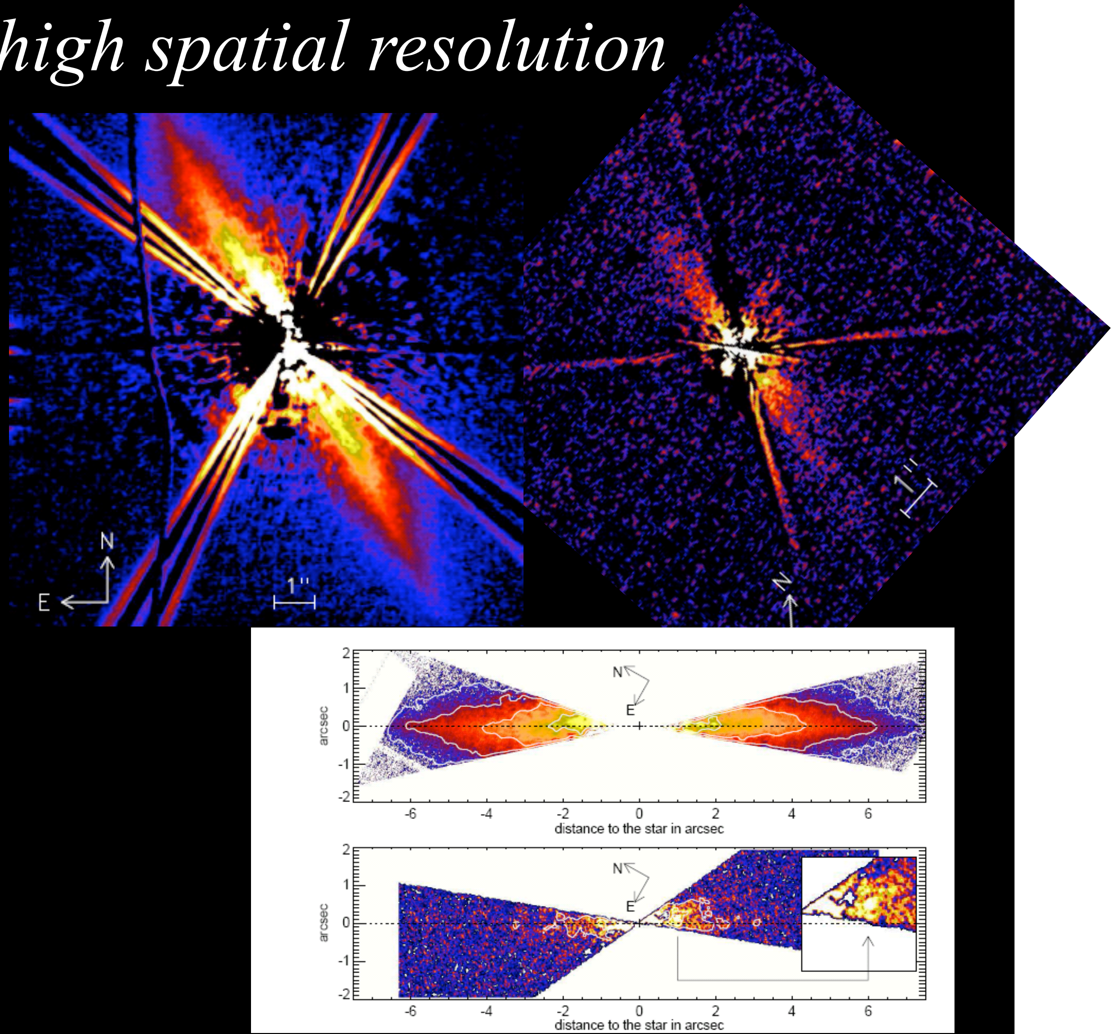
Formation of a DB companion?

(Oppenheimer et al, 2008)

Signatures of planets in disks

Disk structures at high spatial resolution





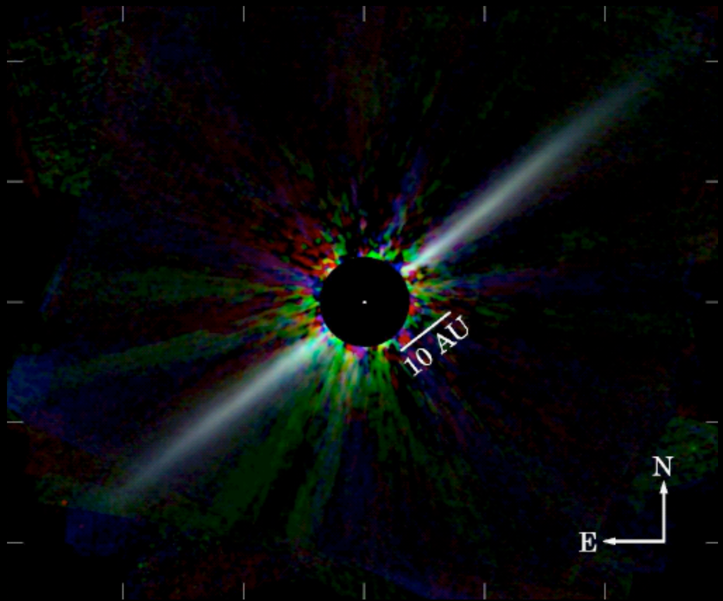
Adonis@3.6m

(Mouillet et al, 96)

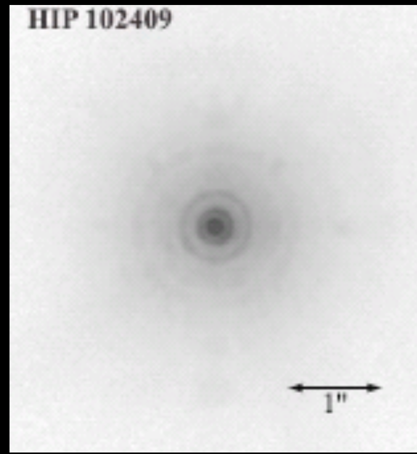
Naco@VLT (Lyot/4QPM)

(Boccaletti et al, 2008)

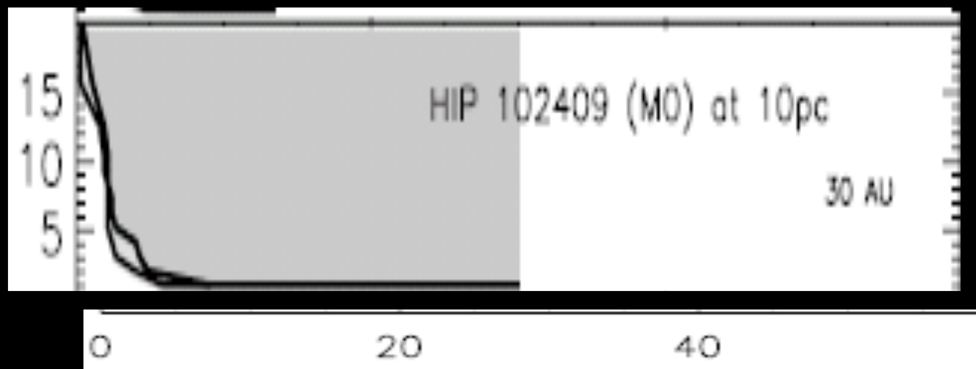
Signatures of planets in disks
Search for planetary/BDs companions



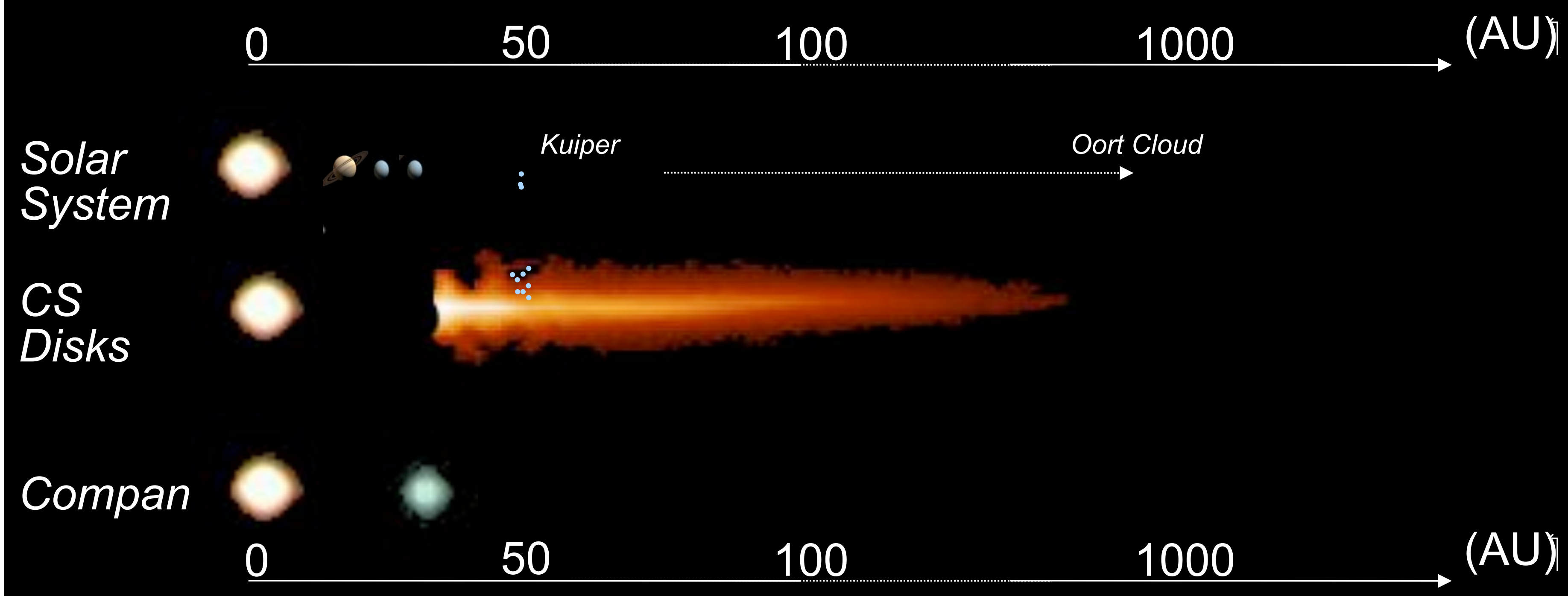
AU Mic



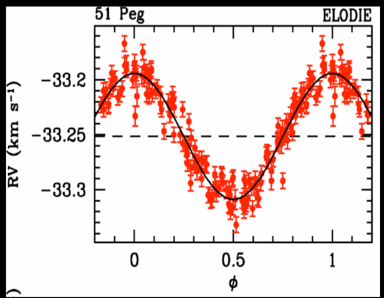
NACO; L band
No planet > 1 Mjup, > 5AUs
Kasper et al (2007)



Keck AO
Fitzgerald et al (2007)
(see also Metchev et al, 2005)

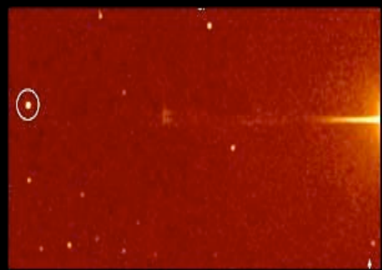


RV, Transit,
Micro-lensing (< 5 AU)

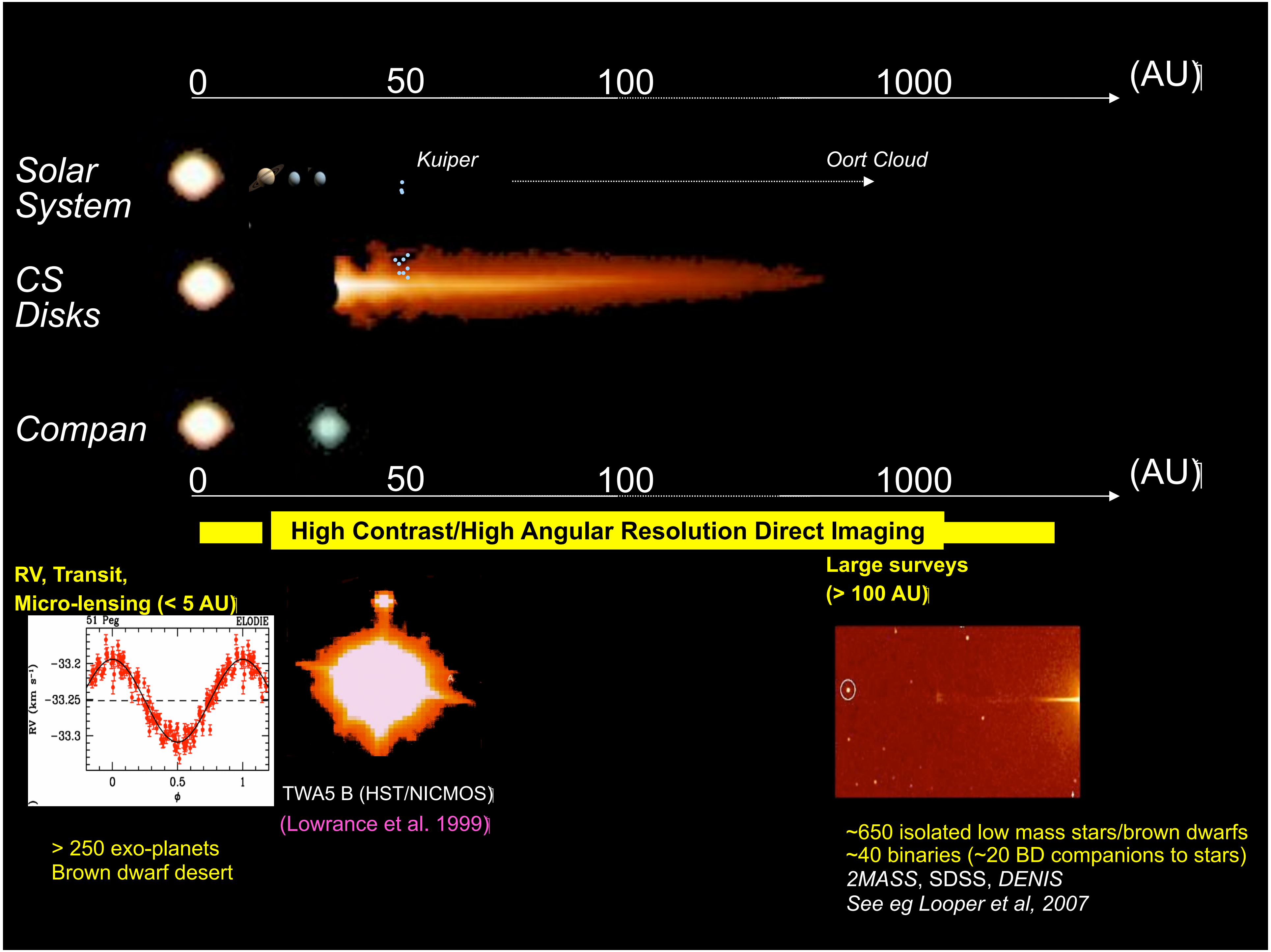


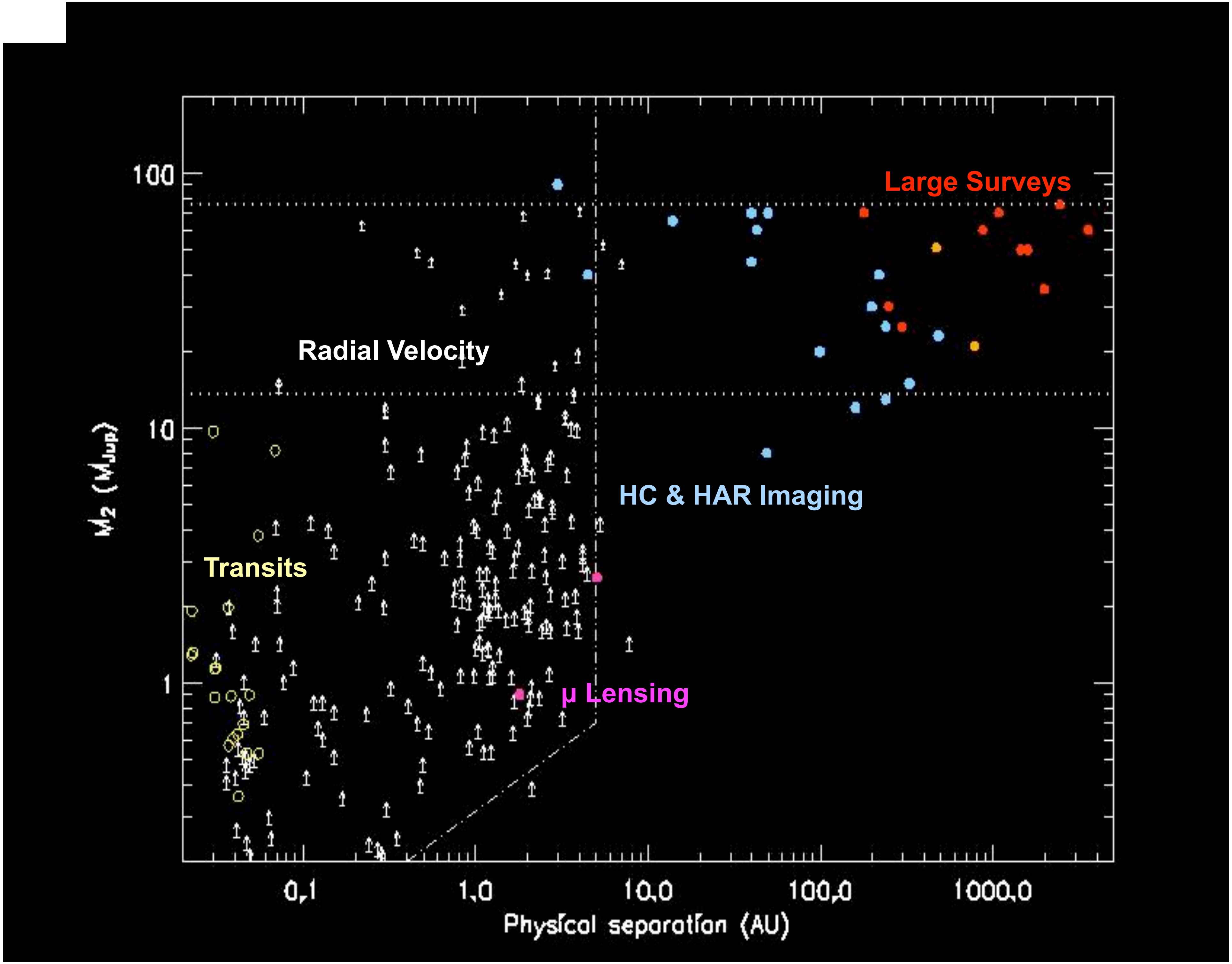
> 250 exo-planets
Brown dwarf desert

Large surveys
(> 100 AU)



~650 isolated low mass stars/brown dwarfs
~40 binaries (~20 BD?)
2MASS, SDSS, *DENIS*
See eg Looper et al, 2007


0
50
100
1000
(AU)
Solar System
Kuiper
Oort Cloud
CS Disks
Compan
0
50
100
1000
(AU)
High Contrast/High Angular Resolution Direct Imaging
RV, Transit,
Micro-lensing (< 5 AU)
51 Peg
ELODIE
−33.2
−33.25
−33.3
RV (km s⁻¹)
0
0.5
1
ϕ
> 250 exo-planets
Brown dwarf desert
TWA5 B (HST/NICMOS)
(Lowrance et al. 1999)
Large surveys
(> 100 AU)
~650 isolated low mass stars/brown dwarfs
~40 binaries (~20 BD companions to stars)
2MASS, SDSS, DENIS
See eg Looper et al, 2007



Large Surveys
Radial Velocity
HC & HAR Imaging
Transits
µ Lensing
100
10
1
M2 (MJup)
0.1
1.0
10.0
100.0
1000.0
Physical separation (AU)

Direct detection & characterization of planets

Why direct imaging ?

- Advantages
  - Planet photons are detected F(Teff, masse, age)
  - Detection is fast (do not need to wait for a full period)
  - Orbit parameters and mass determination via photometry *(model dependant)*
  - Direct mass determination when coupled to RV data (dynamical masses)
  - Atmosphere characterization:
    - temperature, chemical composition, albedo

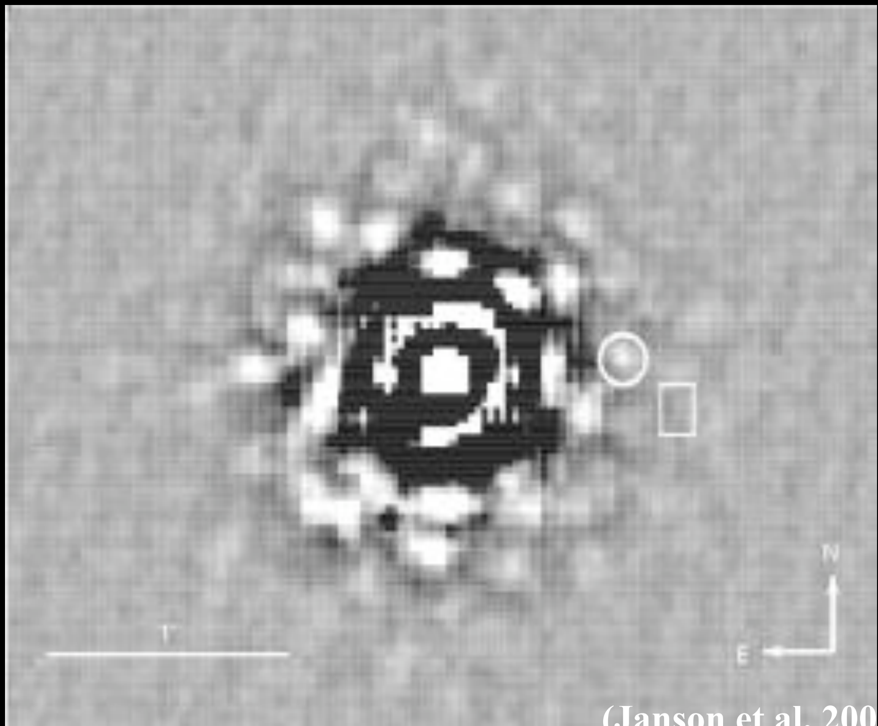
    ⇒ test of atmospheric models & evolutionary models (age)

- Complementarity with other techniques (RV, astrometry)
  - Targets types, no inclination ambiguity
  - Information obtained
  - Interest for coupling those techniques whenever possible

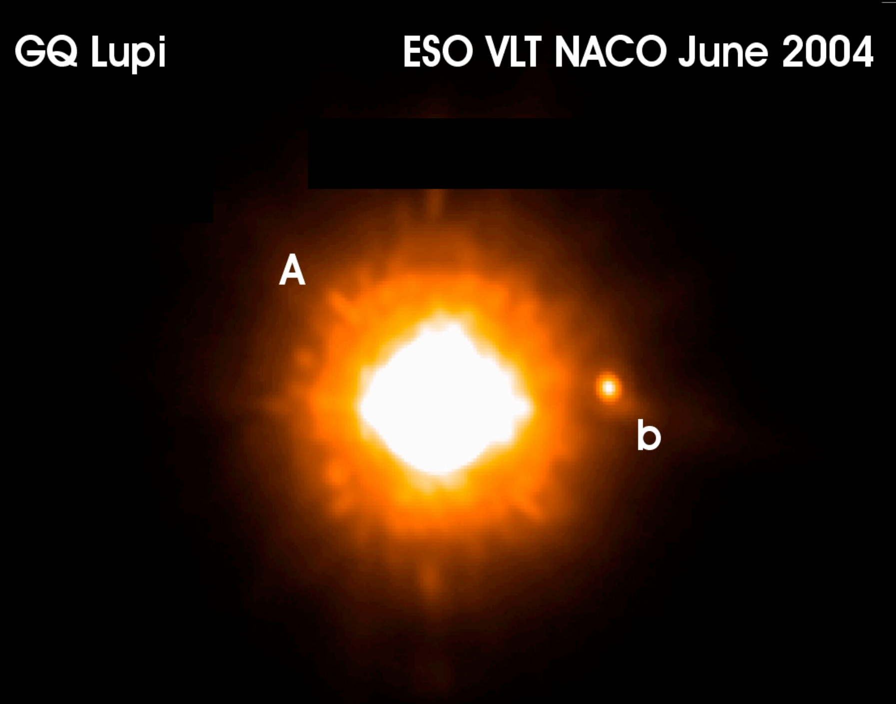
Larger telescopes, improved AO systems

ESO3.6m/Come-On+ 1994

VLT/NACO 2005



(Janson et al. 2007)

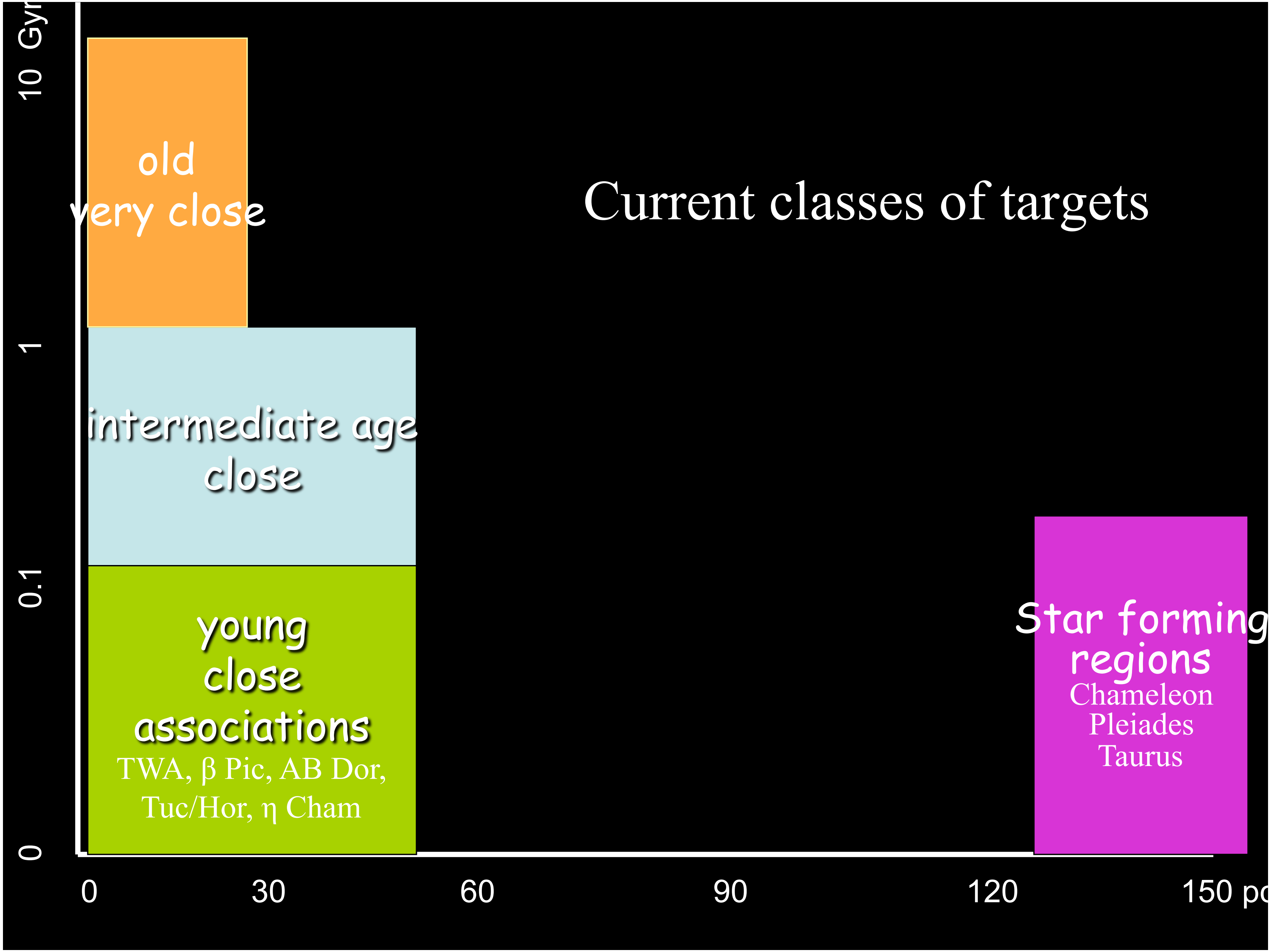


(Neuhäuser et al 05)

Direct detection & characterization of planets

Specific advantages of AO observations

- Ground based telescopes equipped with AO
  - Near IR wavelengths+ thermal IR well suited for planet/ BD detection *and*
  - High spatial resolution => possibility to investigate the close vicinity of the stars
- Significant progress since the 90's
  - Larger telescopes and improved AO systems
  - Improved coronagraphic devices (phase masks; SDI, etc) => enhanced dynamical range => detect fainter & closer



Current classes of targets
10 Gyr
1
0.1
0
0
30
60
90
120
150 pc
old
very close
intermediate age
close
young
close
associations
TWA, β Pic, AB Dor,
Tuc/Hor, η Cham
Star forming
regions
Chameleon
Pleiades
Taurus

0.1-10 Gyr stars

AO surveys

0.1-1 Gyr

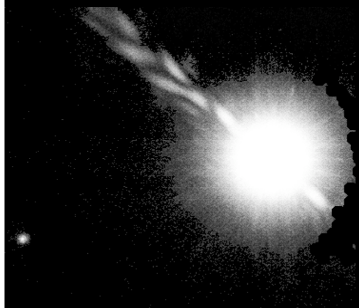
- Gemini/Hokupa'a	Classical	31	Potter et al. (2002)
- Keck/NIRC	AO-Corono	102	McCarthy & Zuckerman (2004)
Lick/GEMINI	AO-Corono	178	
-Subaru/CIAO	AO-corono		Nakajima et al (2005)
-Palomar PALAO	AO-Corono	101	Metchev et al. (2005, 2006)
KeckII/NIRC2			

Typical detection limits: MB ~ 10 Mjup @ 10 - 20 AU => BDs

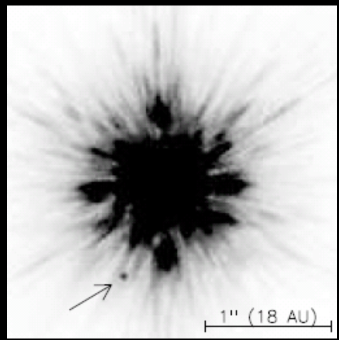
1-10 Gyr

- Gemini/Hokupa'a	AO-Classical	39	Close et al. (2002, 2003)
- VLT/Gemini/Subaru	AO-Classical	36 (<30 pc)	Siegler et al., (2003, 2005)
- CFHT/PUE'O	AO-Classical	(<12 pc)	Beuzit et al. (2004)
-Gemini/Altair-NIRI	AO-Saturated	41 (<20pc)	Daemgen et al. (2007) Myrs)
- VLT/NACO	AO-Classical/SDI		*Biller et al. (2006); Montagnier et al. (2006)*
-*(+HST eg Lowarance, 2005)*			

Typ. detection limits: 20 Mjup (1Gyr)/ 60 Mjup (10 Gyr) @ 1 - 10 AU => BDs



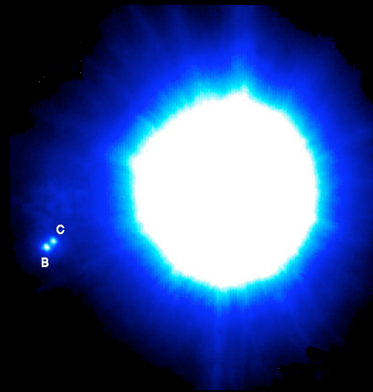
HD203030 B
40 pc
0.13-0.4 Gyr
15-34 MJup
490 AUs
Palao/Palomar
Unusually cool (1200 K)
(Metchev et al 2006)



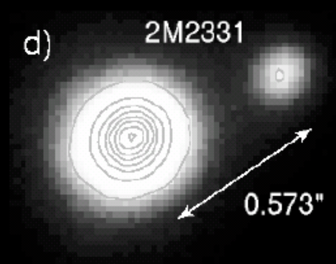
HR7672 B

>0.1 Gyr
~60 MJup
14 AUs
Gemini/Keck
(Liu et al 2002)

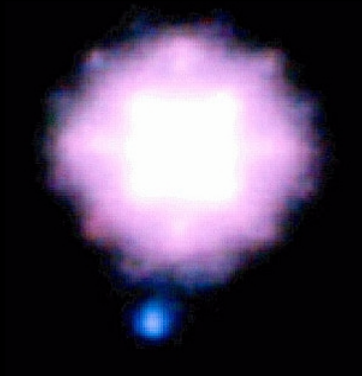
HD49197 B
45 pc
~0.5 Gyr
~60 MJup
43 AUs
Palao/Palomar
(Metchev et al 2004)



HD130948 BC
19 pc
<0.8 Gyr
Binary BD: 75 + 65 Mjup
52AU/bin 2.4 AUs
Hokupa'a/Gemini
(Potter et al 2002)



2M2331
5 Gyr
~62 MJup @ ~ 14 AUs
25 pc
Parent star: M8
Hokupa'a/Gemini
Close et al (2002)



SCR1845 B
0.1-10 Gyr
8-60 MJup @ ~ 5 AUs
3.8 pc
Parent star: M8
NACO/SDI
Biller et al (2006)

Search for BDs/planets around old stars hosting planets
AO surveys

• Targets: stars with RV planets: 0.1 - 10.0 Gyr; close-by (< 50 pc)

KeckII/kCam AO	Saturated	25	Luhman & Jayawardhana (2002)
- NTT/Sofi	Classical-Saturated	-	Mugrauer et al. (2004, 2006, 2007)
- VLT/NACO	AO-Corono	26	Chauvin et al. (2006, 2007)
- Spitzer	Classical-midIR	48	Luhman et al. (2006)
VLT/NACO	AO-SDI		Montagnier et al (2008)

• Typ. detection limits: 20 Mjup (1Gyr) ; 60 Mjup (10 Gyr) @ 10-20AU

• No BD found with AO, but

- One distant (>450 AU) BD found around HD3651 (Mugrauer et al, 05); mass estimated from spectroscopy ~60 MJup (Leggett, 2007)
- One distant (1520AU) BD found around GL 570: mass estimated from Leggett ~40 MJup (+2 M dwarfs); (Burgasser 2003; Leggett 2007)

Young (<0.1 Gyr), close (< 100 pc) associations

AO searches

- Keck/NIRC	*AO-Corono*	*-*	*MacIntosh et al. (01); Kaisler et al. (01)*
- ESO3.6m/ADONIS	*AO-Corono*	*29*	*Chauvin et al. (2002, 2003)*
- NTT3.5m/Sharp	*Saturated*	*32*	*Neuhäuser et al. (2003, 2005)*
- VLT/NACO	*AO-Saturated*	*28*	*Masciadri et al. (2005)*
- VLT/NACO	*AO-Lp*	*22*	*Kasper et al. (2007)*
-*VLT & MMT*	*AO-SDI*	*45*	*Biller et al. (2007), Close et al. (2005)*
-Gemini/GPDS	AO-ADI	85	Lafrenière et al (2007)
- VLT/NACO	AO-Corono	-	*Melo et al.; Chauvin et al.*
- Gemini/NICI	AO-Corono	-	*Liu et al.*

Typ. detection limits:
~3-5 M_{jup} @ 10 - 40 AU (1 MJup, 5AU at L band)=> Planets and brown dwarfs

Few BDs and planetary mass objects detected

Young (<0.1 Gyr), close (< 100 pc) associations

Observations of brown dwarfs/planetary mass companions with AO

GSC8057 B
50 Myr
~30 MJup
200AU
Naco/VLT
(Chauvin et al 2003)

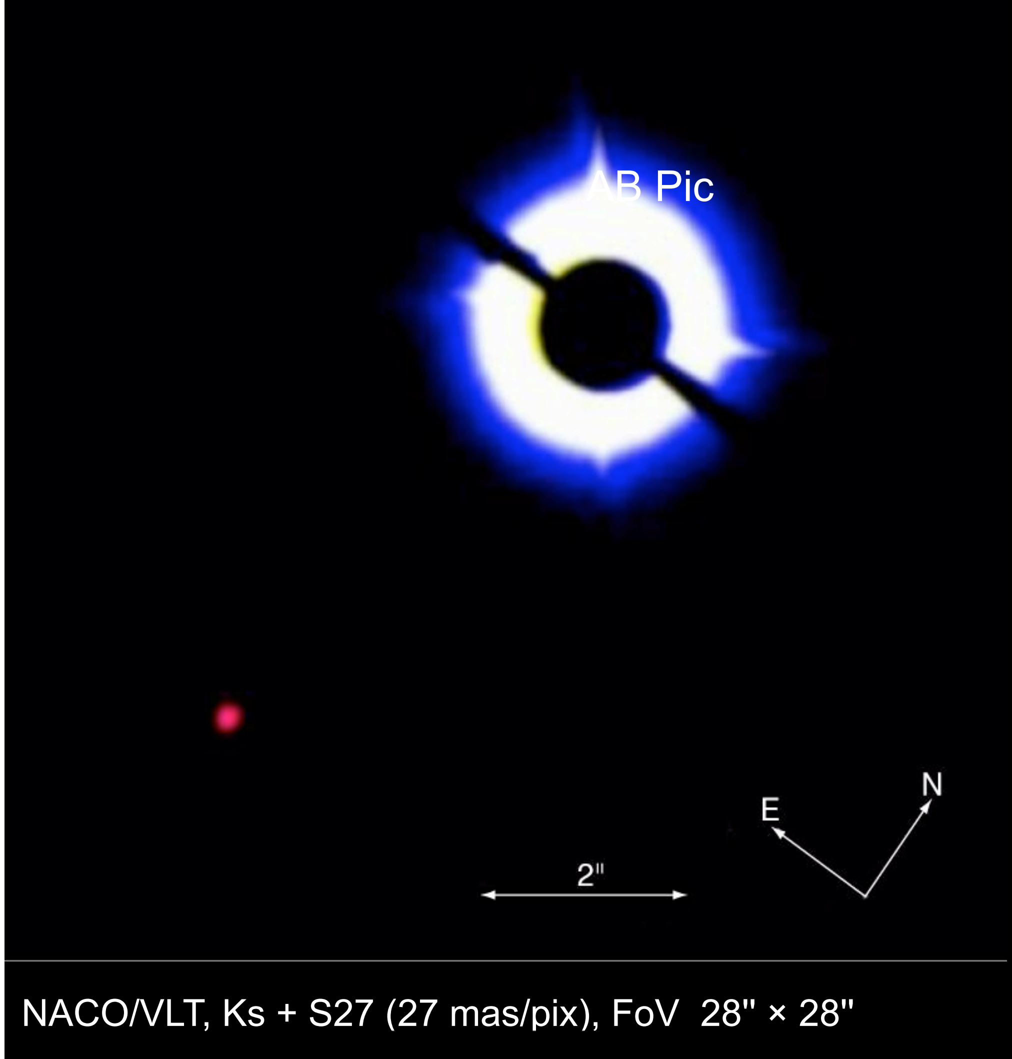
ABPic B
~30 Myr
13 MJup
250 AU
Naco/VLT
(Chauvin et al 2005)

2M1207
~8 Myr
~5 MJup
55 AU
Naco/VLT
(Chauvin et al 2004)

In addition to young bound BDs found with HST

- TWA5 B (10 Myr; 20 MJup; 100 AU; Lowrance et al 1999)
- HR7329 B (<30 Myr; 50 MJup; 200AU; Lowrance et al 2000)

A very low mass brown dwarf around the young star AB Pic



M ~ 13.5-20 Mjup

Spectral type L1

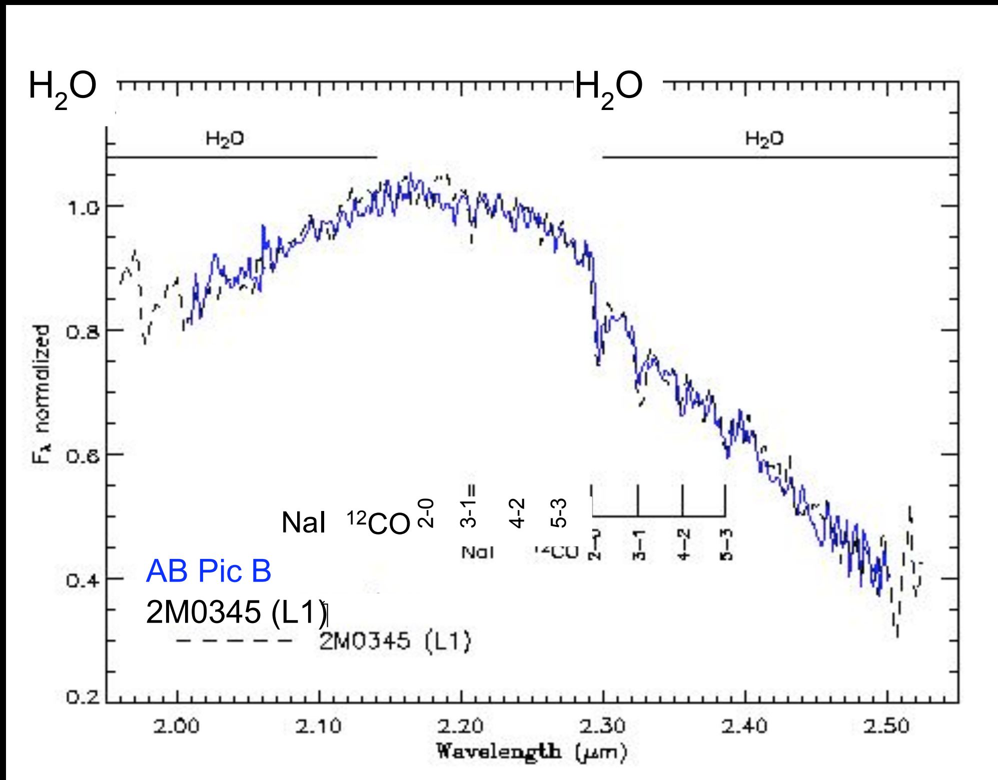
Sep: 270 AU

(Chauvin et al.,2005)

! Use of stellar evolutionary models !

Low mass Brown dwarf around the young star AB Pic
Investigating AB Pic B atmosphere

Identification of atomic and molecular lines: H_20, CO, CH_4, FeH, NaI, CaI, KI…
Confirmation of a cool atmosphere



A planetary mass companion to 2Mass 1207B

TWHya association

MA ~ 24 MJup

5-12 Myr

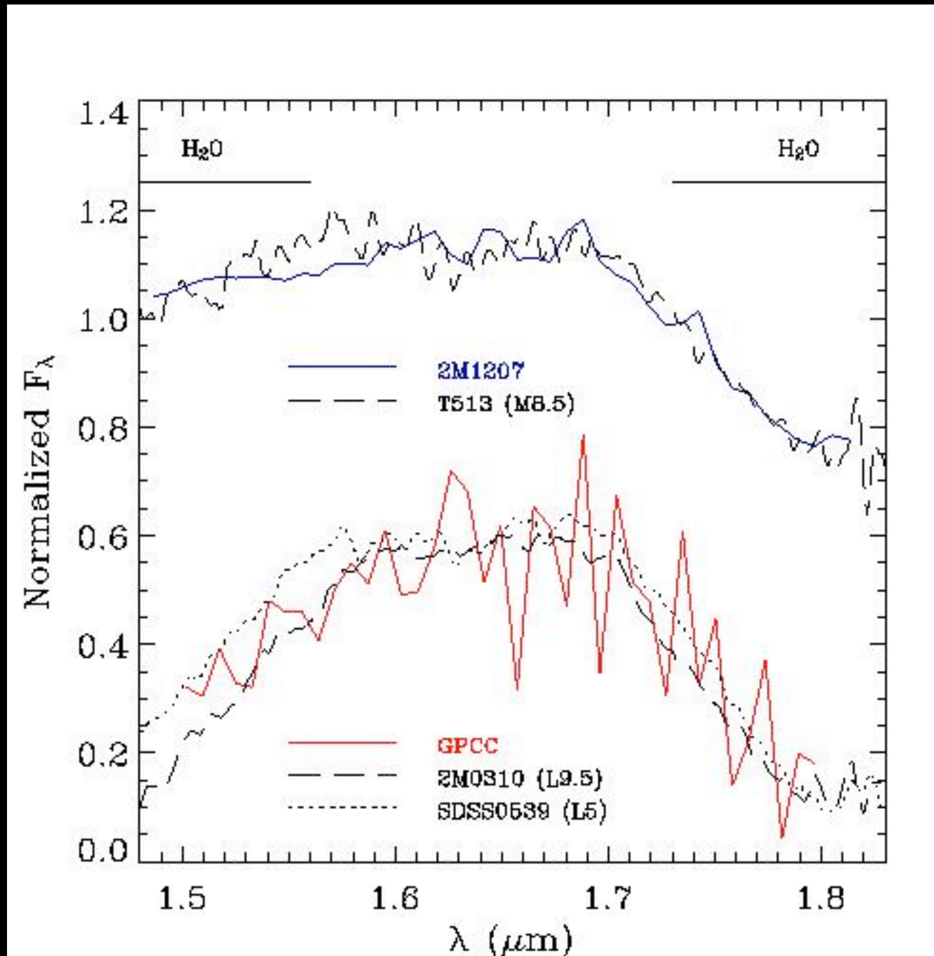
70 pc

MB ~ 8 MJup

Sep ~55 AU

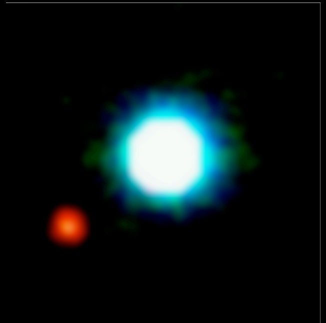
Naco/VLT, IR WFS

A planetary mass companion to 2Mass 1207
Investigating 2Mass1207 B atmosphere



(Chauvin et al. 2005)

How did 2Mass1207 (and VLM BD) form ?
Planet and BD definition ?



- Formation scenari
  - Core-accretion (Pollack et al. 1996)
  - Disk Instability (Boss 1997)
  - Collapse/Fragmentation (stars & BDs)
- Planetary mass companions found so far did not form via core accretion/disk instability
  - Objects too far to form in a disk with reasonable mass
    - Uscoctio108: 14 MJup, 600 AU ; AB Pic: 13 MJup,275 AU; GQ Lup : 20 MJup, 100 AU
  - Disk mass required vs primary mass:
    - 2M1207B: Mdisk > 0.3 MA (=> Link with (lutra)cool BD binaries? Eg Siegler et al, 2007)
  - Timescales for planets formation at large distances too large

⇒*They formed like binaries stars*

- Most of the RV planets formed through core-accretion
  - But how did the most massive form? Also Corot planets …

Overlap between planet and brown dwarf distributions

Potential pb to characterize objects within the overlap

Planet/BD occurrence around young stars

- Occurrence of BDs
  - < 2% have DBs in the range 25-250 AUs (Lafreniere et al, 2007)*
- Occurence of planets
  - Lafreniere et al (2007)
    - <13% have planetary mass companions in the range 25-50 AUs
    - <9% have planetary mass companions in the range 25-250 AUs
    - <28% have planetary mass companions in 10-25 AUs
  - Nielson et al (2008)*: Very few giant planets at large separations
    - <20% of stars have planets with a in the range 20-100 AUs (95% confidence level)
    - <8% of stars have planets with a in the range 20-100 AUs (68% confidence level)

** Nielson et al: 60 stars from Mascriadi (2005) and Biller et l (2007) surveys*

** Lafreniere et al: 85 stars*

Star forming regions (> 100 pc)

Sensitive to brown dwarfs at most

Link with surveys for multiplicity (sub/stellar) (Bouy et al, Burgasser et al, etc)

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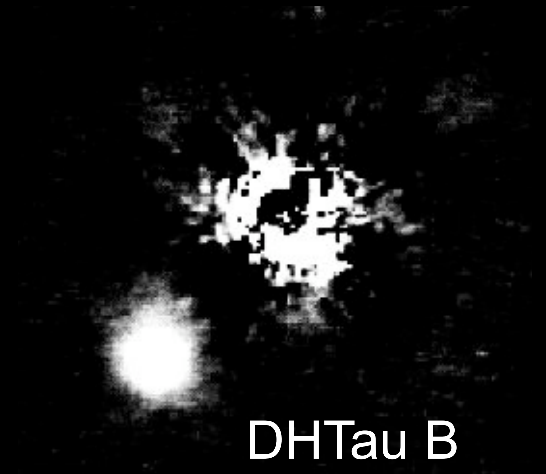
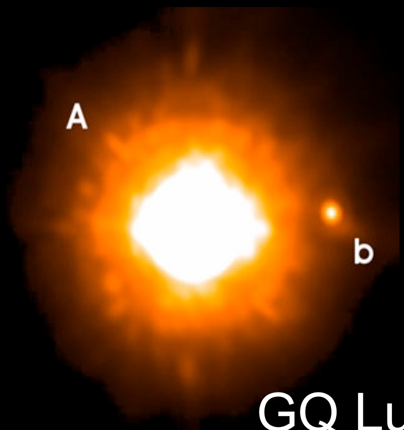


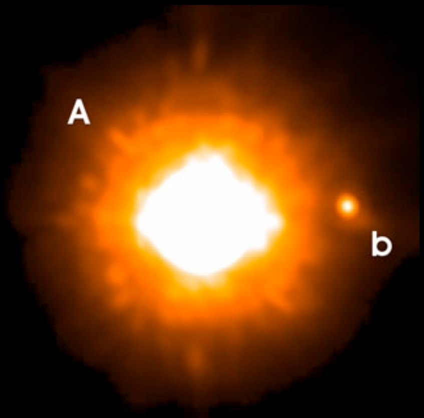
DHTau B
~150 pc
3-10 Myr
30-50*M*Jup
330 AU
Ciao/Subaru
(Itoh et al 2005)

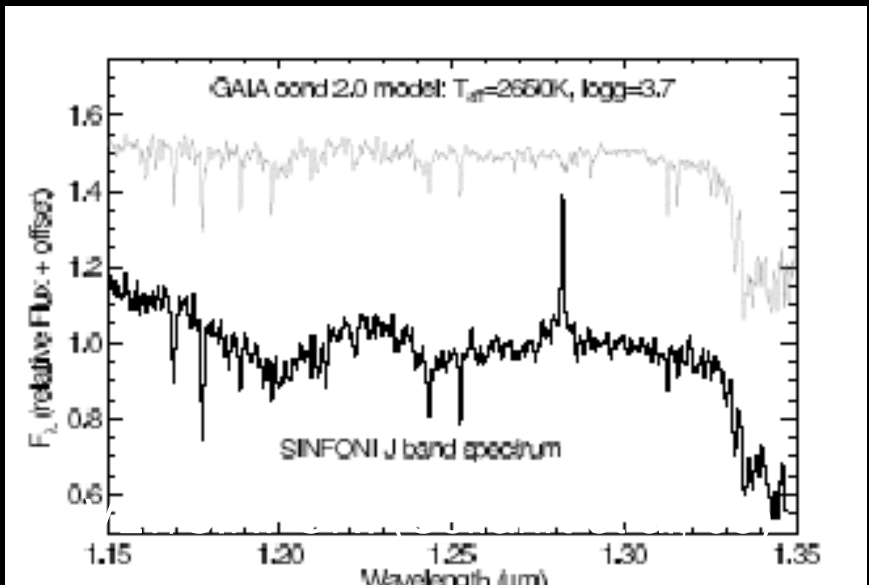


GQ Lup B
140 pc
1-5 Myr?
20-40 MJup
100 AU
Naco/VLT
(Neuhäuser et al 2005)

Mass estimates are model dependant

Example of GQLup





Estimated mass from photometry:

20-40 MJup (Neuhauser, 05)

10-20 Mjup (Marois et al, 07)

! Use of stellar evolutionary models !

Estimated mass from spectroscopy:

10-40 Mjup (Mac Elwain et al, 07)

10-40 MJup (Seifahrt et al, 08)

! Use of stellar atmosphere models !

Characterization of stars hosting planets

- Targets: stars with RV planets: 0.1 - 10.0 Gyr; close-by < 50 pc
- What do we want to know ?
  - Multiplicity: massive companions at long-periods
  - Improvement of mass determination
  - When multiple, dynamical impact on inner planets ?
- Material:
  - High contrast and classical imaging

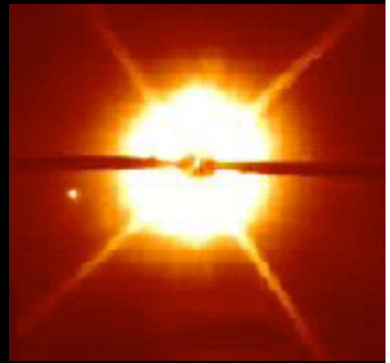
KeckII/kCam	AO	Saturated	25	Luhman & Jayawardhana (2002)
- NTT/Sofi		Classical-Saturated	-	Mugrauer et al. (2004, 2006, 2007)
- VLT/NACO		AO-Corono	26	Chauvin et al. (2006, 2007)
- VLT/NACO		AO-Classical	103	Eggenberger et al. (2007)
- Spitzer		Classical-midIR	48	Luhman et al. (2006)
VLT/NACO		AO-SDI		Montagnier et al (2008)

and also classical, non AO imaging (to investigate large separations)

Characterization of stars hosting planets
Multiplicity

- Detected companions :
  - Mostly stellar objects
  - 2 BD (GJ570; HD3651)
  - 3 WD (Gl86; Mugrauer et al,05; Lagrange et al, 06; HD27442:Chauvin et al, 07; HD147513, Mayor et al, 2004)
- Impact on planet frequency:
  - No impact of binarity on the RV planet frequency (Bonavita and Desidera, 07) (but still, lack of data at separations shorter than 50 AUs)

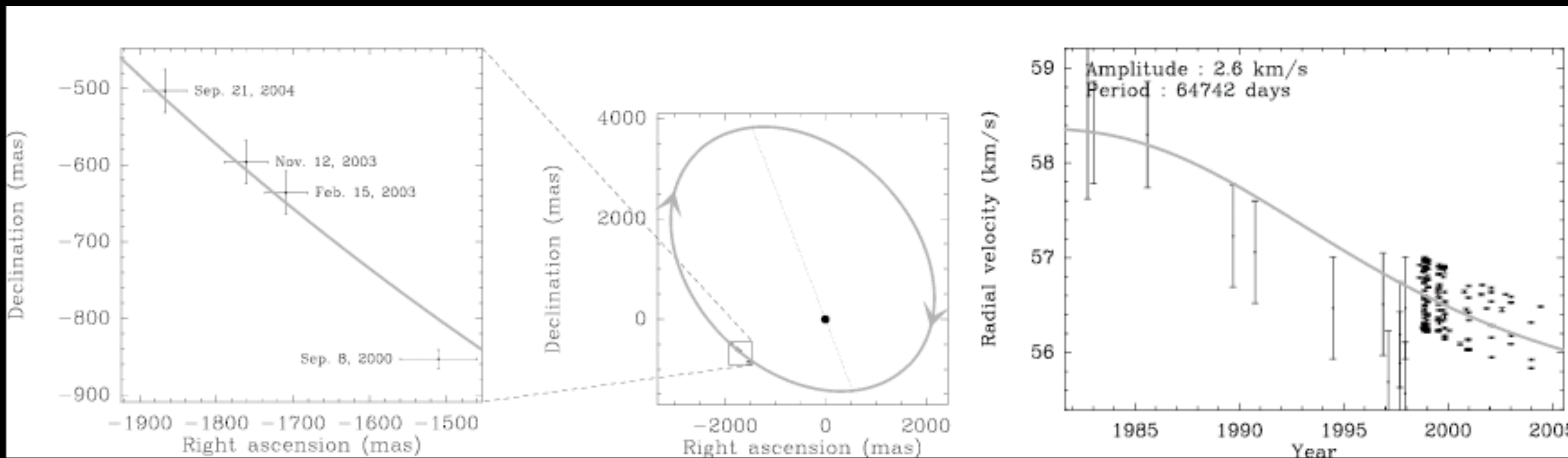
Characterization of stars hosting planets
Dynamics of close binary systems



- Astrometric orbits=> improved knowledge on the system
- GL86B: white dwarf (0.5 MSun); sep. ~20 AU; e>0.4
- Coupling AO and RV data => constrains on the initial system: a*init*=35AU; e*init*=0.5; M*init*=1.01 MSun

(Lagrange et al, 2006)

see also Neuhauser et al, 2007 for gamma Cep



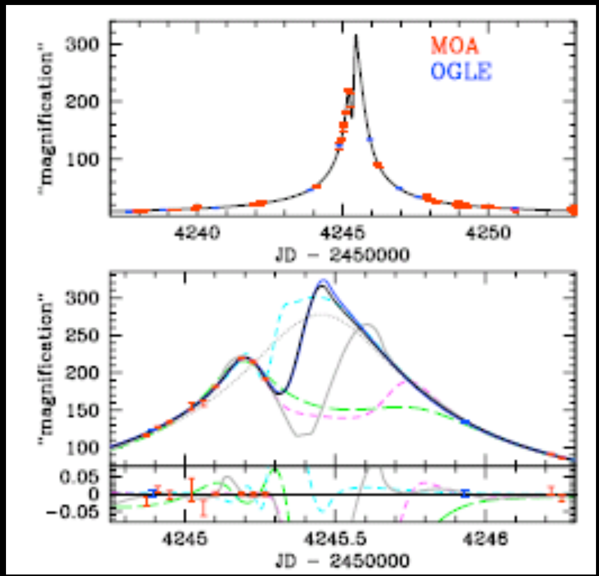
Characterization of stars hosting planets

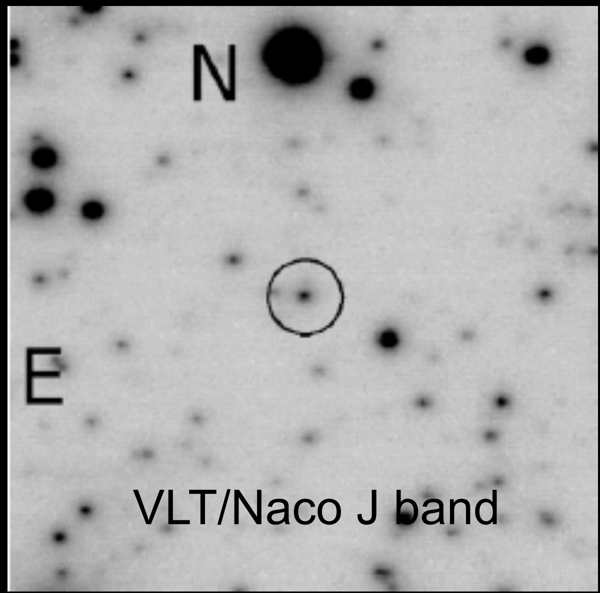
Characterization of a star hosting a 3MEarth planet

Lensing MOA 2007-BLG192

- MA~60 MJup
- MB~3MEarth

(Bennett et al, 2008)





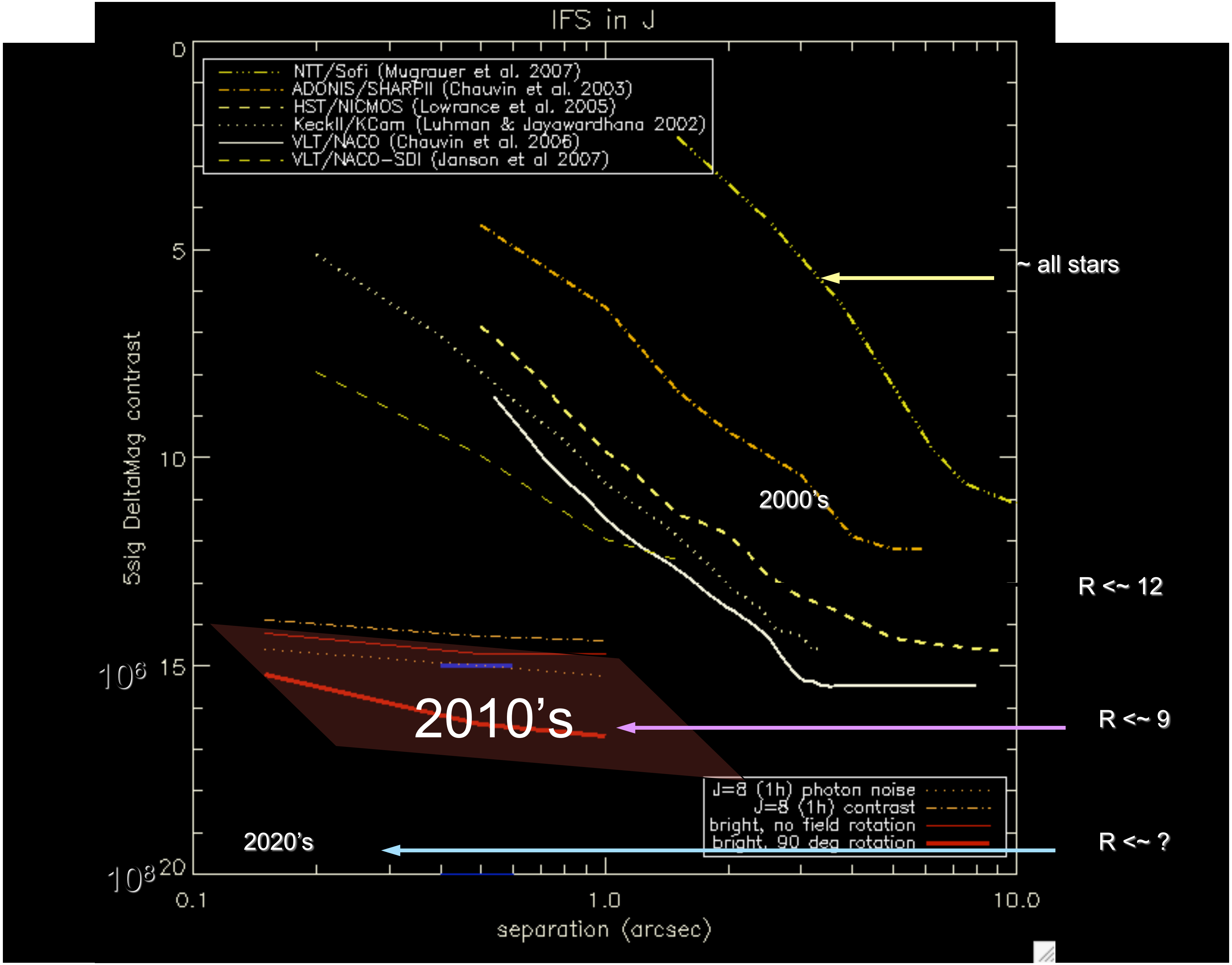
Adaptive Optics & Extrasolar Planetary Systems

Lessons learned and needs for the future

- A few detections of BDs bound to stars
  - Enough data for statistical analysis: question the brown dwarf desert for intermediate separations
- A few detections of planetary mass companions to stars and/or brown dwarfs
  - >5 Jupiter mass planets; separation a few tens AUs
  - These planetary mass companions formed like binaries => Are they planets or brown dwarfs? What are the distributions of planets masses formed by the different mechanisms?
  - High uncertainties on masses: age determination; evolutionary models => improve models, get more data to test the models, couple with RV techniques for dynamical mass determination
- Begining of spectroscopic investigation of the atmospheres
  - Teff and age determination
  - Uncertainties on atmospheric models for low mass objects => improve models , get more data to test the models, couple with RV techniques for dynamical mass determination
- Today's detections of planets possible only around young (a few-a few tens Myrs) systems
  - Improve detection limits

Adaptive Optics & Extrasolar Planetary Systems
Future prospects (planets)

- Same techniques, with improved capabilities
  - Improved imaging capabilities => less massive planets, closer to the stars, older systems
  - Improved spectroscopic capabilities
  - Significant amount of telescope time: statistics (cf RV studies)
- New types of detection using AO:
  - Astrometric measurement of star's wobble
  - Polarimetry
- Coupling AO and RV/astrometric measurements



IFS in J
NTT/Sofi (Mugrauer et al. 2007)
ADONIS/SHARPII (Chauvin et al. 2003)
HST/NICMOS (Lowrance et al. 2005)
KeckII/KCam (Luhman & Jayawardhana 2002)
VLT/NACO (Chauvin et al. 2006)
VLT/NACO-SDI (Janson et al 2007)
~ all stars
2000's
R <~ 12
2010's
R <~ 9
2020's
R <~ ?
J=8 (1h) photon noise
J=8 (1h) contrast
bright, no field rotation
bright, 90 deg rotation
5sig DeltaMag contrast
separation (arcsec)
0
5
10
15
20
10^6
10^8
0.1
1.0
10.0