Direct imaging and Spectroscopy of Exo-Planets

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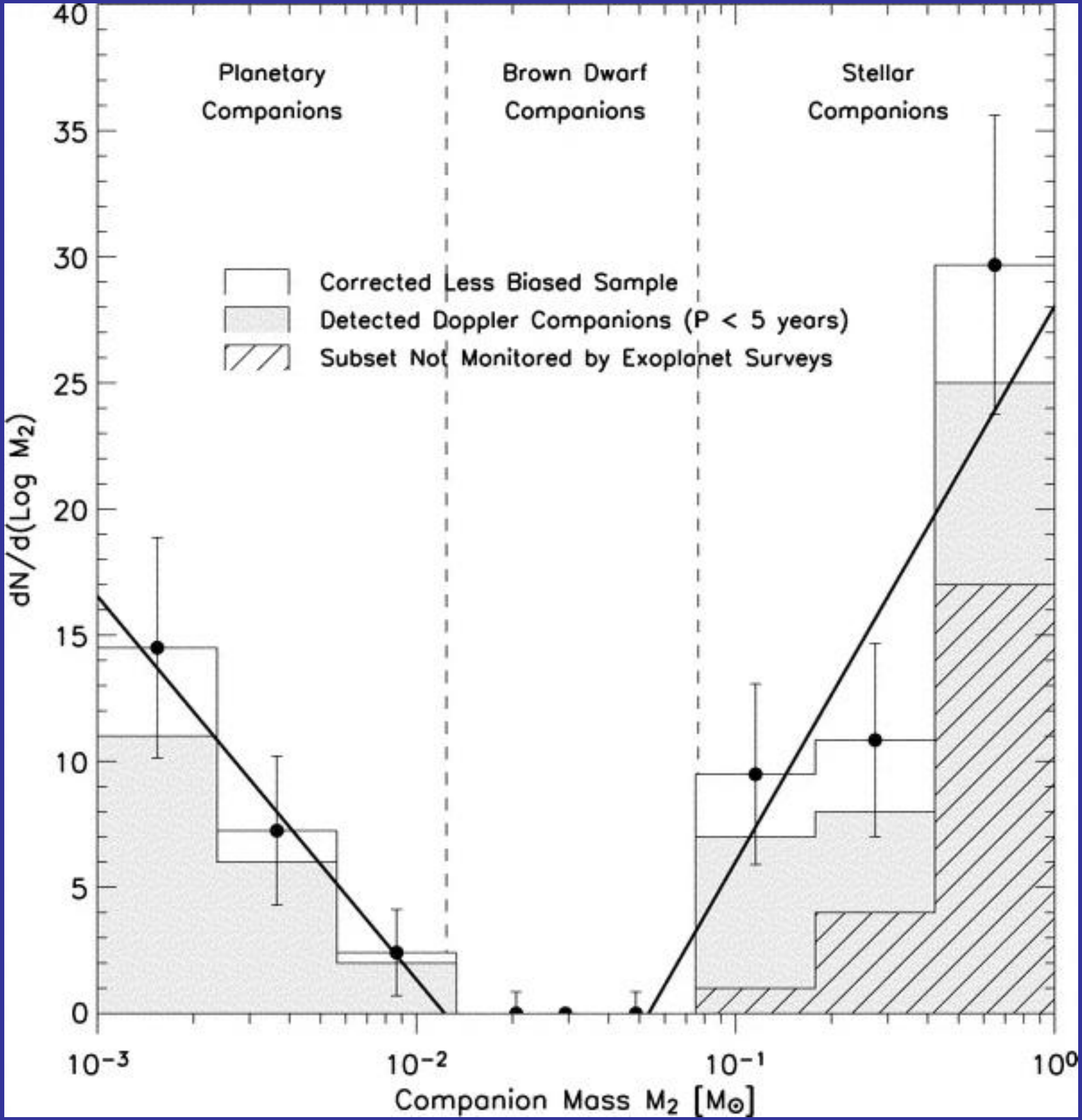
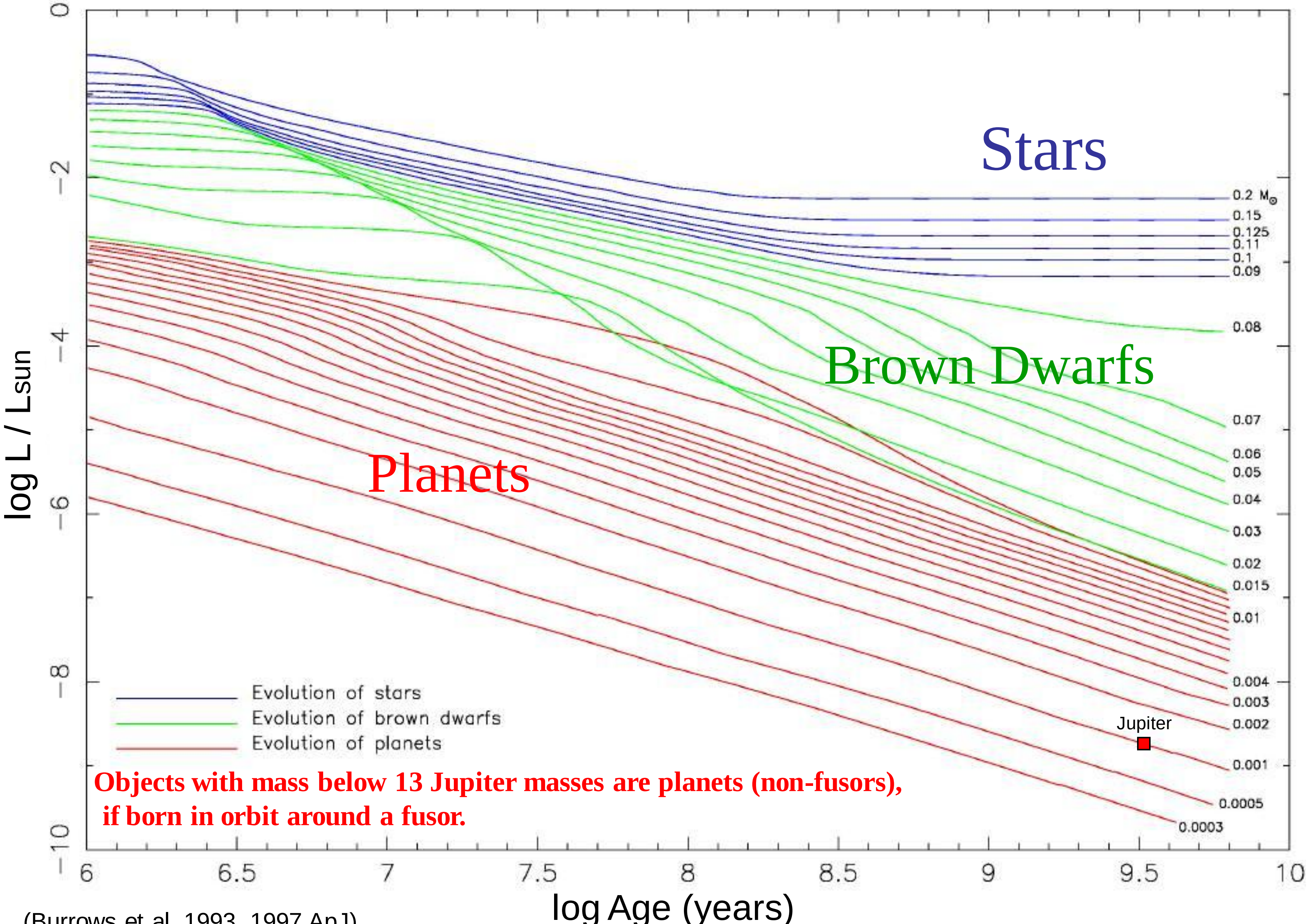
The brown dwarf desert: 20 to 50 Jup masses



Grether & Lineweaver 2006

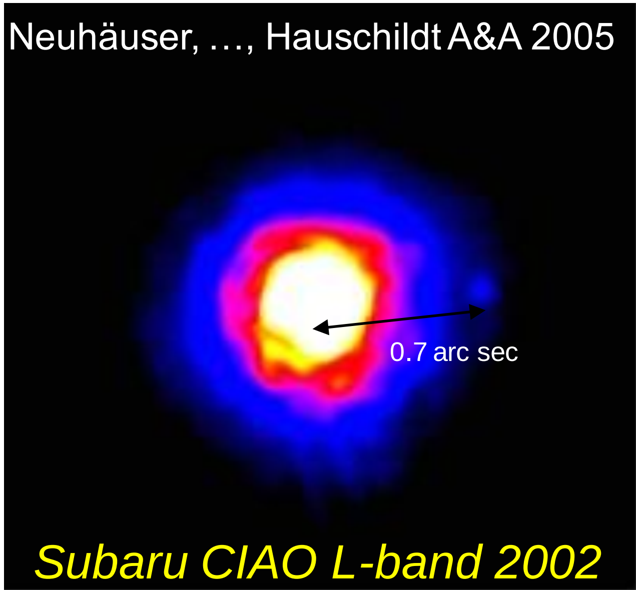
Objects below ~ 35 Jup masses form *differently*, i.e. planets …

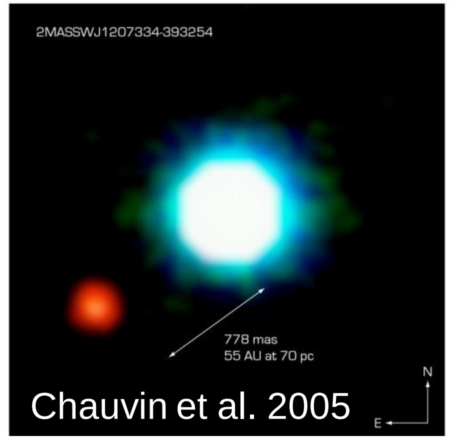
Luminosity vs. age (stars, brown dwarfs, and planets)

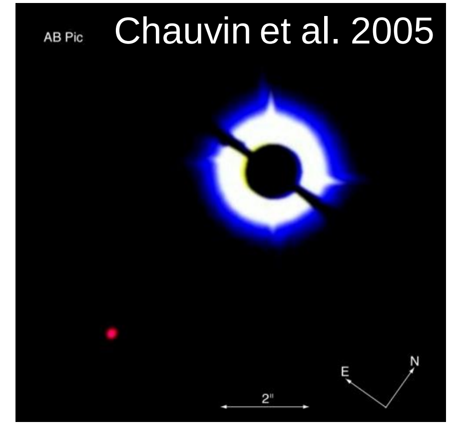


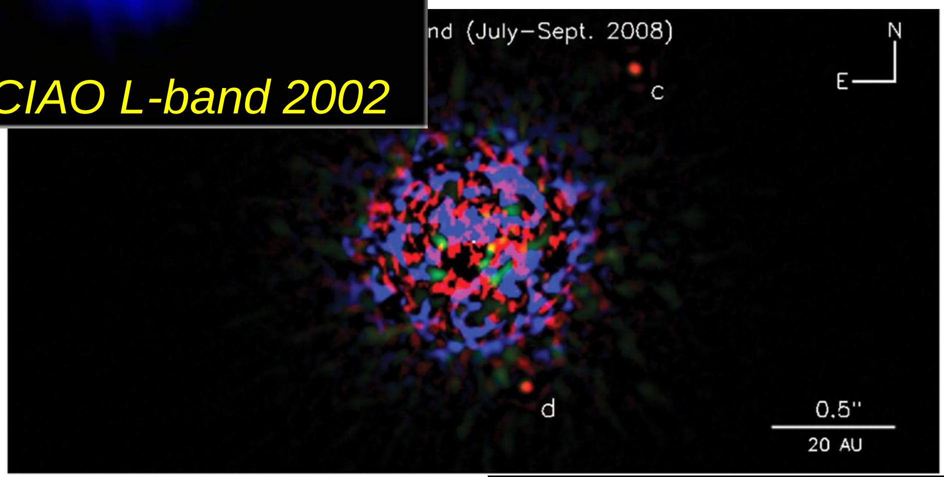
Objects with mass below 13 Jupiter masses are planets (non-fusors), if born in orbit around a fusor.

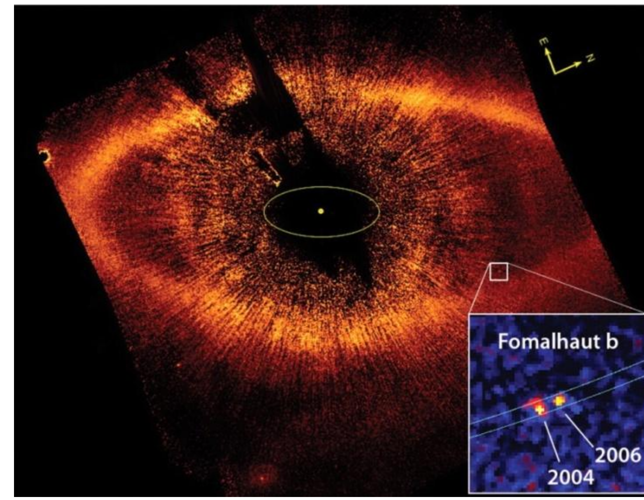
(Burrows et al. 1993, 1997 ApJ)

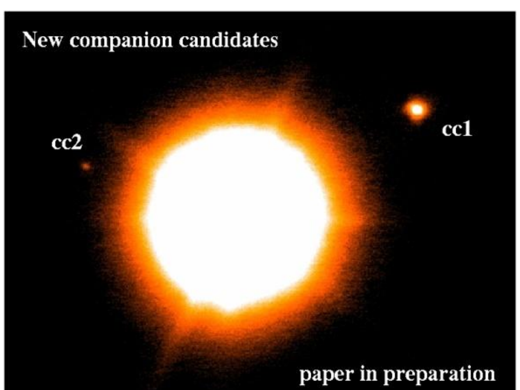

Neuhäuser, …, Hauschildt A&A 2005
0.7 arc sec
Subaru CIAO L-band 2002

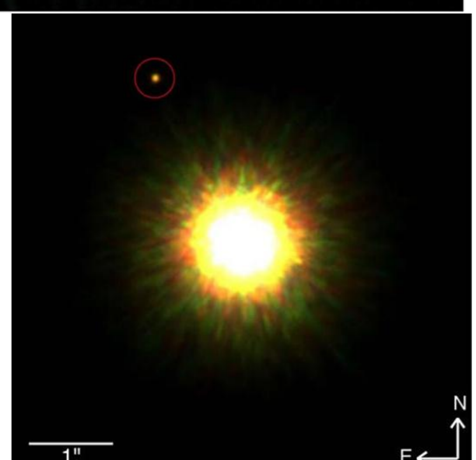

2MASSWJ1207334-393254
778 mas
55 AU at 70 pc
Chauvin et al. 2005
N
E

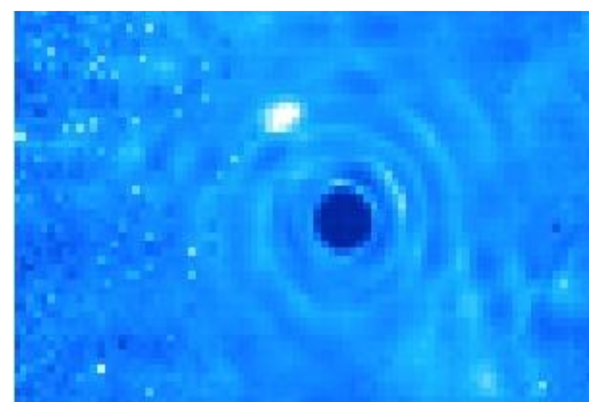

AB Pic
Chauvin et al. 2005
2"
E
N


nd (July–Sept. 2008)
N
E
c
d
0.5"
20 AU


Fomalhaut b
2006
2004


New companion candidates
cc2
cc1
paper in preparation


N
E
1"



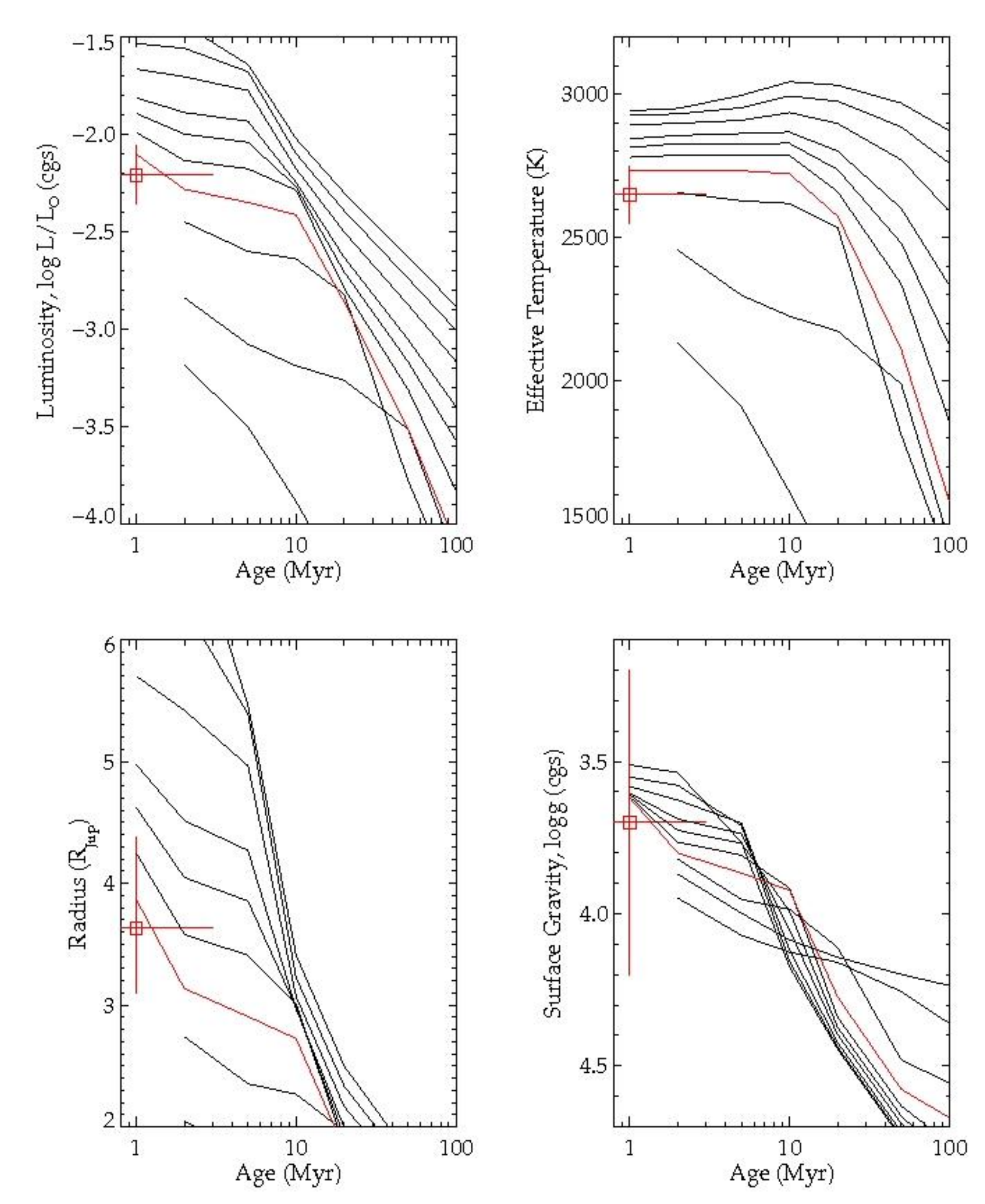
(Burrows et al. tracks for masses 10 to 70 M_jup)

Determination of mass

By comparison with evolutionary models & tracks (hot start)

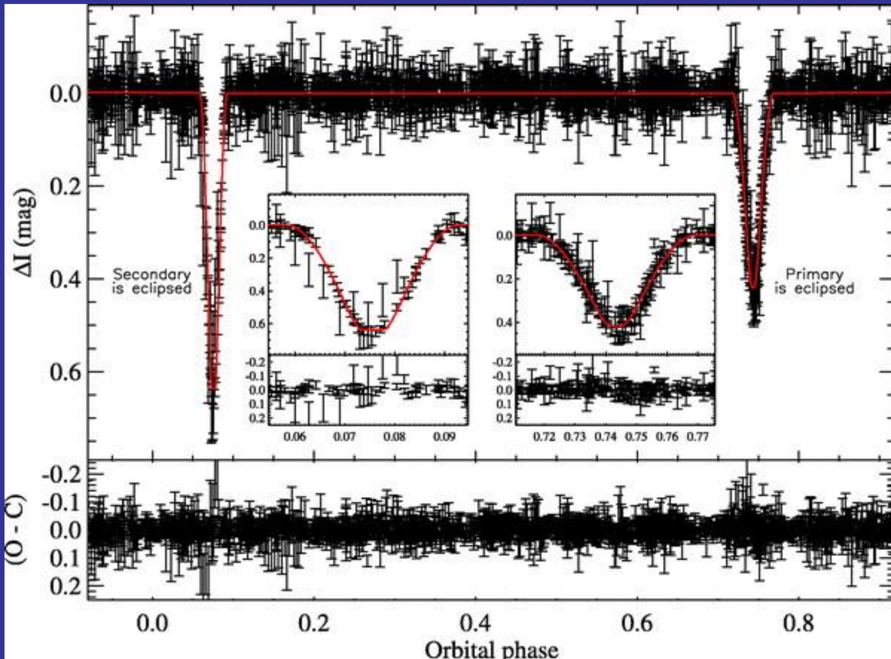
Observables:
Luminosity L
Temperature T
Gravity log g
Radius R
Age (of host star)

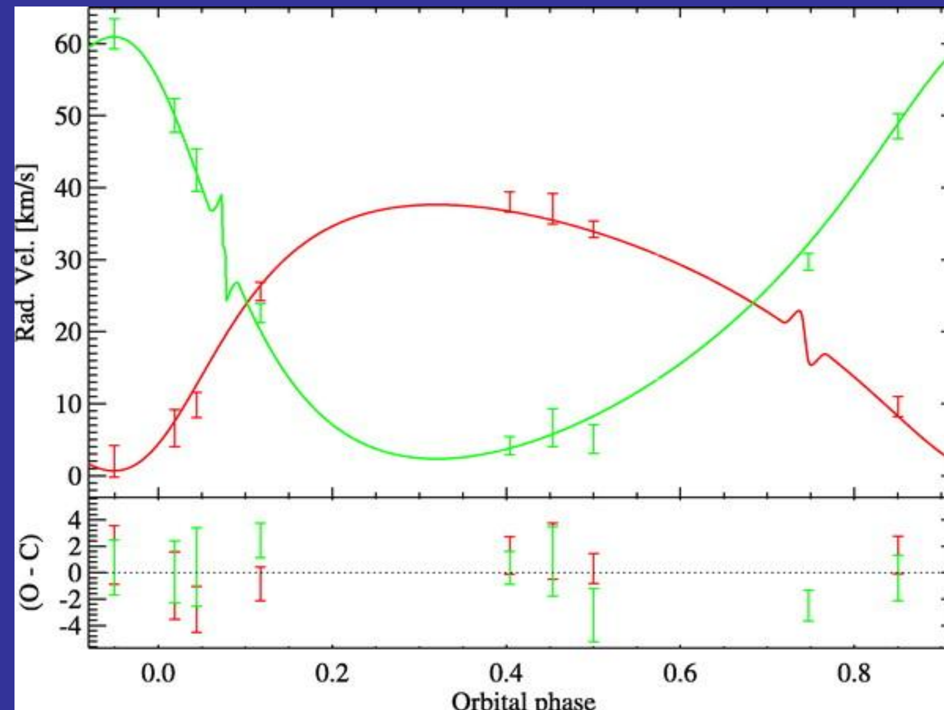
Model yields mass of the companion

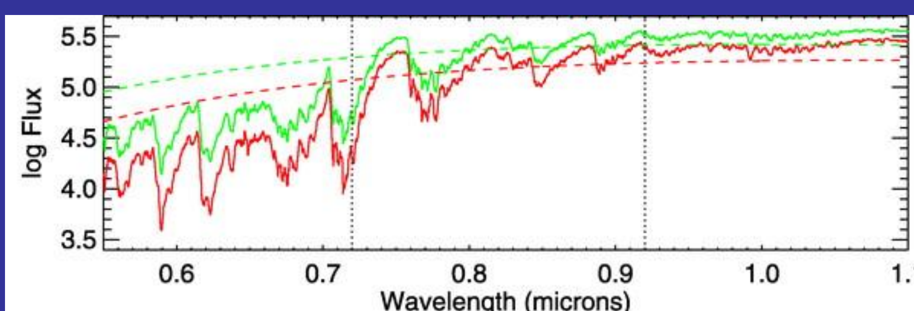


Example given here:
GQ Lup b and
Burrows et al. 1997 models
➔ 20-25 M_jup (4 to 36 M_jup), figure from Andreas Seifahrt PhD thesis (red: 25 Jup)

Calibrating tracks with eclipsing double-lined brown dwarf – brown dwarf binary (2M0535 in Orion region, i.e. few Myr)







➔Masses from Kepler s 3rd law:

A has 59.5 4.8 M_jup but spots

B has 37.5 2.9 M_jup

(Stassun et al. 2007 Nat. & ApJ)

Observables:

Object name	Luminosity $\log(L_{bol}/L_\odot)$	Magnitude M_K [mag]	Temperature T_{eff} [K]	Age [Myrs]	References
Reference object (eSB2 brown dwarf - brown dwarf binary 2M0535):					
2M0535 A	-1.65 ± 0.07	5.29 ± 0.16	2715 ± 100	0.1-3	Stassun 07
B	-1.83 ± 0.07	5.29 ± 0.16	2820 ± 105	0.1-3	Stassun 07
Directly detected planet candidates:					
DH Tau b	-2.75 ± 0.10	8.31 ± 0.23	2750 ± 50	0.1-4	Itoh 05
GQ Lup b	-2.38 ± 0.25	7.67 ± 0.16	2650 ± 100	0.1-3	Neuh. 05
2M1207 A	-2.76 ± 0.05	8.35 ± 0.05	2425 ± 160	5-12	Chau. 05a
b	-4.75 ± 0.06	13.33 ± 0.12	1590 ± 280	5-12	Chau. 05a
AB Pic b	-3.76 ± 0.06	10.85 ± 0.11	2040 ± 160	20-40	Chau. 05b
CT Cha b	-2.68 ± 0.21	8.83 ± 0.50	2600 ± 250	0.1-4	Schmidt 08
1RXSJ1609 b	-3.57 ± 0.15	10.36 ± 0.35	early L	1-10	Lafr. 08
HR 8799 b	-5.1 ± 0.1	12.66 ± 0.11		30-1000	Mar. 08
c	-4.7 ± 0.1	11.74 ± 0.09		30-1000	Mar. 08
d	-4.7 ± 0.1	11.56 ± 0.16		30-1000	Mar. 08
Fom b	≤ -6.5	$M_H \geq 23.5$		100-300	Mar. 08
β Pic b		$M_{L'} = 9.8 \pm 0.3$		8-20	Lagr. 09

Model derived masses:

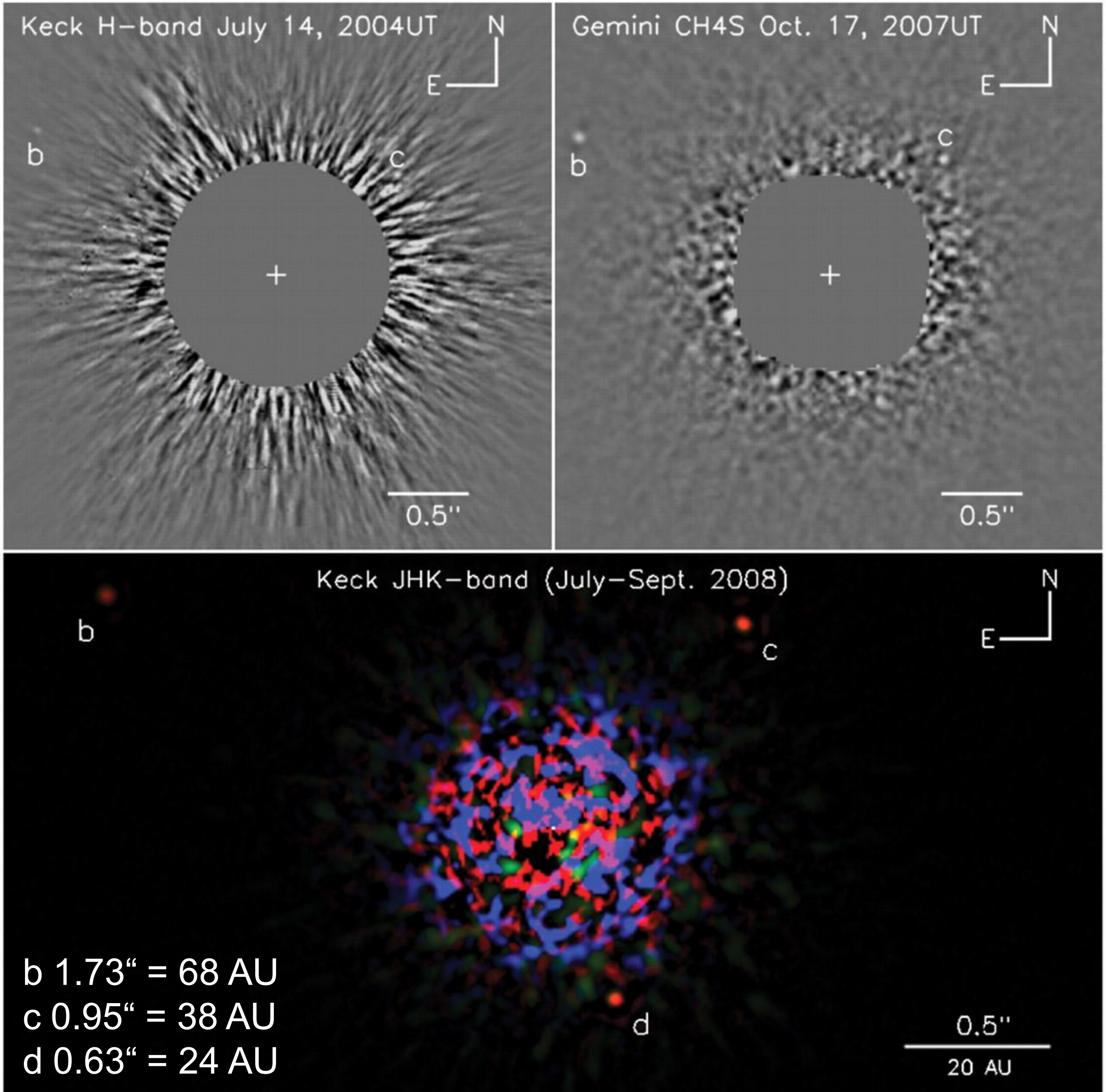
Object name	Burrows 1997 (L, age)	Chabrier 2000 (L, T, K, age)	Baraffe 2003 (L, T, K, age)	Marley 2007 ($\geq$ 10 Jup)	Baraffe 2008 ($\geq$ 10 Myrs)
Reference object (eSB2 brown dwarf - brown dwarf binary 2M0335):					
2M0535 A	50 (45-60)	55 (30-60)	50 (45-80)		
B	37 (33-46)	45 (40-50)	43 (40-65)		

true 37.5 jup

Itoh et al. Subaru

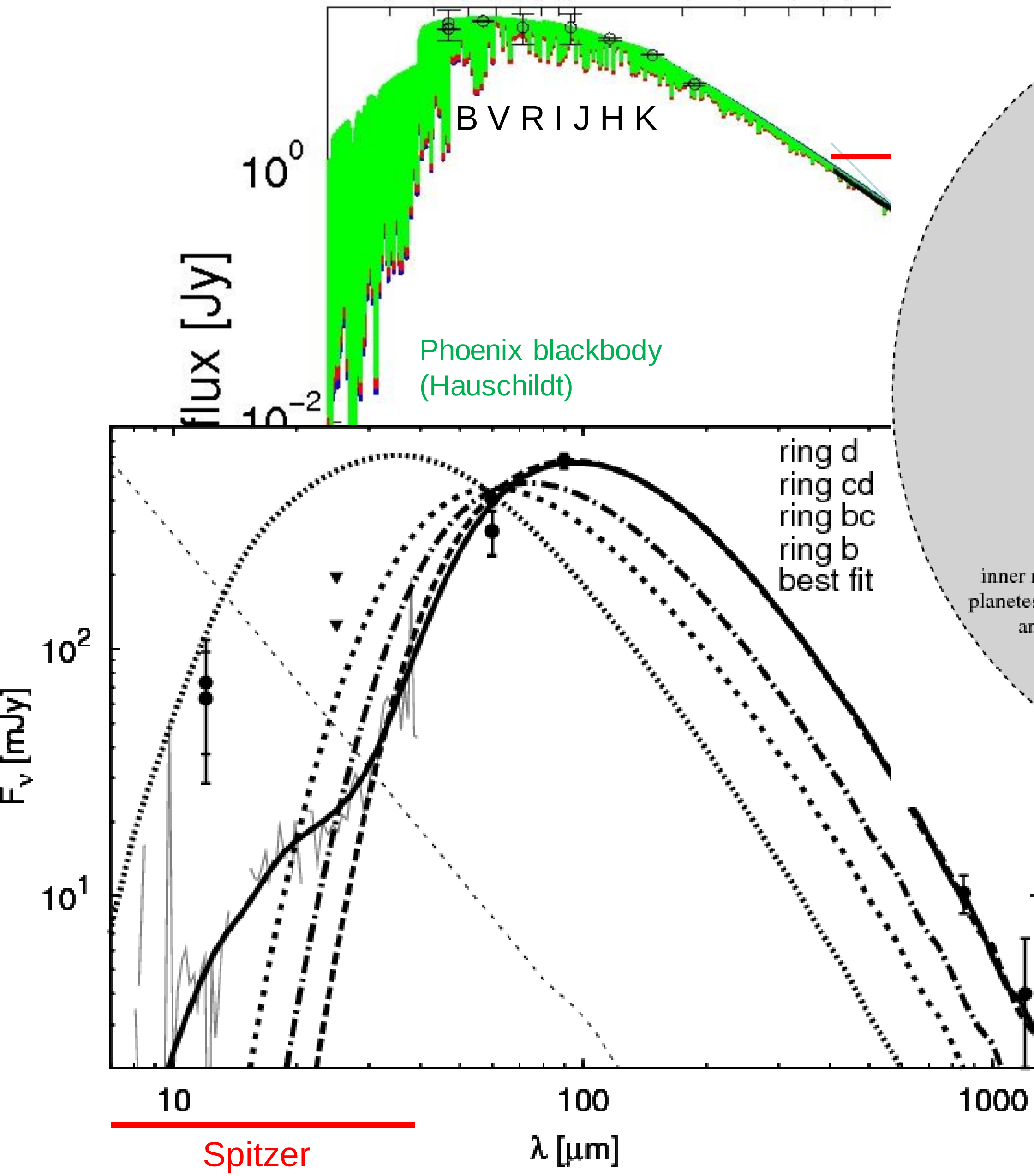
(Schmidt, RN, Seifahrt, Conf. Proc., astro-ph)

HR 8799

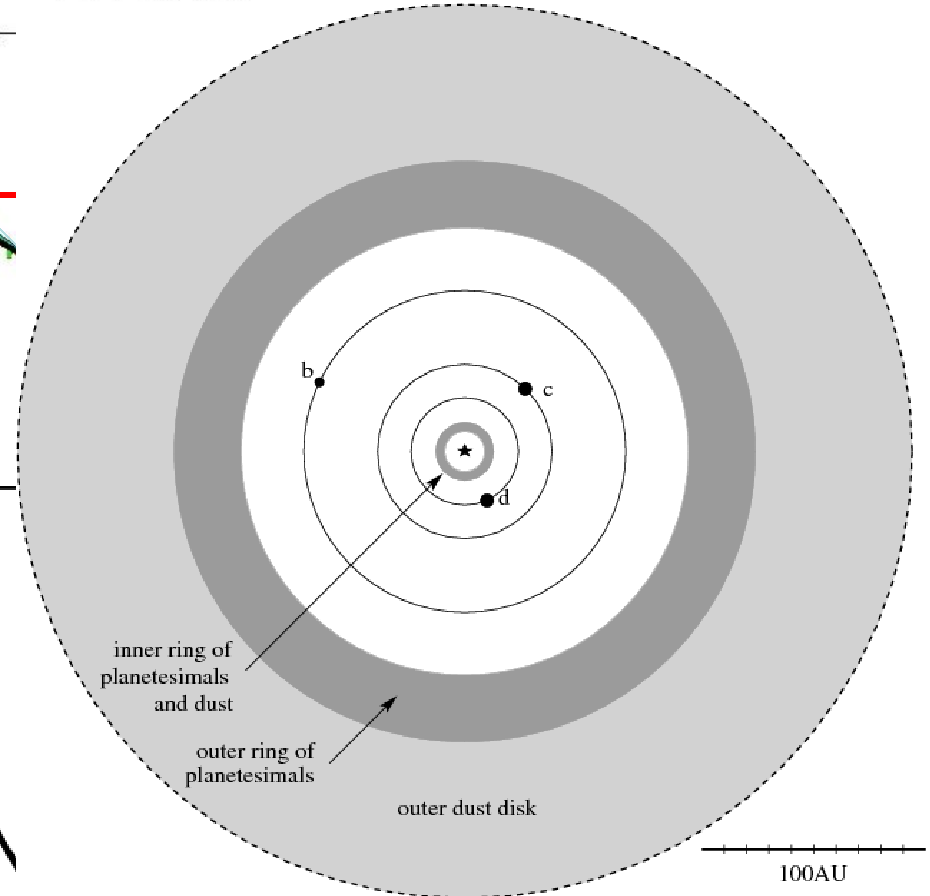


Marois et al. 2008

SED and disk around HR 8799



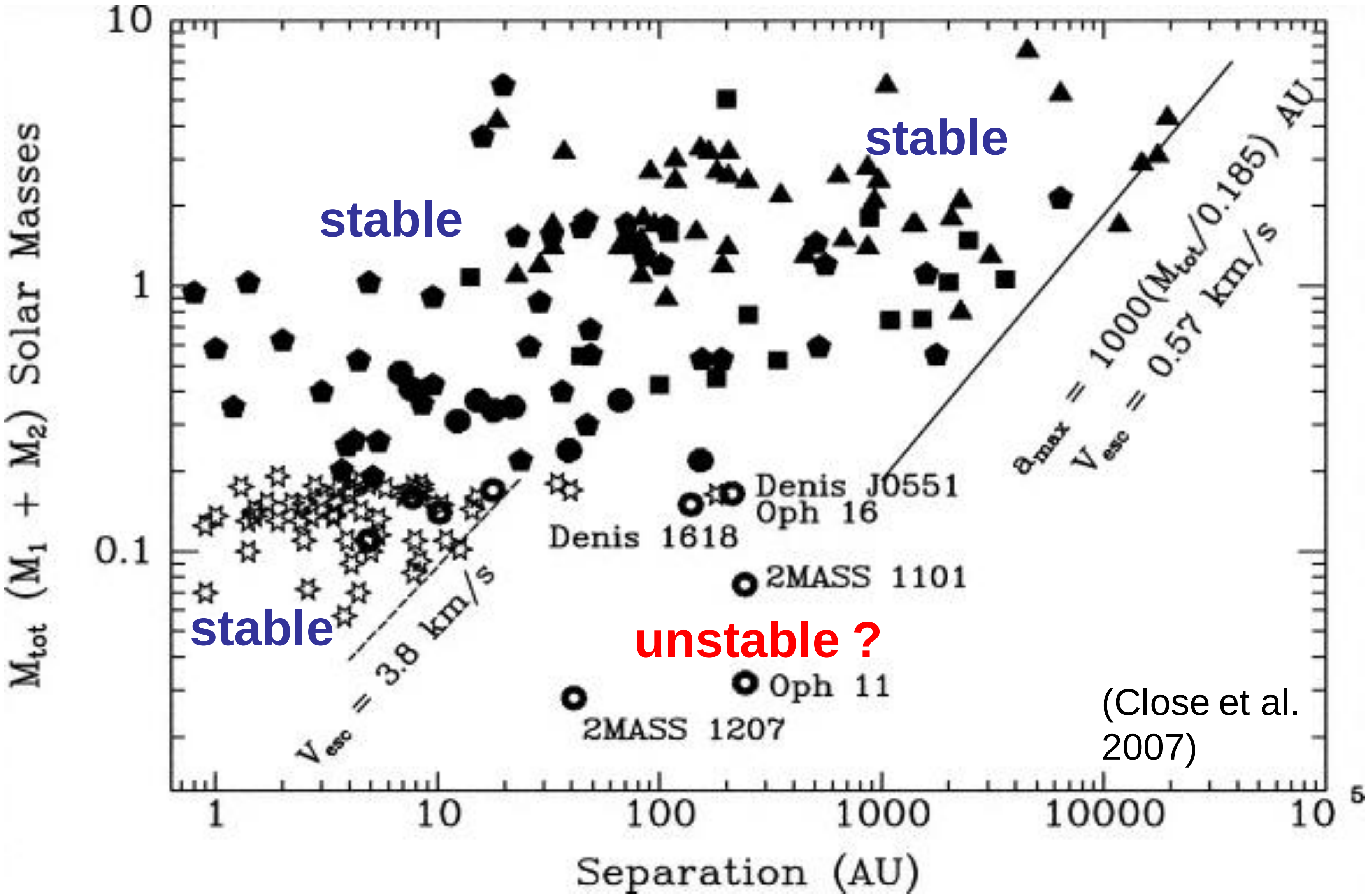
HR 8799

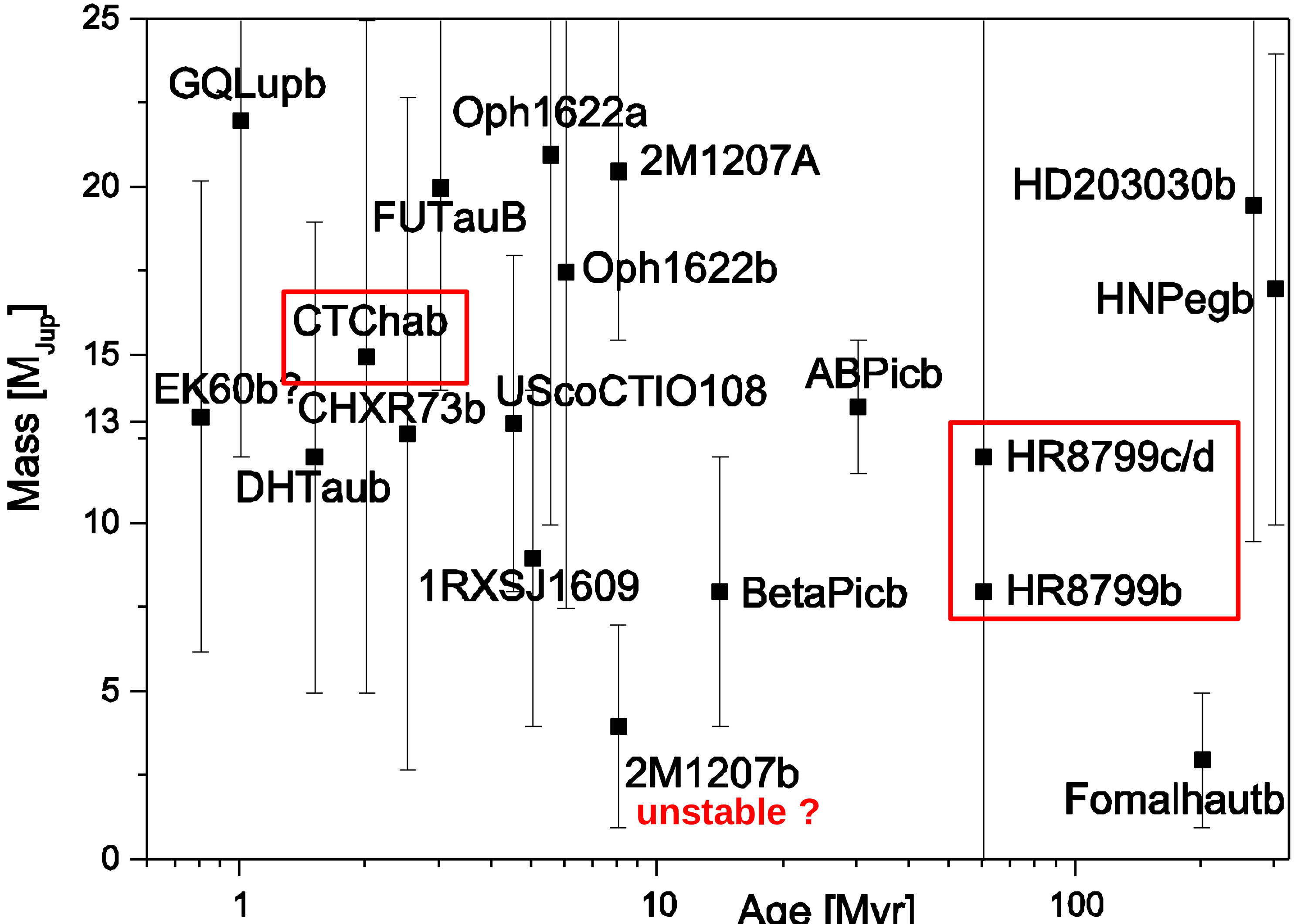


Inner ring at 3 to 15 AU.

Companions and dust rings stable, only if masses are low, hence planets.

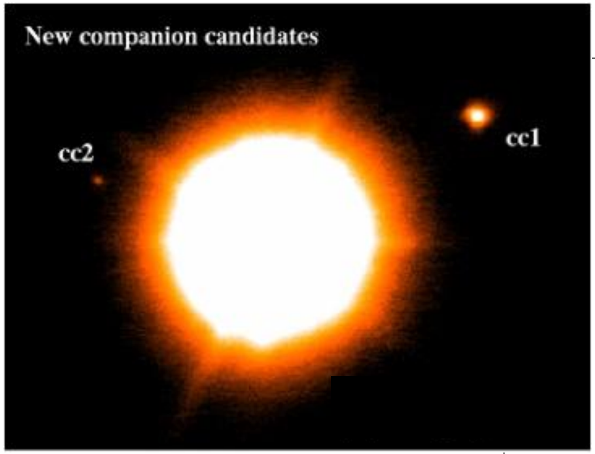
(Reidemeister, Krivov, …, Neuhäuser 2009 A&A 503, 247)

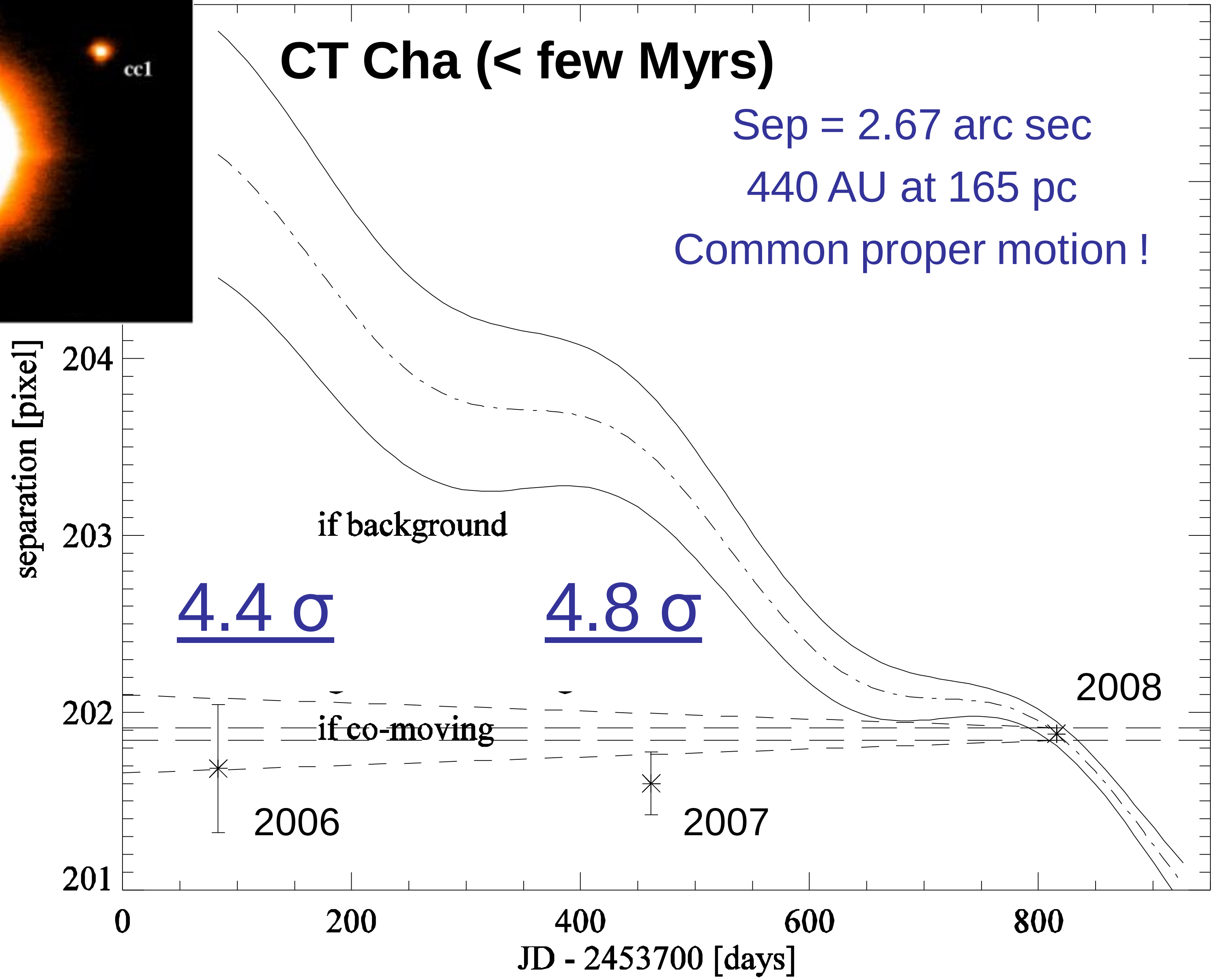

stable
stable
stable
unstable ?
Denis J0551
Oph 16
Denis 1618
2MASS 1101
Oph 11
2MASS 1207
V_esc = 3.8 km/s
a_max = 1000(M_tot/0.185) AU
V_esc = 0.57 km/s
M_tot (M_1 + M_2) Solar Masses
Separation (AU)
10
1
0.1
1
10
100
1000
10000
10^5
(Close et al. 2007)



+ SCR1845b, 100-10000 Myr, 9-65 M_{Jup}

(Schmidt, Neuhäuser, Seifahrt, 2009, AIP Conf. Proc. 1158, 231, also on astro-ph)





Schmidt, Neuhäuser, Seifahrt, … Hauschildt 2008 A&A

Schmidt, Neuhäuser et al. 2009 Cool Stars XV Proceedings

Problem:

Hot-start model tracks may not be valid for objects younger than ~ 10 Myrs

CT Cha b
and Drift-Phoenix
(Helling, Hauschildt):

T= 2600 K   250 K

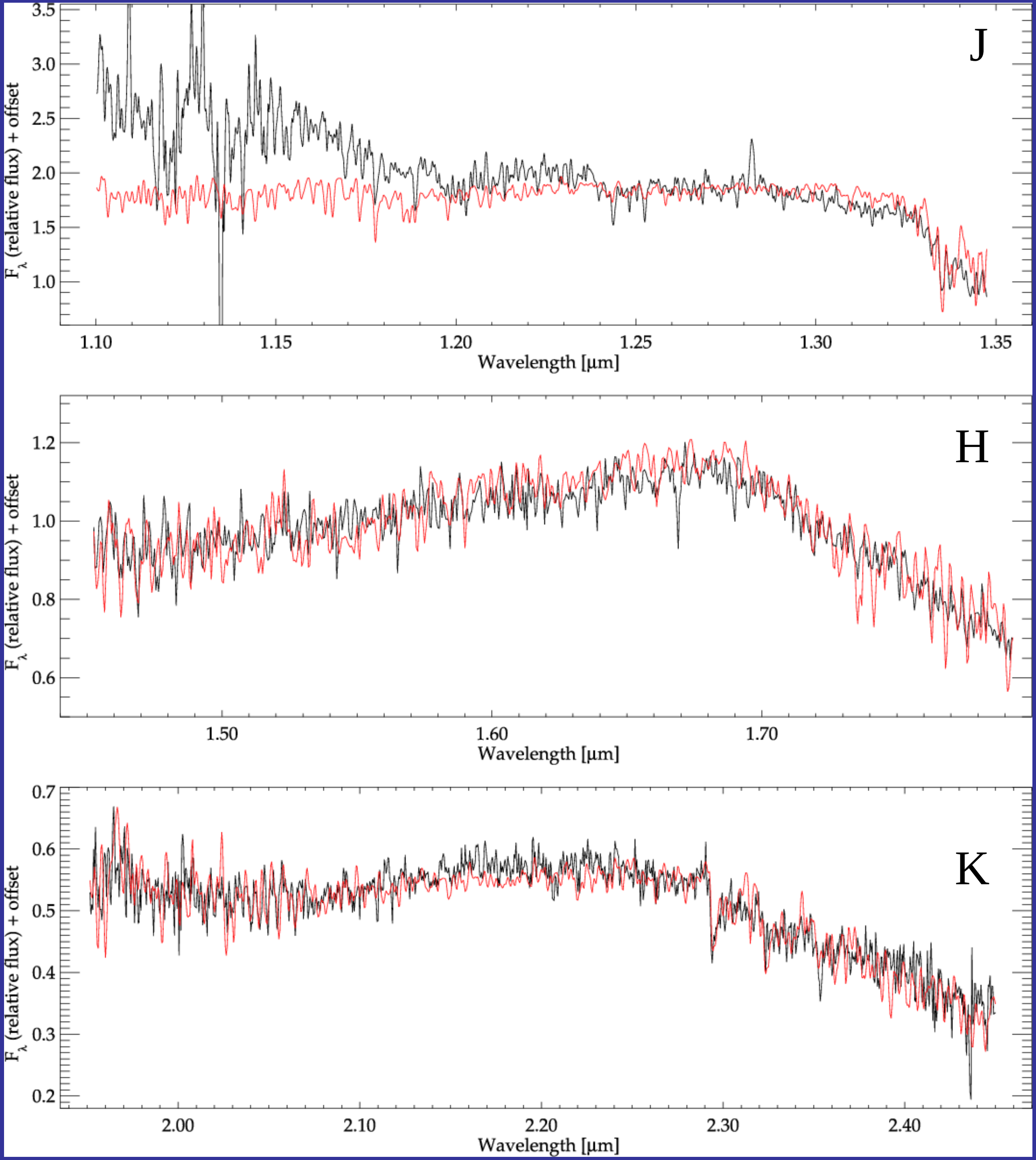
A_V= 5.8   0.8 mag

Log g = 4.0   0.5 dex

➔ Mag, A_V and distance give luminosity L

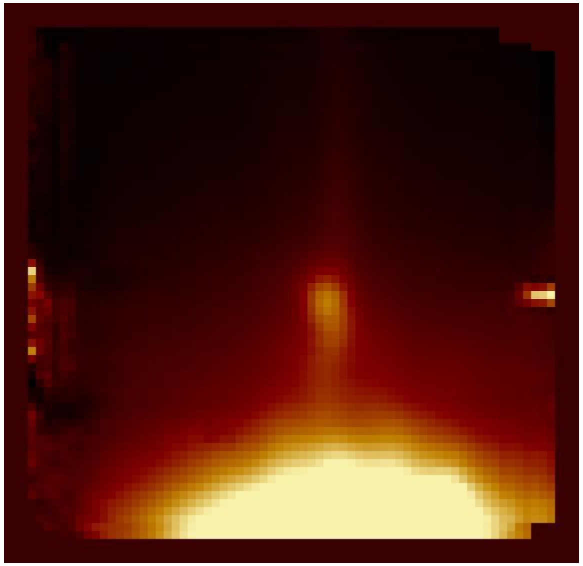
➔ L and T give radius (~ 2.2   0.7 R_jup)

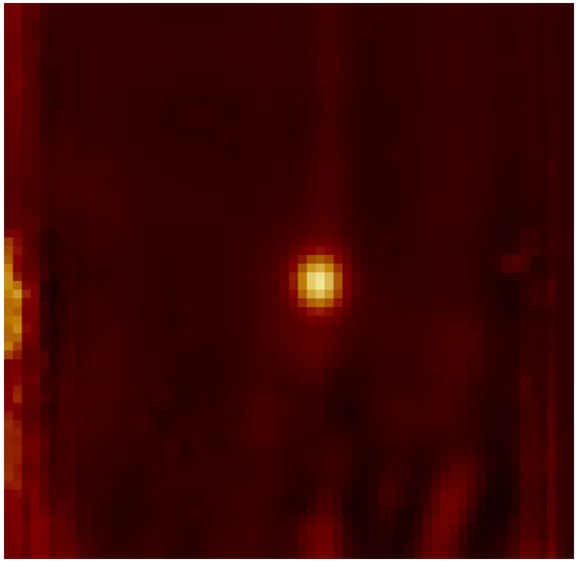
VLT Sinfoni spectra



Schmidt, Neuhäuser, Seifahrt, … Hauschildt, 2008 A&A

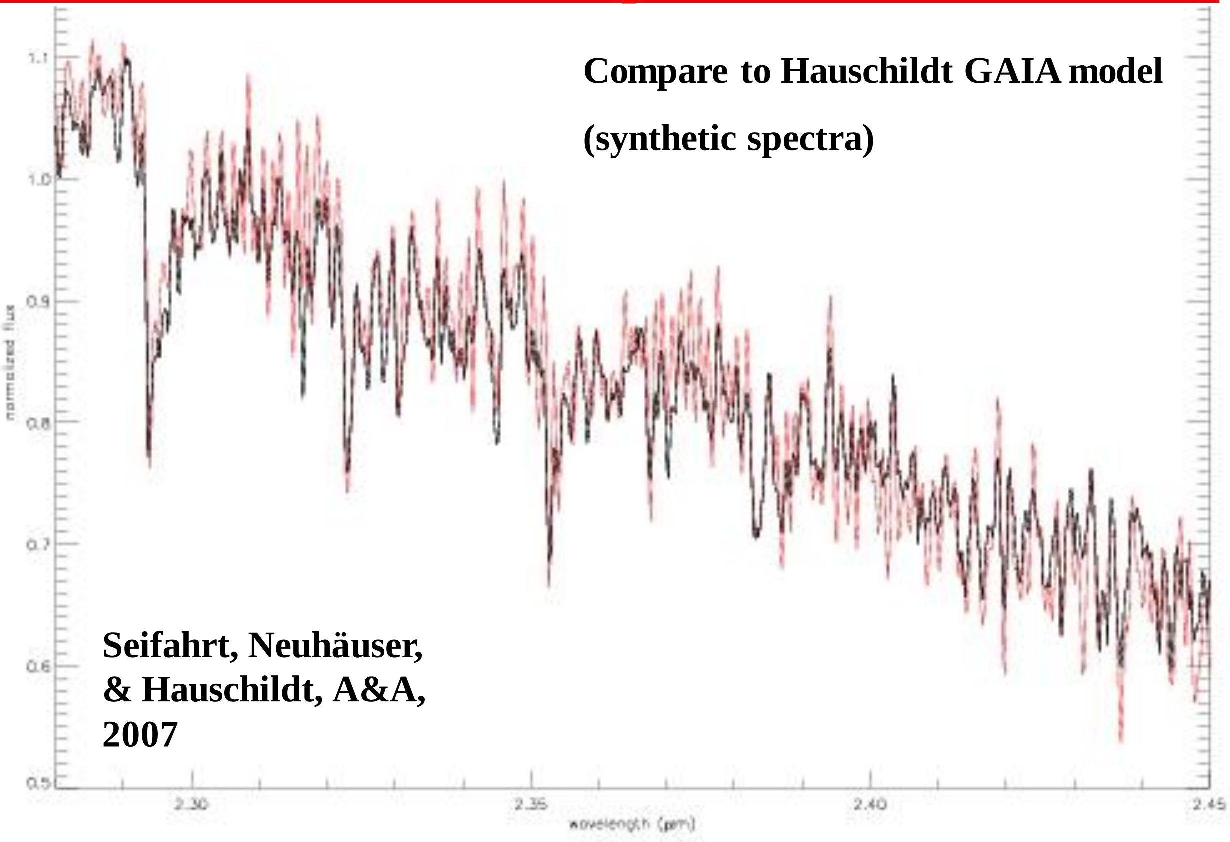
GQ Lup: VLT / Sinfoni JHK-band spectra: R=4000, S/N > 100





Compare to Hauschildt GAIA model

(synthetic spectra)



Seifahrt, Neuhäuser, & Hauschildt, A&A, 2007

Conclusion:

Given the age ranges and all models,
Planet status is dubious in all cases but maybe Fomalhaut b and HR 8799 bcd

Problem:

Hot-start models differ a lot and may not be valid below ~ 10 Myrs

Solution:

Fitting higher-resolution spectra to model atmospheres ➔ T, Av, and g
Mag, Av, and distance give luminosity L
L & T give radius R then R & g give mass

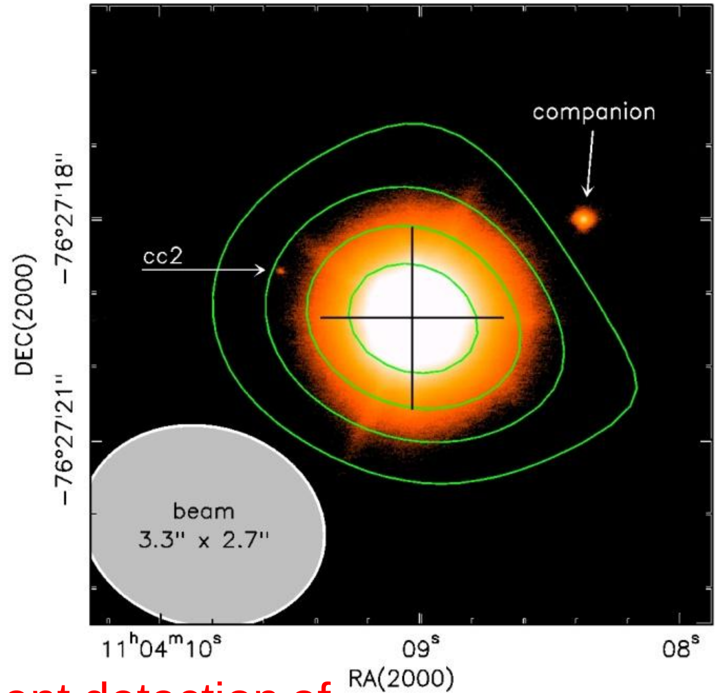
Problem here:

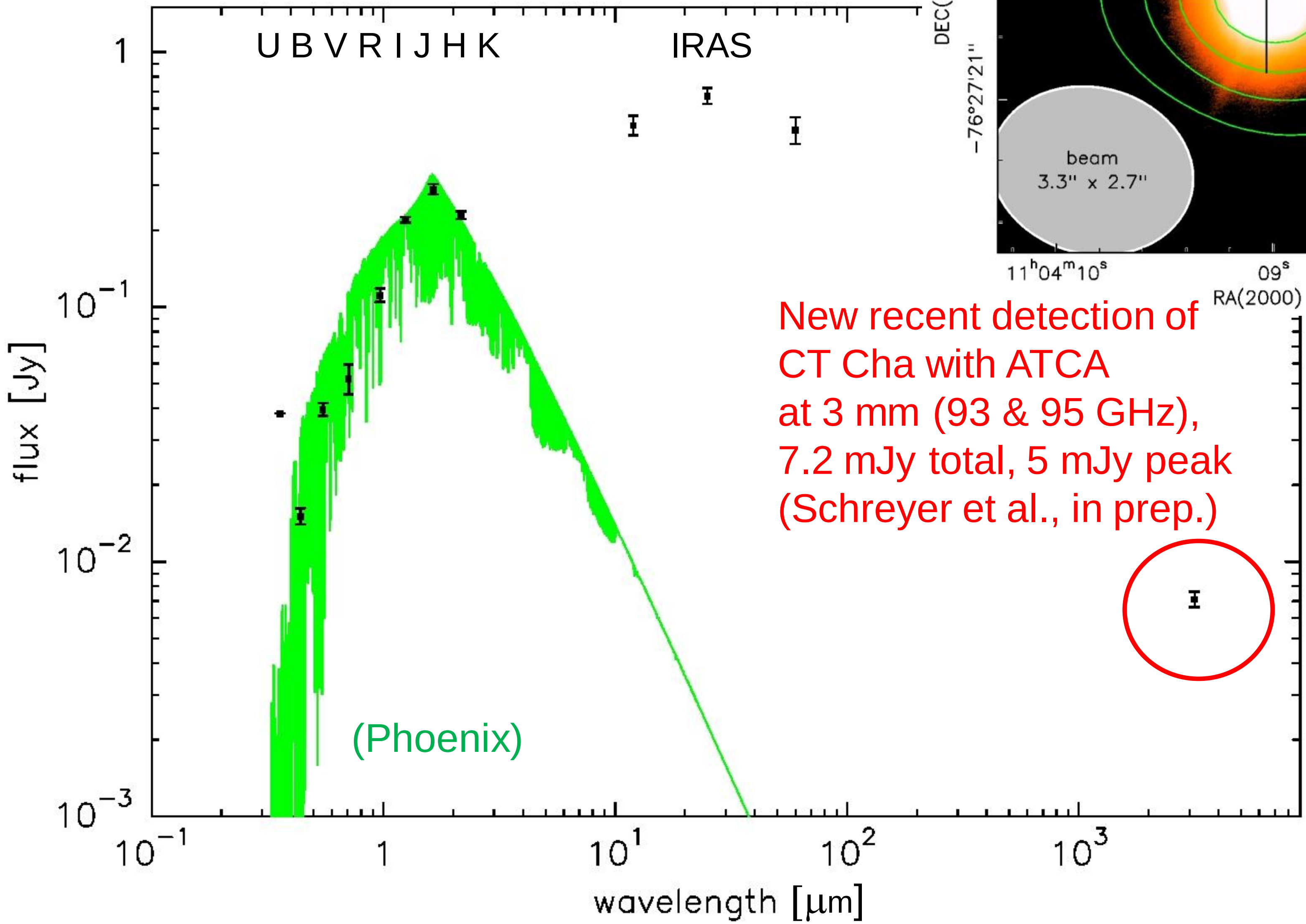
Gravity determination not yet precise enough (0.5 dex)

Direct imaging planets can constrain and probe

➔ Planet formation time-scale (youngest star with planet)
➔ Migration scenarios (most exo-Jupiters at snow line ?)

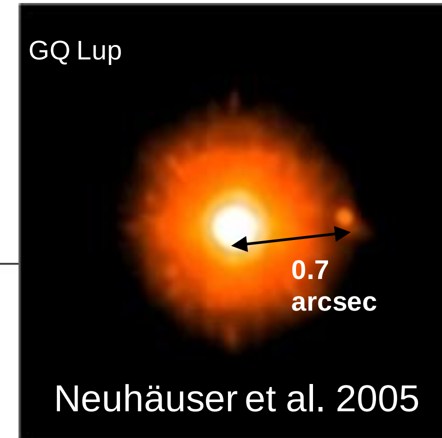
The disk around
classical T Tauri star CT Cha
(companion at 440 AU separation

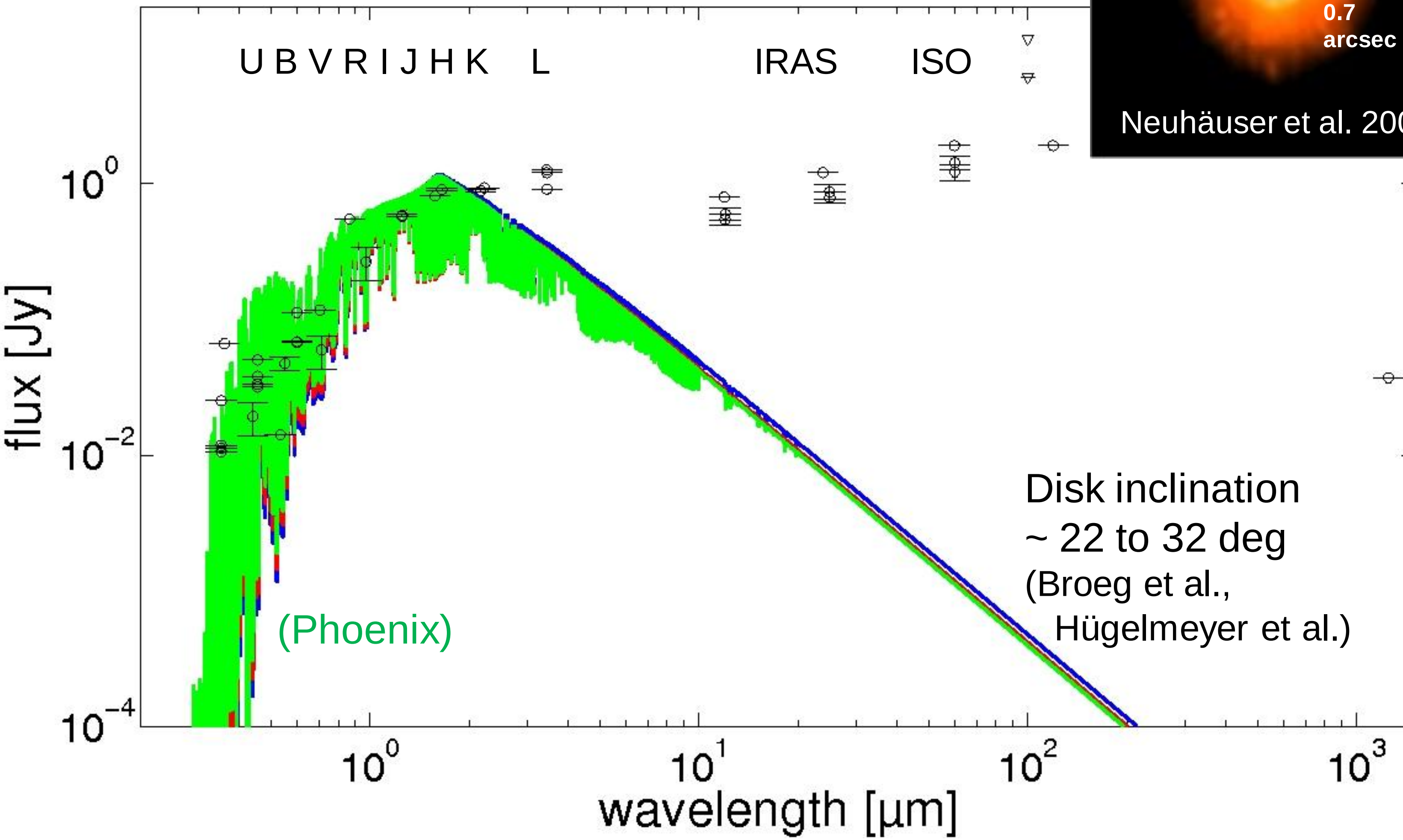




New recent detection of
CT Cha with ATCA
at 3 mm (93 & 95 GHz),
7.2 mJy total, 5 mJy peak
(Schreyer et al., in prep.)

Another classical T Tauri star
with sub-stellar companion
(planet or brown dwarf)
and with IR excess, i.e. (gas) disk





Strong IR excess in both CT Cha and GQ Lup

➔ massive large disks (?) ➔ wide sub-stellar companions could form in disk instability (?)

Summary:

➔ Direct detection of planets is possible (wide separations)

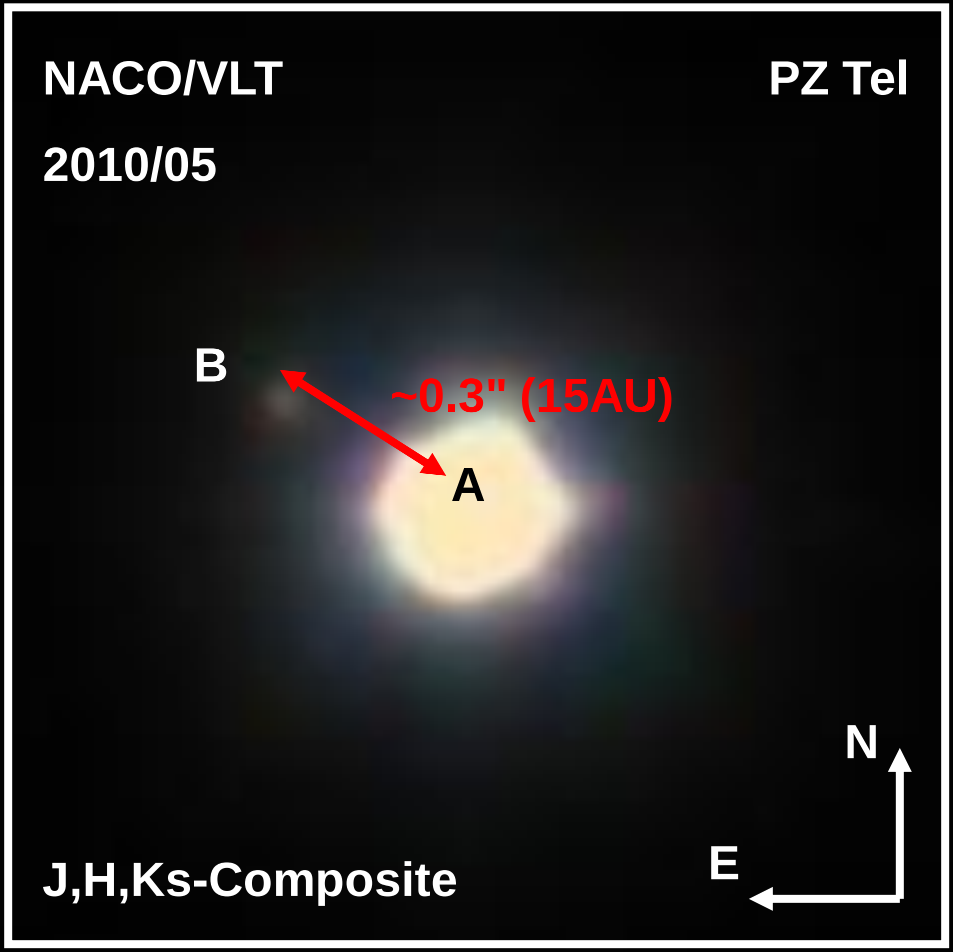
➔ Mass determination still very challenging (model dependent)

➔ JHK spectra and model atmospheres yield T, g, R, then mass

➔ direct imaging of young planets can constrain
planet formation time-scale and migration theories

NB 1:

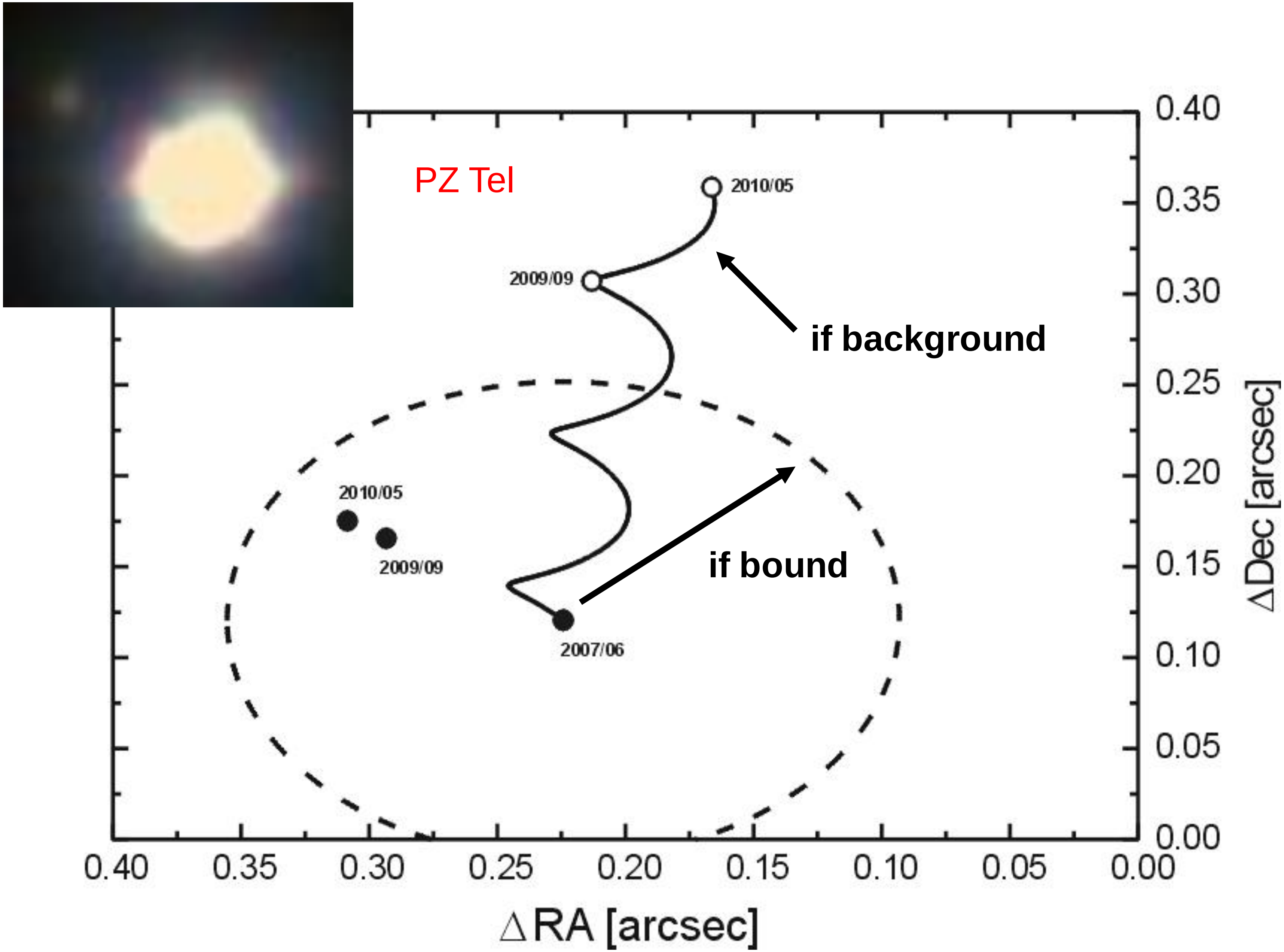
PZ Tel – new brown dwarf companion



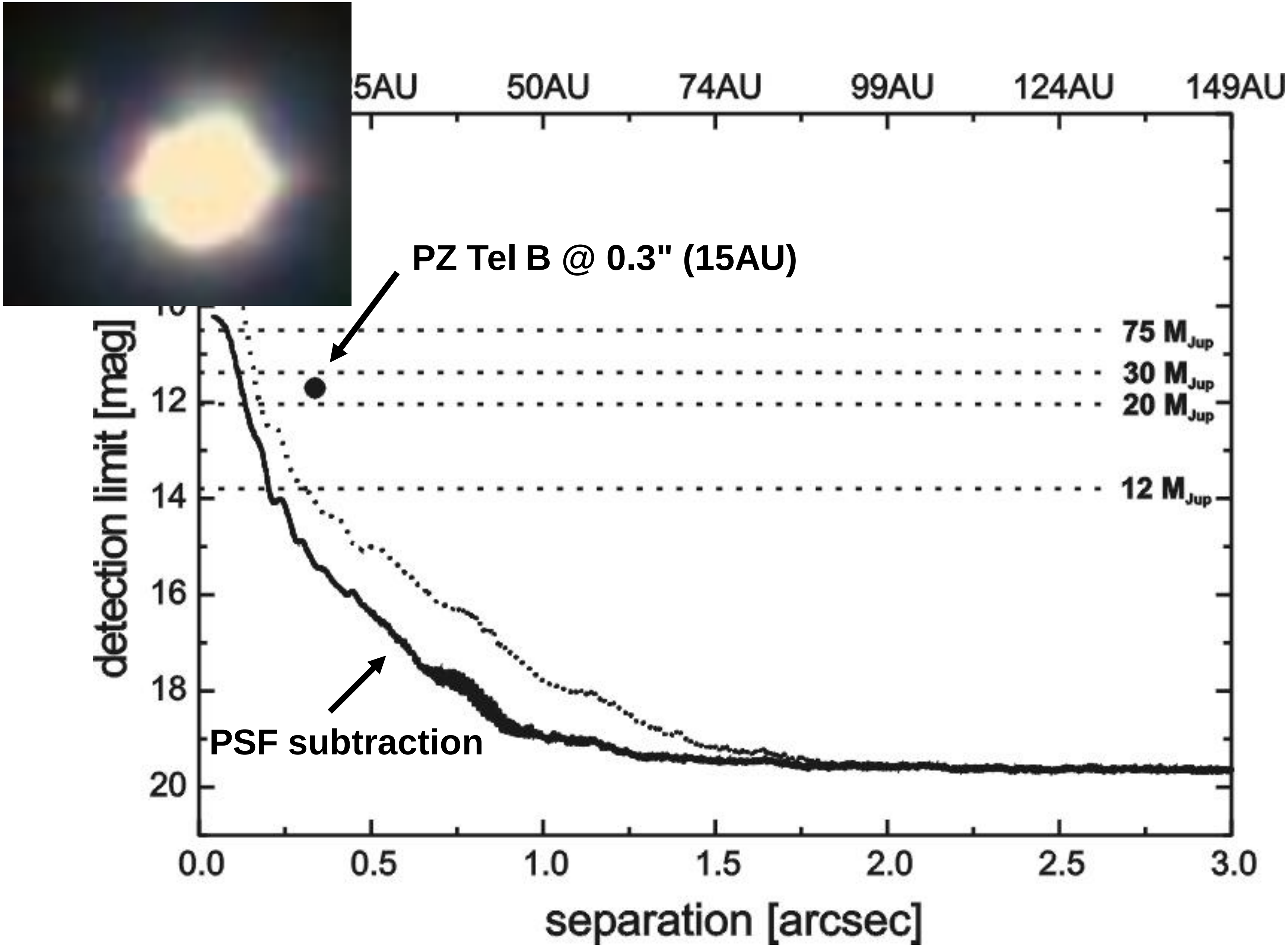
Mugrauer et al. 2010, A&A in press, arXiv:1008.4506

JHK colors give spectral type (late M)

➔ brown dwarf of ~ 40 Jup masses (at age and distance of host star)



PZ Tel
2010/05
2009/09
if background
2010/05
2009/09
if bound
2007/06
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
ΔDec [arcsec]
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
ΔRA [arcsec]


25AU
50AU
74AU
99AU
124AU
149AU
PZ Tel B @ 0.3" (15AU)
75 MJup
30 MJup
20 MJup
12 MJup
detection limit [mag]
12
14
16
18
20
PSF subtraction
0.0
0.5
1.0
1.5
2.0
2.5
3.0
separation [arcsec]

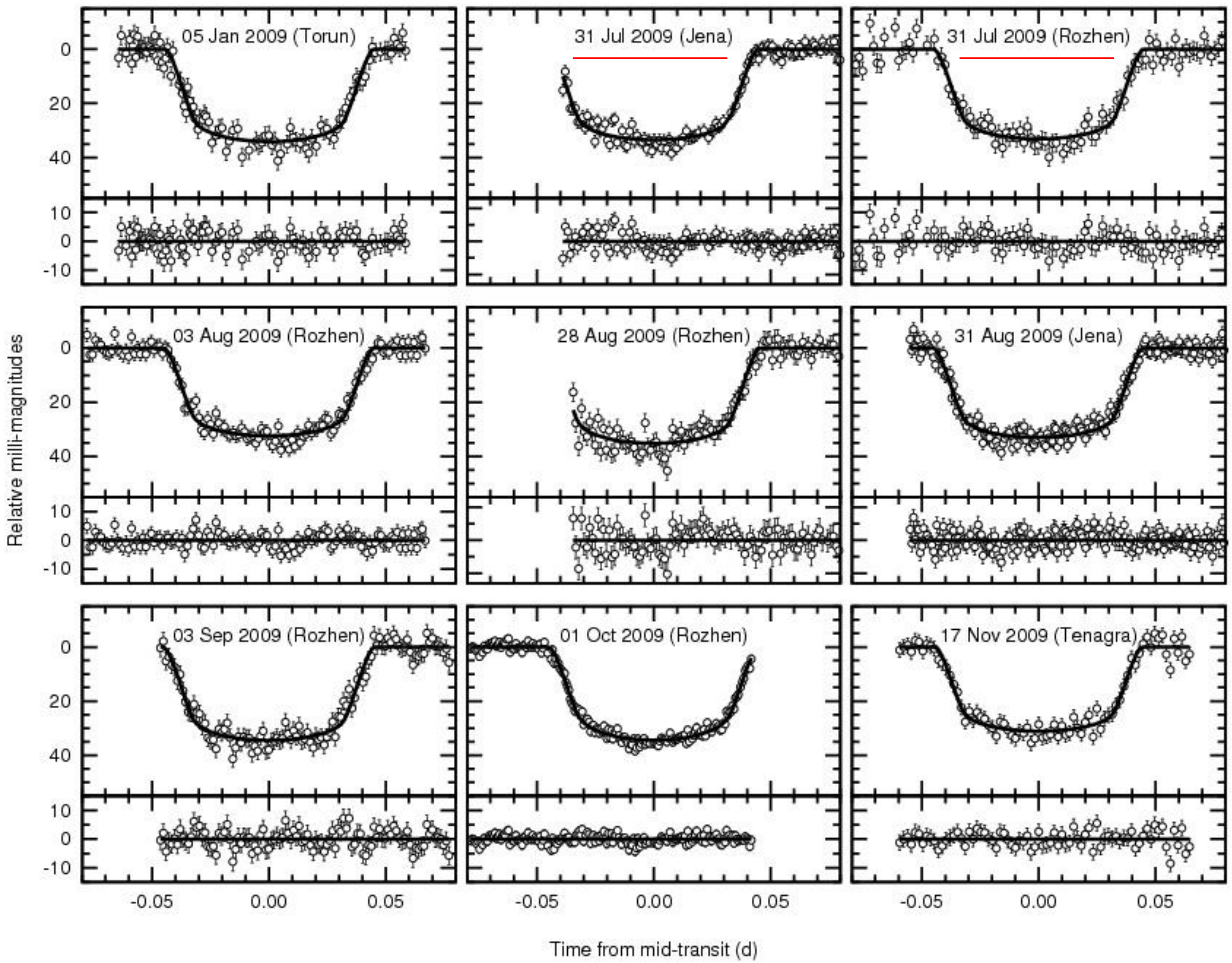
NB 2:

Planet transit observations in Jena

90-cm telescope in Großschwabhausen (GSH) near Jena

Three telescopes with four instruments for
imaging, photometry, Lucky Imaging, and spectroscopy

Wasp-10: 9 light curves of 8 transits from 4 different observatories



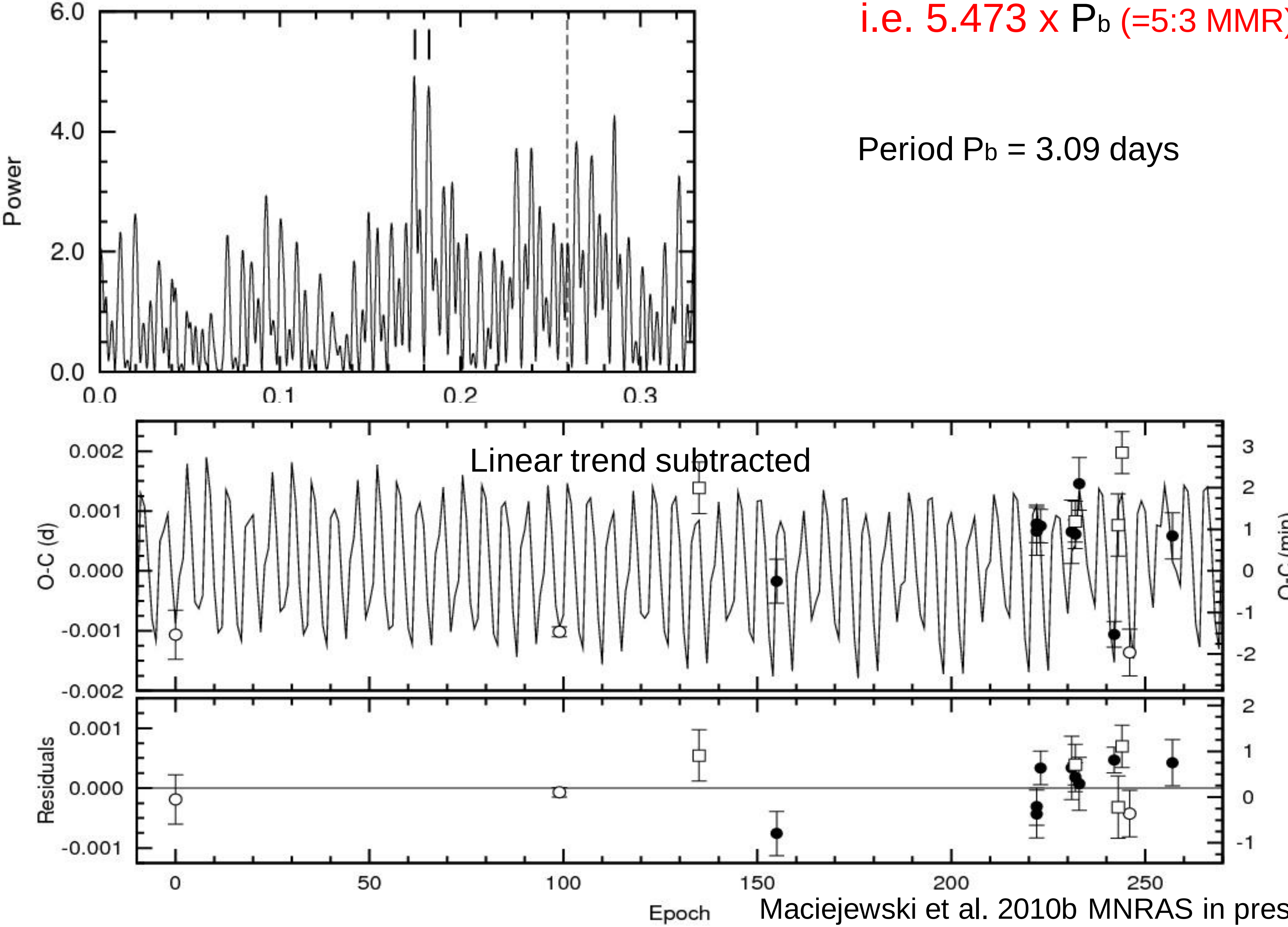
Relative photometry rms +/- 1.1 to 2.7 milli-mag

Mid-transit times error +/- 18 to 45 sec

Maciejewski et al. 2010b MNRAS in press

Wasp-10: 2 different frequencies: f=0.183/P (poor) and f=0.175/P (good) i.e. 5.473 x P_b (=5:3 MMR)

Period P_b = 3.09 days



Maciejewski et al. 2010b MNRAS in press

Wasp-10: after removing Wasp-10b from RadVel data,

one new frequency: 12 days
(rotation period of star)

12 day rotation period
also seen in WASP photometry
(Christian et al. 2009)

Peak-to-peak photometric variation
~ 20 milli-mag, typical for spotted star

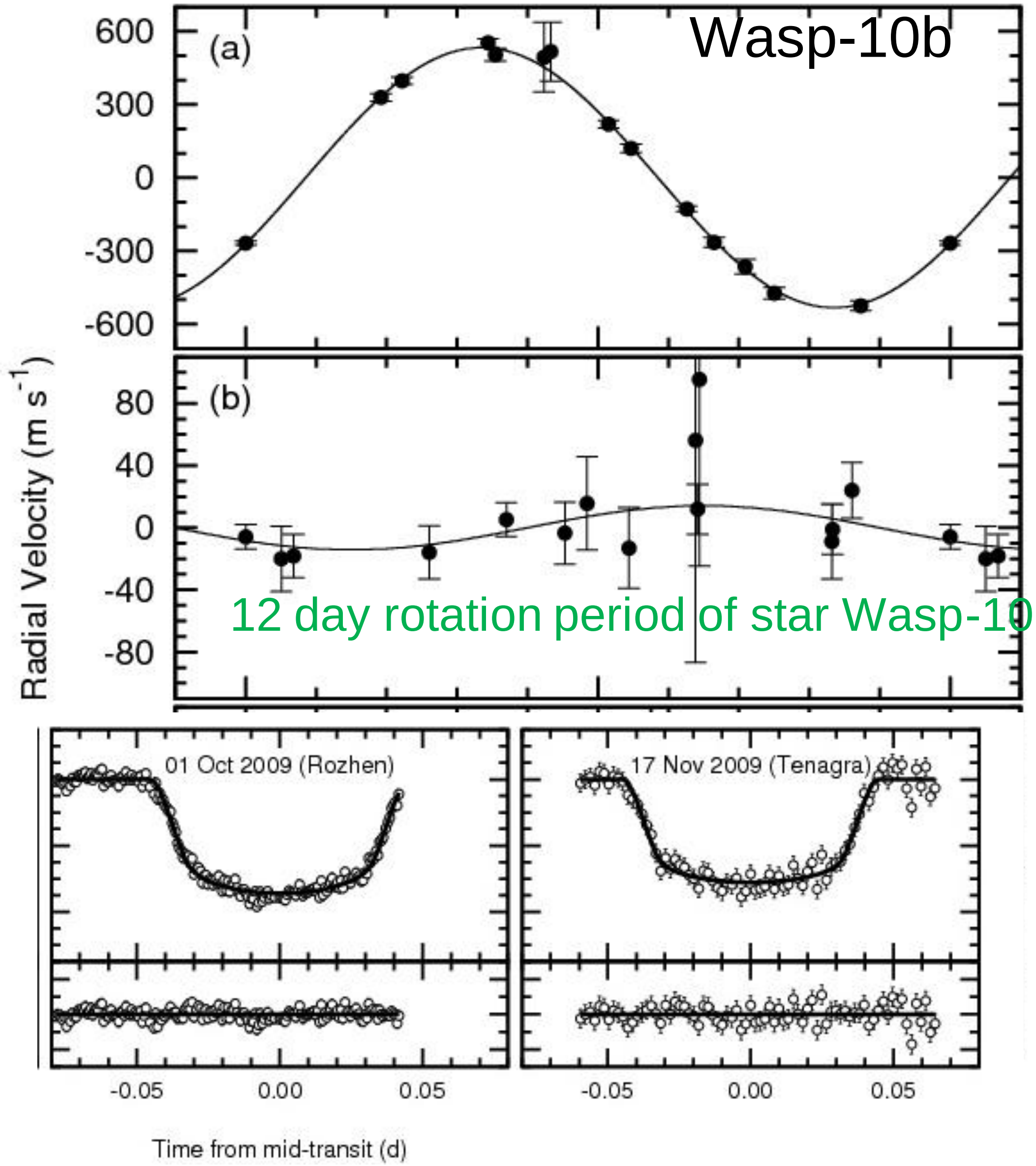
Gyro-chronology :
12 day rotation for
K5 dwarf star gives

Age 200 to 350 Myrs

(intermediate between
Pleiades and Hyades)

i..e two quite young planets

Youth can also explain
the large radius of Wasp-3b
(1.3 Jup radii for 3 Jup masses)
a 10% effect !



Maciejewski et al. 2010b MNRAS in press

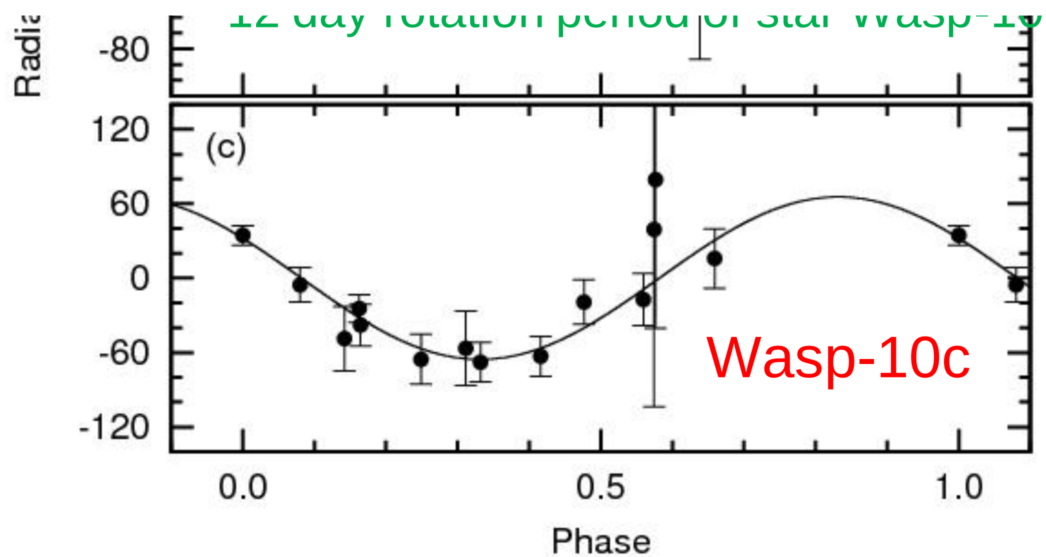
Wasp-10: TTV
best explained by
additional planet
Wasp-10c
with 0.1 Jup mass
in outer 5:3 MMR
with 5.23 day period

(Wasp-10b:
2 Jup mass
With 3.09 day period)

Maciejewski, Dimitrov, Neuhäuser,
…, **Tachihara, Takahashi**, …
2010b MNRAS in press

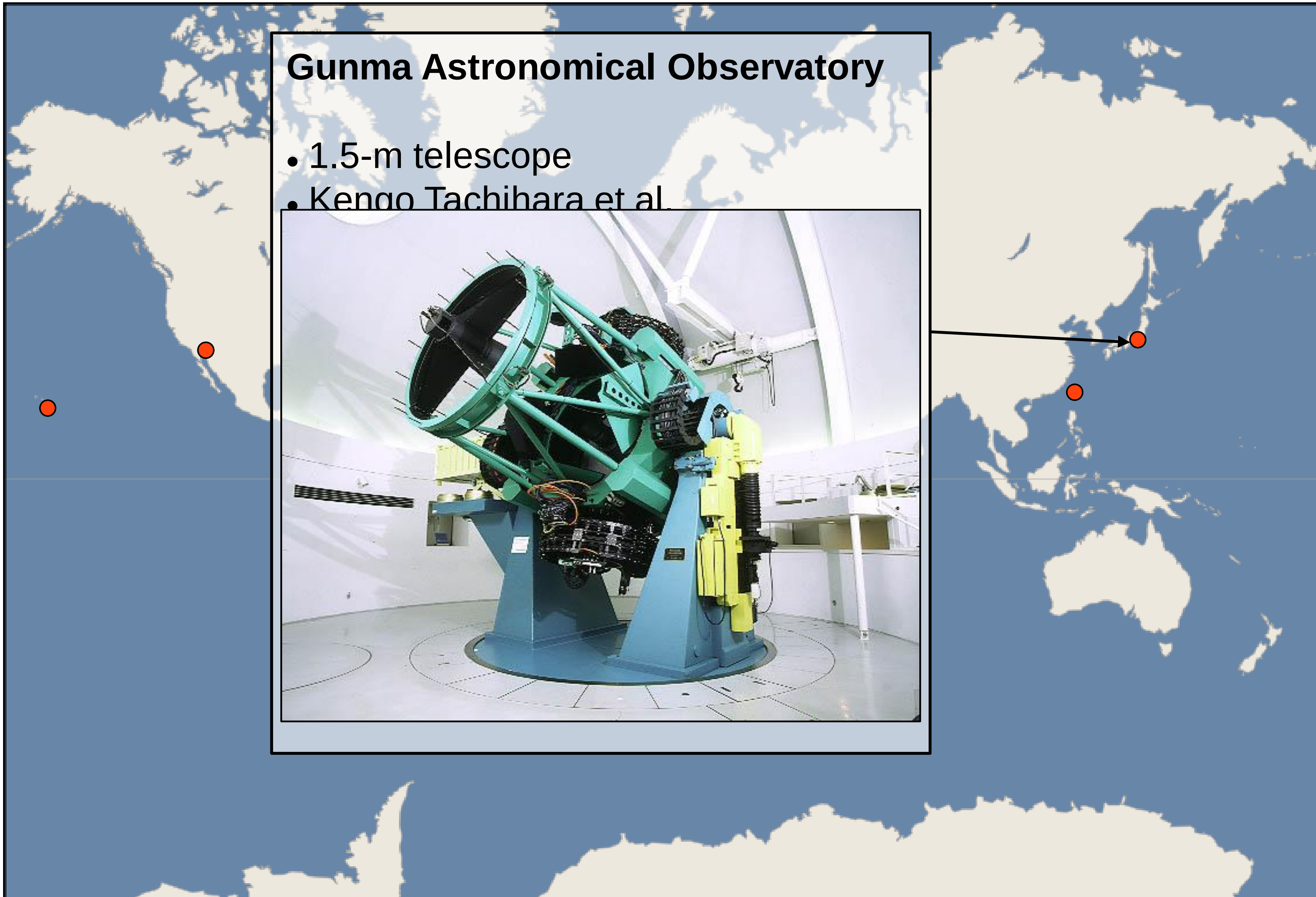
Table 4. Outer-perturber solutions which reproduce the observed $O-C$ variation. P^{ttv} indicates which periodicity in the $O-C$ diagram (P_1^{ttv} or P_2^{ttv}) is reproduced by a solution, a_c denotes the semi-major axis of the perturbing planet, M_c is its mass, P_c is its orbital period, K_c is the expected semi-amplitude of the radial-velocity variation and χ^2_{red} is the lowest value of reduced chi-square for direct model fitting.

No.	P^{ttv}	a_c (au)	M_c (M_J)	P_c (d)	K_c (m s^{-1})	χ^2_{red}
1	1	0.0536	0.10	5.2293	14.2	1.5
2	2	0.0539	0.10	5.2647	14.1	2.5
3	2	0.0682	0.55	7.4962	69.1	2.8
4	1	0.0686	0.55	7.5677	68.9	2.8



Young Exo-planet Transit Initiative (YETI)

network of telescopes at all longitudes
to observe 24 / 7
in order not to miss a transit



Gunma Astronomical Observatory

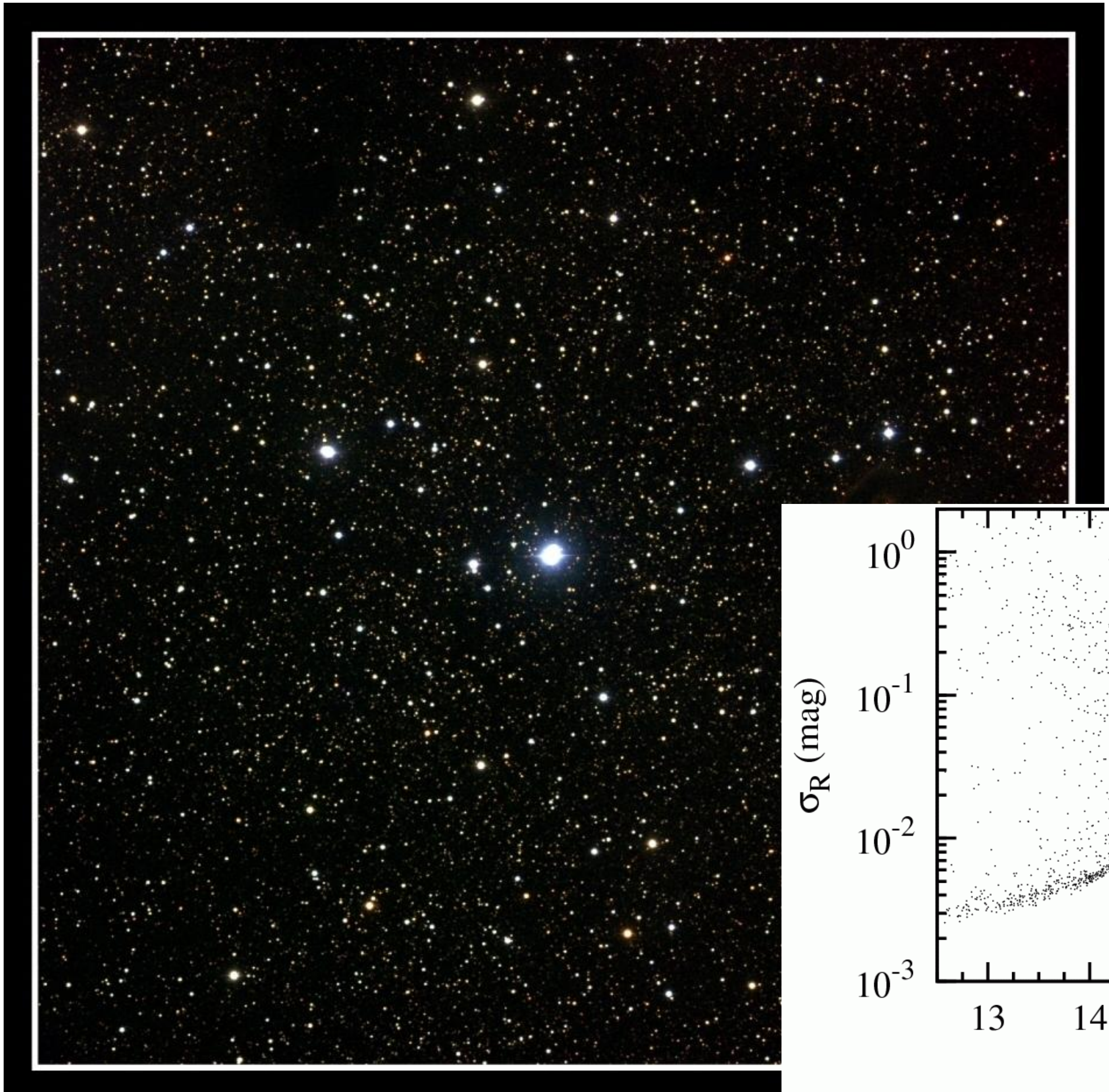
- 1.5-m telescope
- Kengo Tachihara et al.

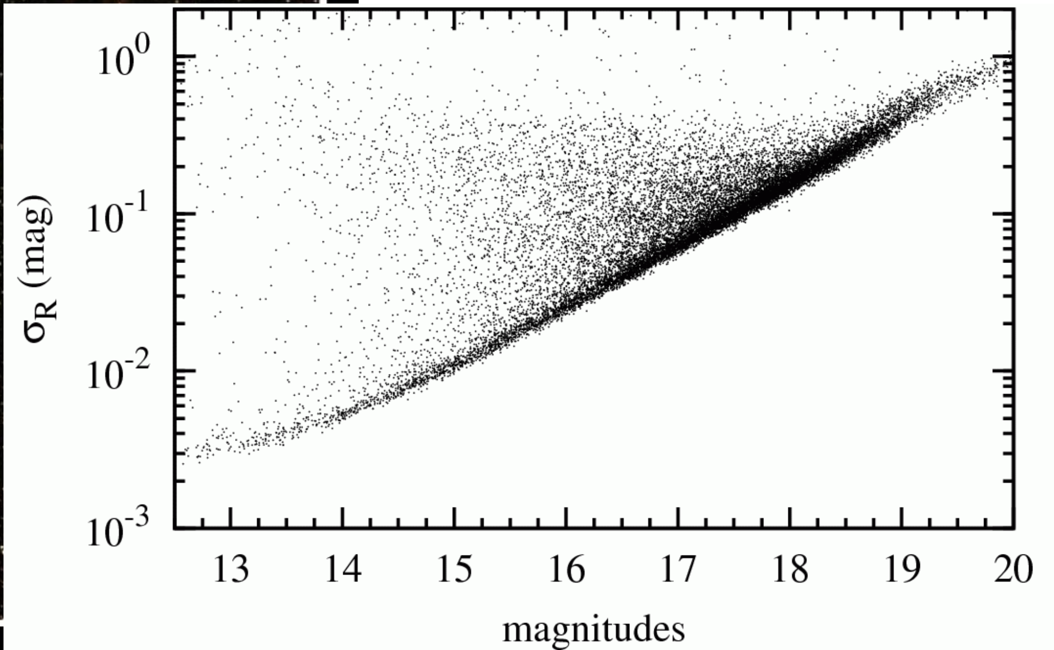
Transit search in young clusters started with Schmidt Teleskop Kamera (STK) at 90 cm:

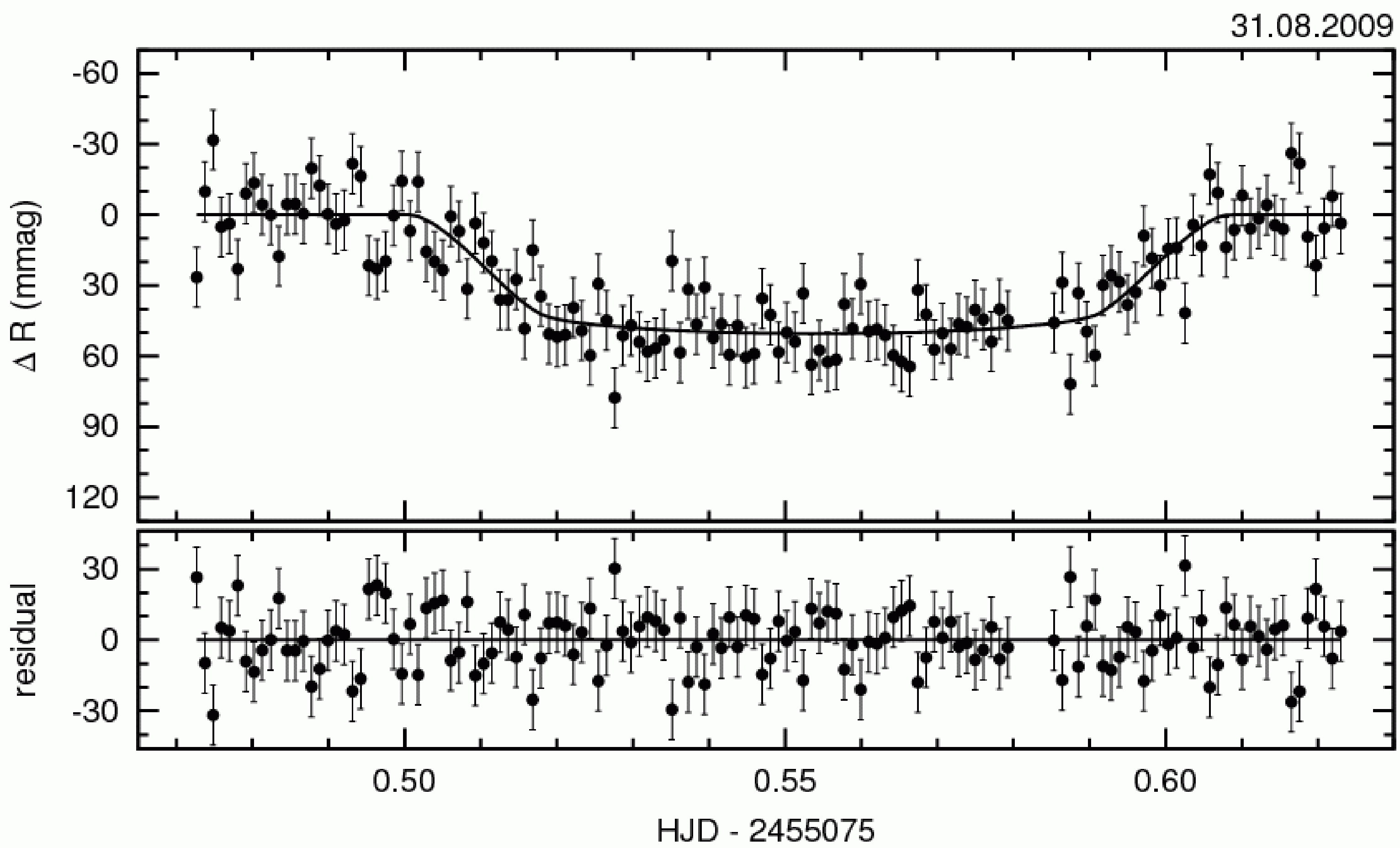
Few Myrs cluster Trumpler-37 with 18000 stars.

Other clusters later.

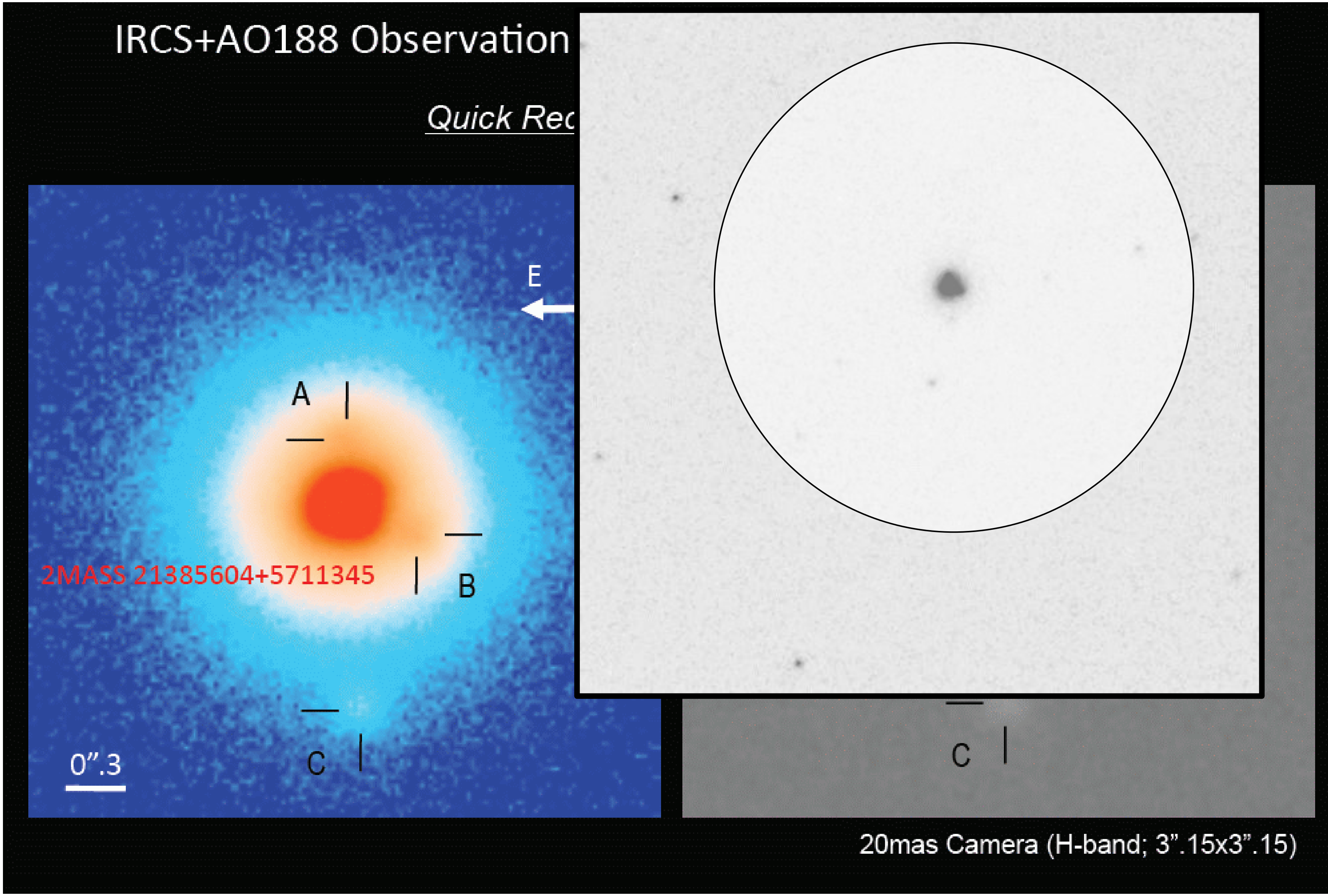
Other telescopes around the world are participating to cover all longitudes to observe 24 / 7.






31.08.2009
-60
-30
0
30
60
90
120
Δ R (mmag)
30
0
-30
residual
0.50
0.55
0.60
HJD - 2455075

SUBARU AO188/IRCS



Hiroshi TERADA

Rad Vel follow-up with Keck on 26 & 28 Feb 2010

Summary:

- ➔ Direct detection of planets is possible (wide separations)
- ➔ Mass determination still very challenging (model dependent)
- ➔ JHK spectra and model atmospheres yield T, g, R, then mass
- ➔ direct imaging of young planets can constrain planet formation time-scale and migration theories

- ➔ New brown dwarf companion found to PZ Tel

- ➔ Planetary Transit Timing Variations find new planets in Wasp-3 & -10
- ➔ Young cluster monitoring to find very young transiting planets