Direct detection of sub-stellar companions in young stars with disks

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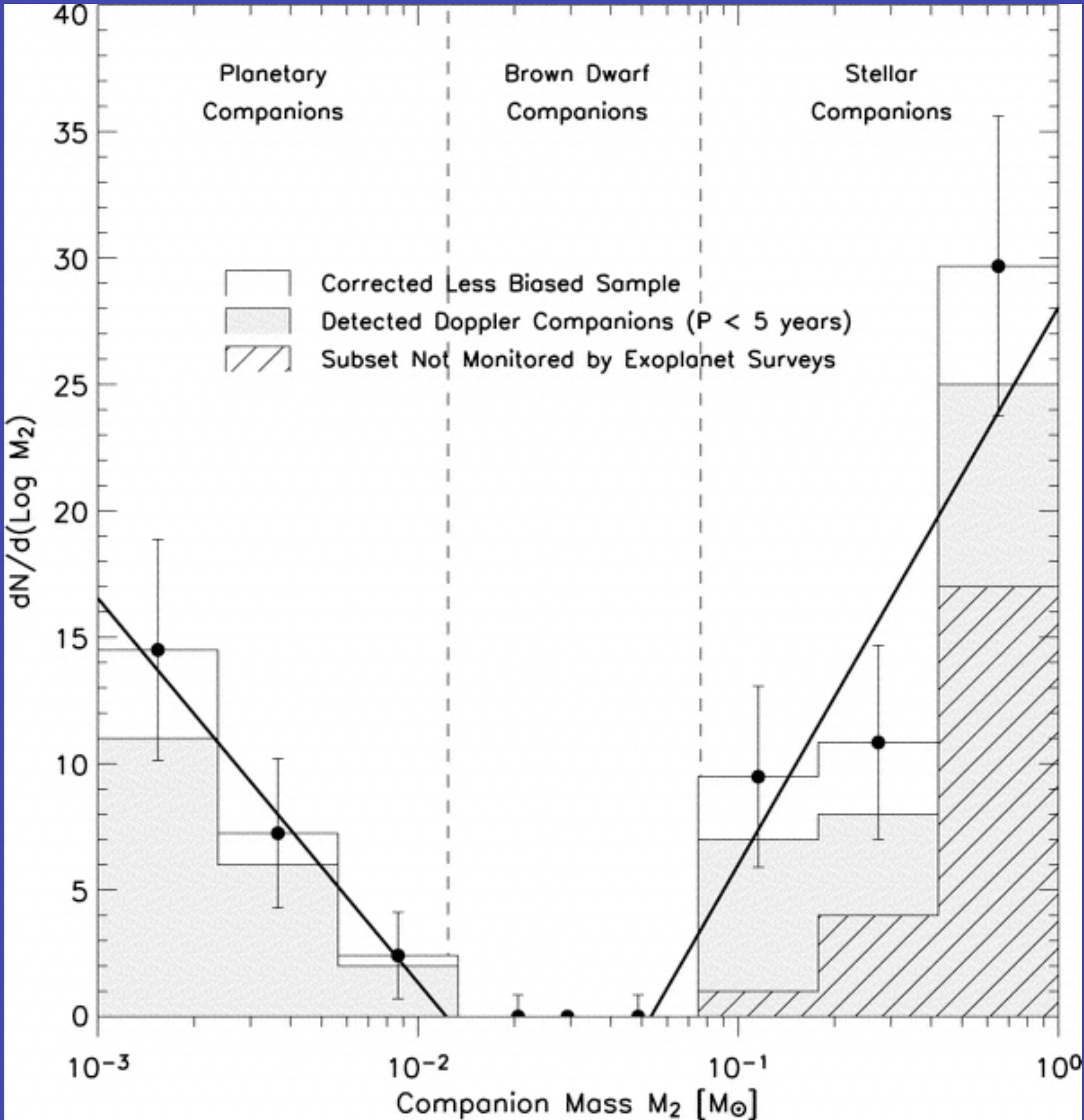
Topics:

→ Homogeneous mass determination of planet candidates imaged directly
→ Stability of star + planet(s) (+ disk) systems, in particular HR 8799
→ Sub-stellar companion and disk around CT Cha (new 3mm data)

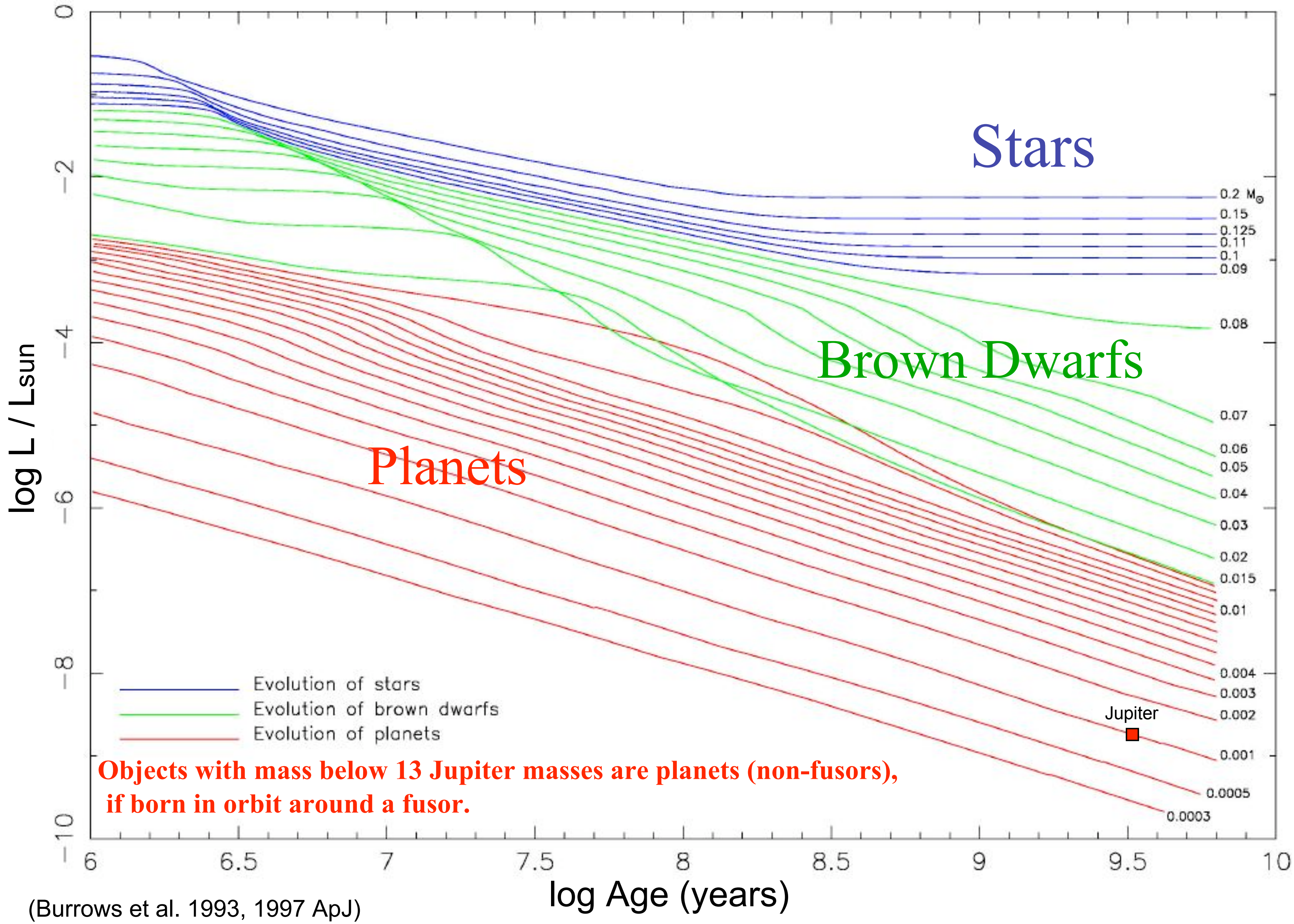
The brown dwarf desert: 20 to 50 Jup masses



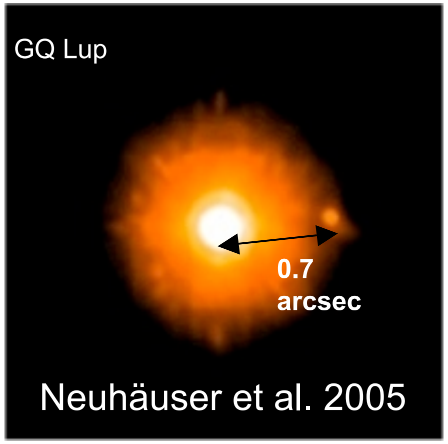
Lineweaver & Grether 2006

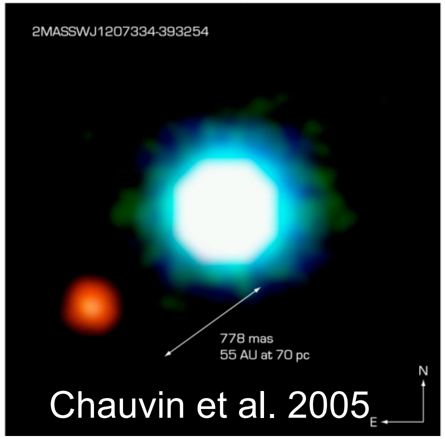
Objects below ~ 35 Jup masses form *differently*, i.e. planets …

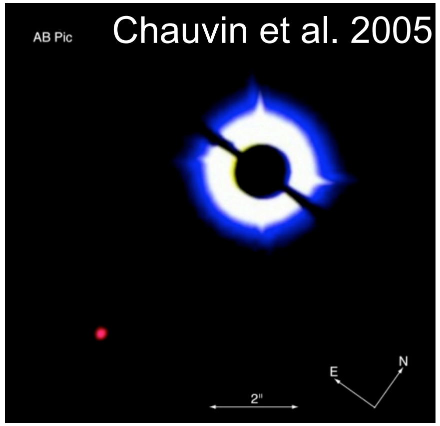
Luminosity vs. age (stars, brown dwarfs, and planets)

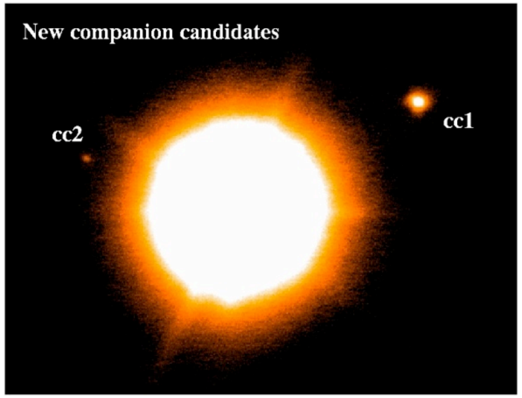


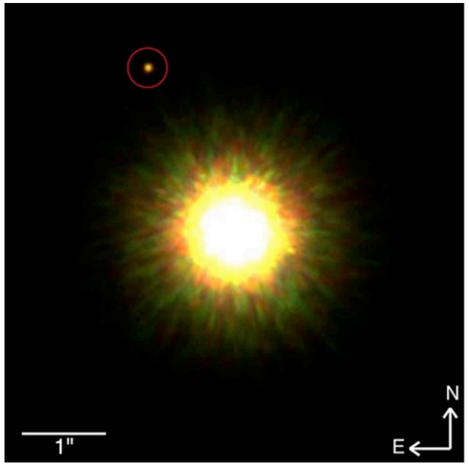
(Burrows et al. 1993, 1997 ApJ)

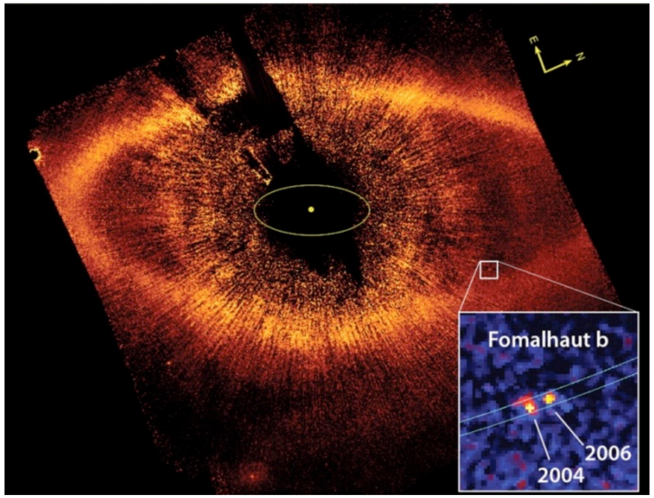

GQ Lup
0.7
arcsec
Neuhäuser et al. 2005

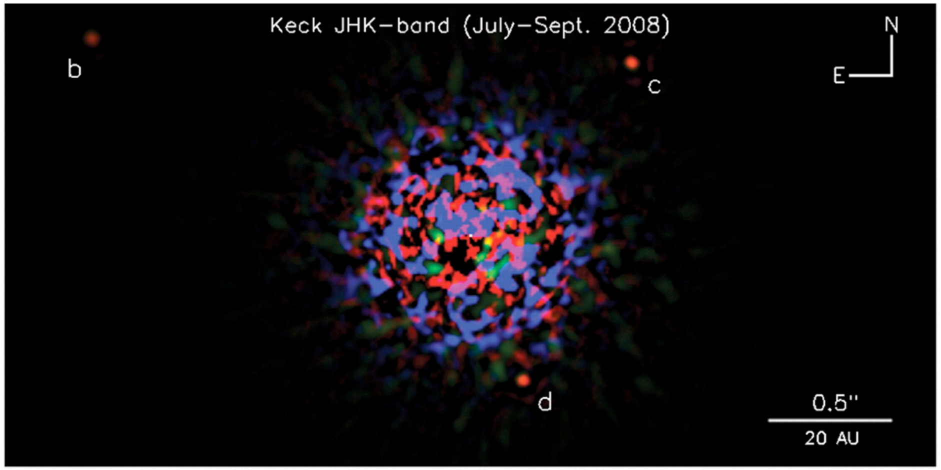

2MASSWJ1207334-393254
778 mas
55 AU at 70 pc
N
E
Chauvin et al. 2005

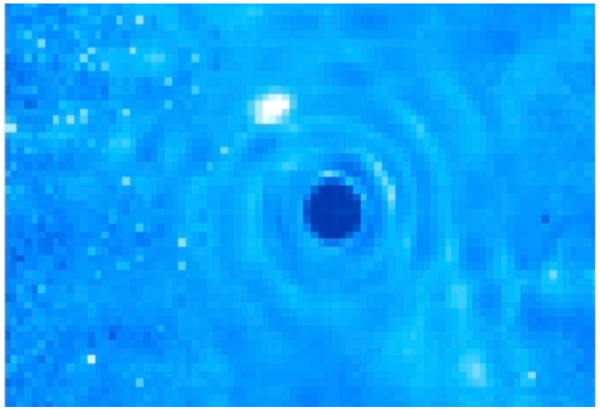

AB Pic
Chauvin et al. 2005
E
N
2"


New companion candidates
cc2
cc1


1"
N
E


Fomalhaut b
2006
2004


Keck JHK–band (July–Sept. 2008)
b
c
N
E
d
0.5''
20 AU



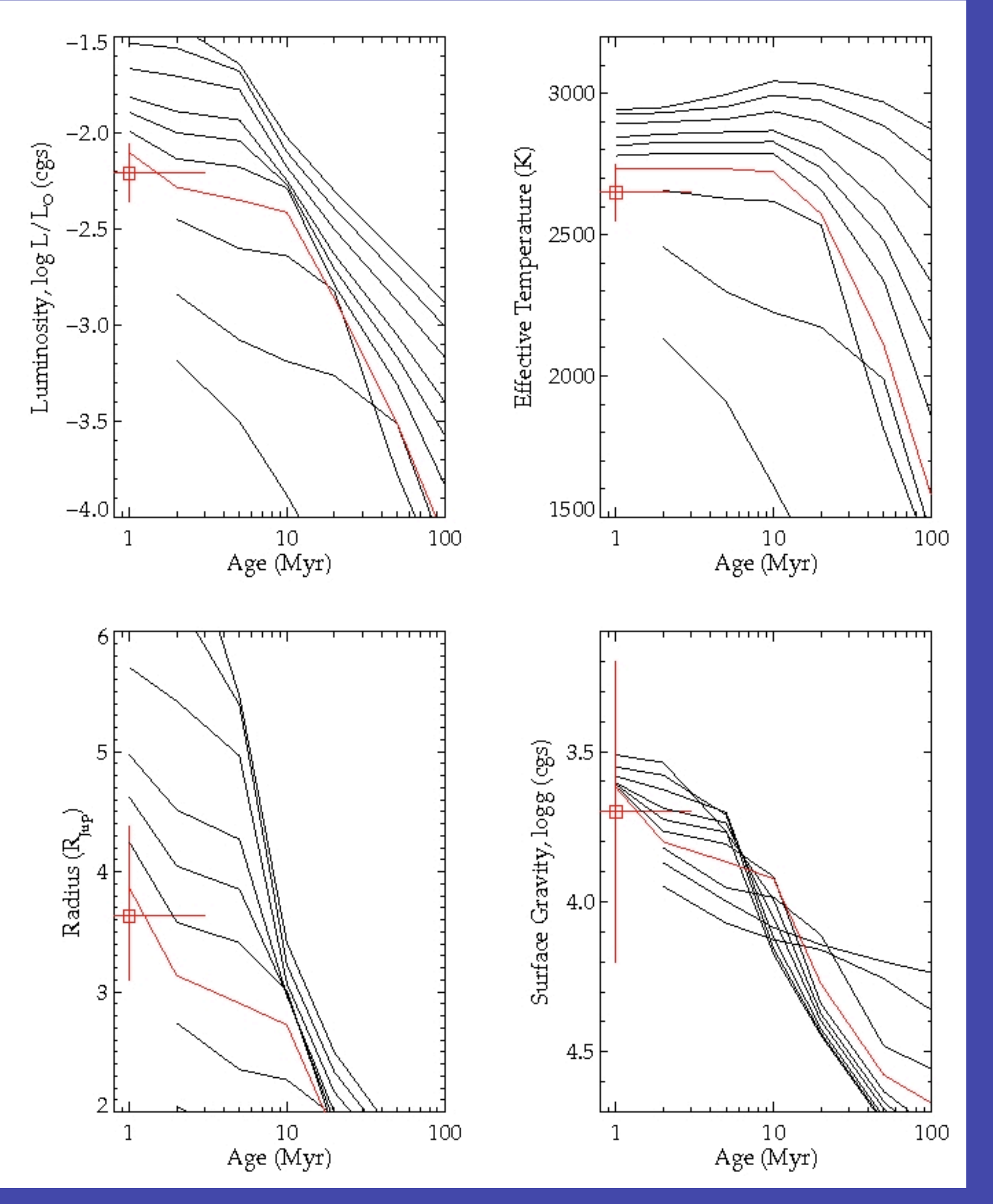
(Burrows et al. tracks for masses 10 to 70 M_jup)

Determination of mass

By comparison with
evolutionary models
& tracks (hot start)

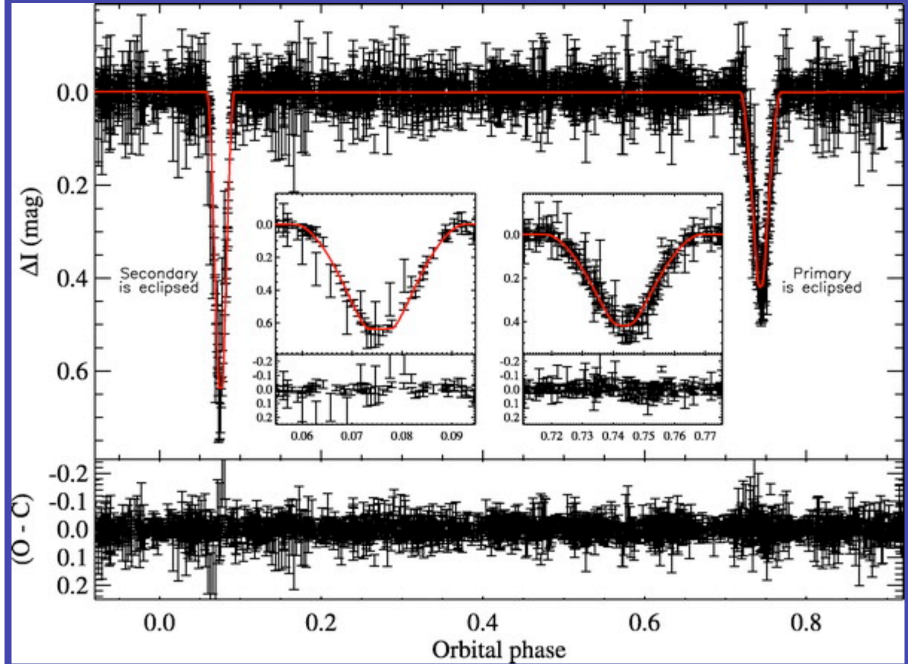
<u>Observables:</u>
Luminosity L
Temperature T
Gravity log g
Radius R
Age (of host star)

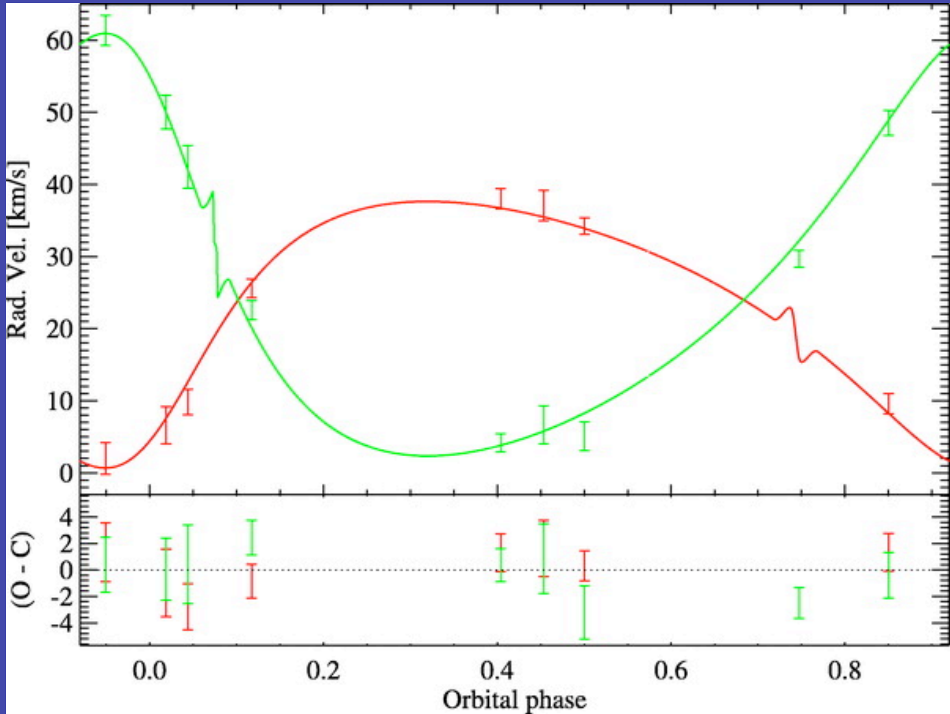
Model yields <u>mass</u>
of the companion

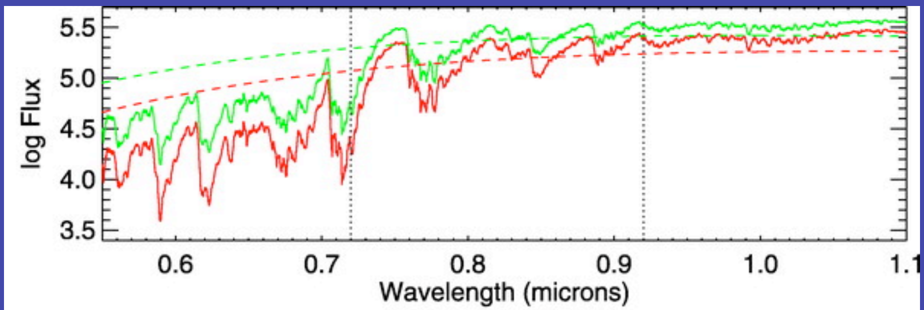


Example given here:
GQ Lup b and
Burrows et al. 1997 models
➔ 20-25 M_jup (4 to 36 M_jup), figure from Andreas Seifahrt PhD thesis (red: 25 Jup)

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

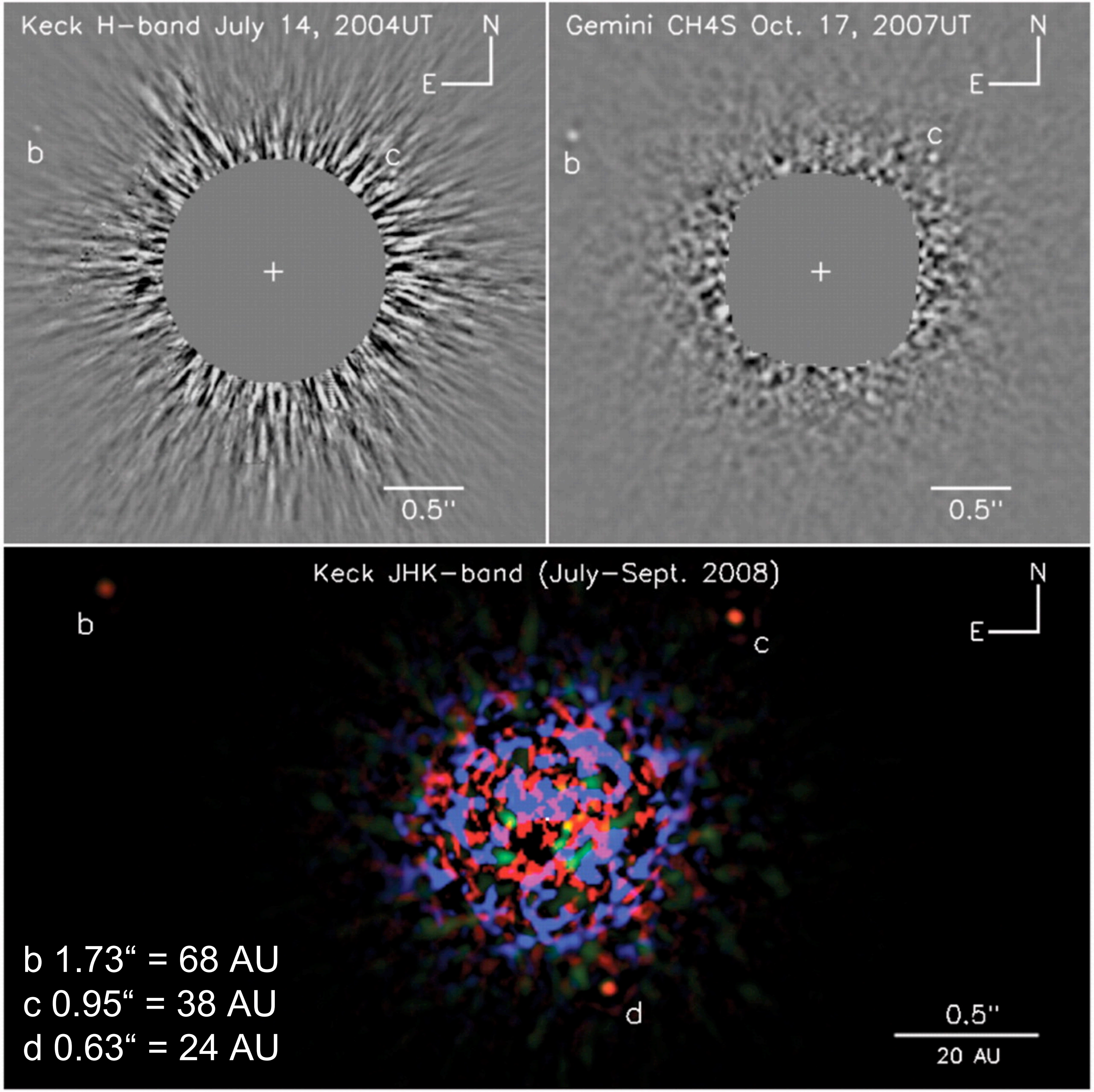
Model derived masses:

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

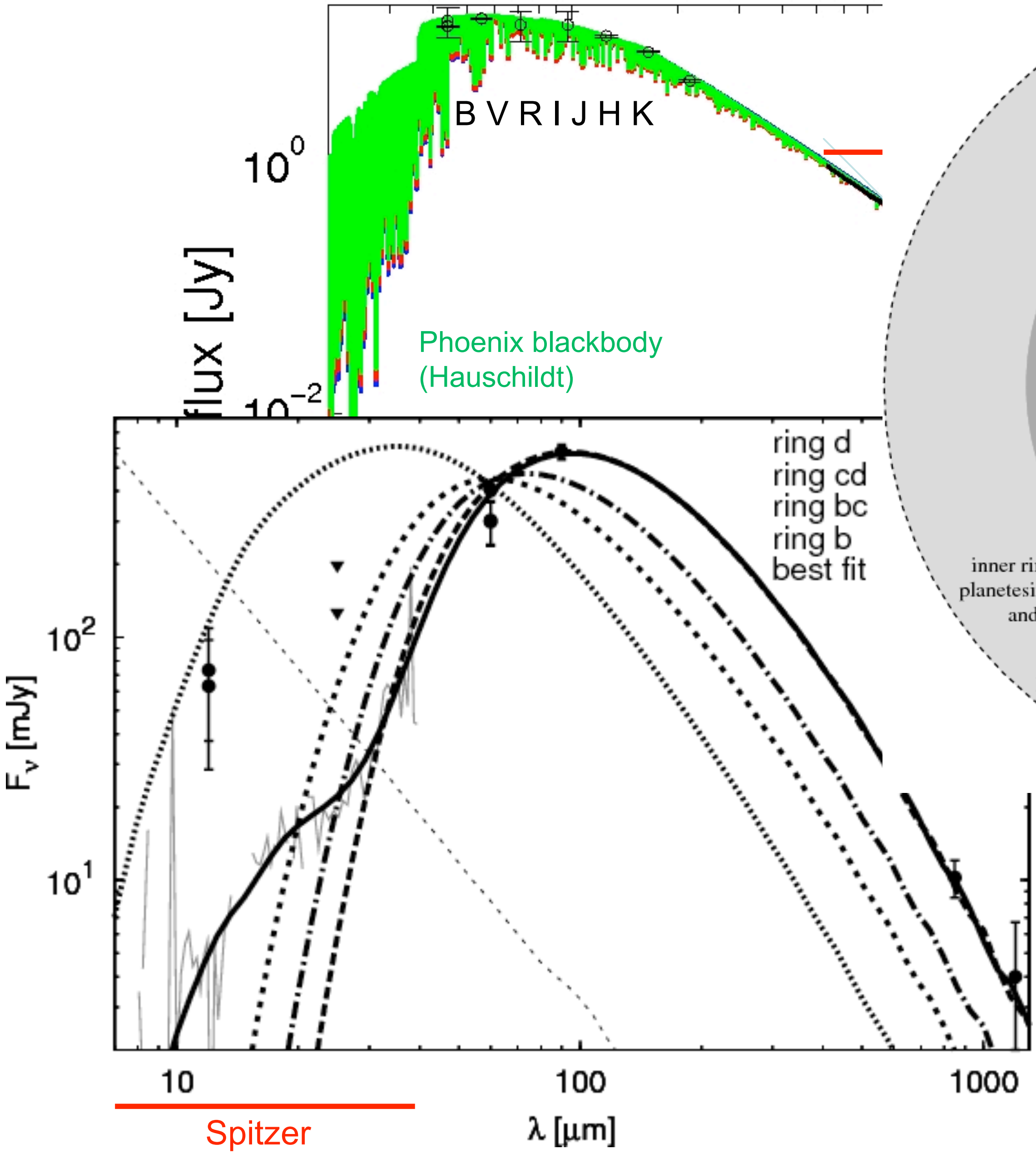
(Schmidt, RN, Seifahrt, Conf. Proc., astro-ph)

HR 8799

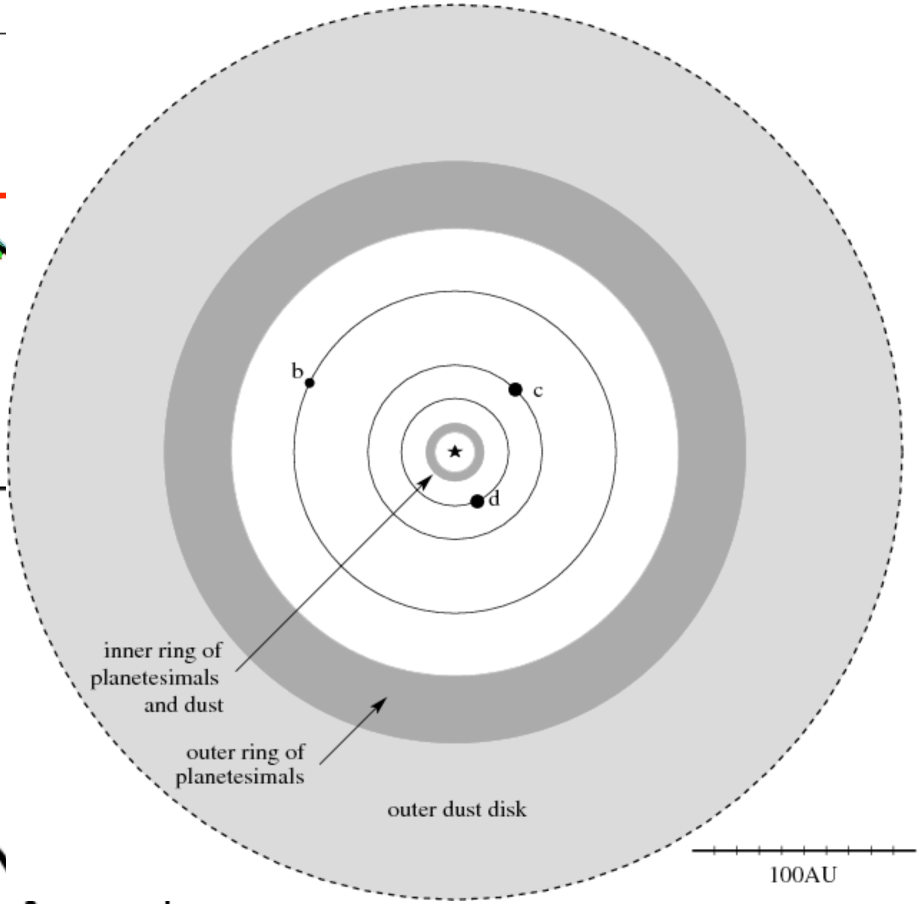


Marois et al. 2008

SED and disk around HR 8799



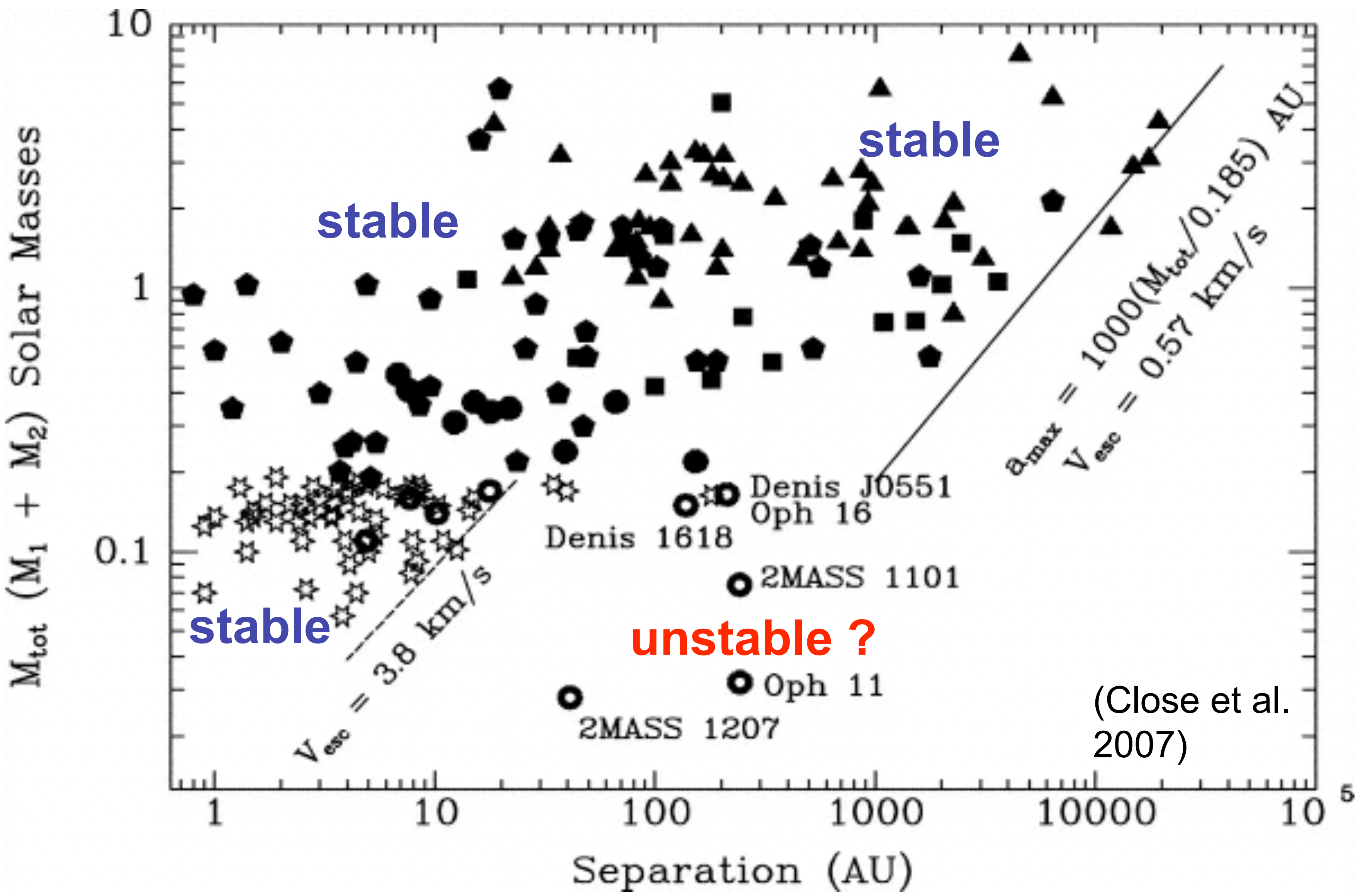
HR 8799

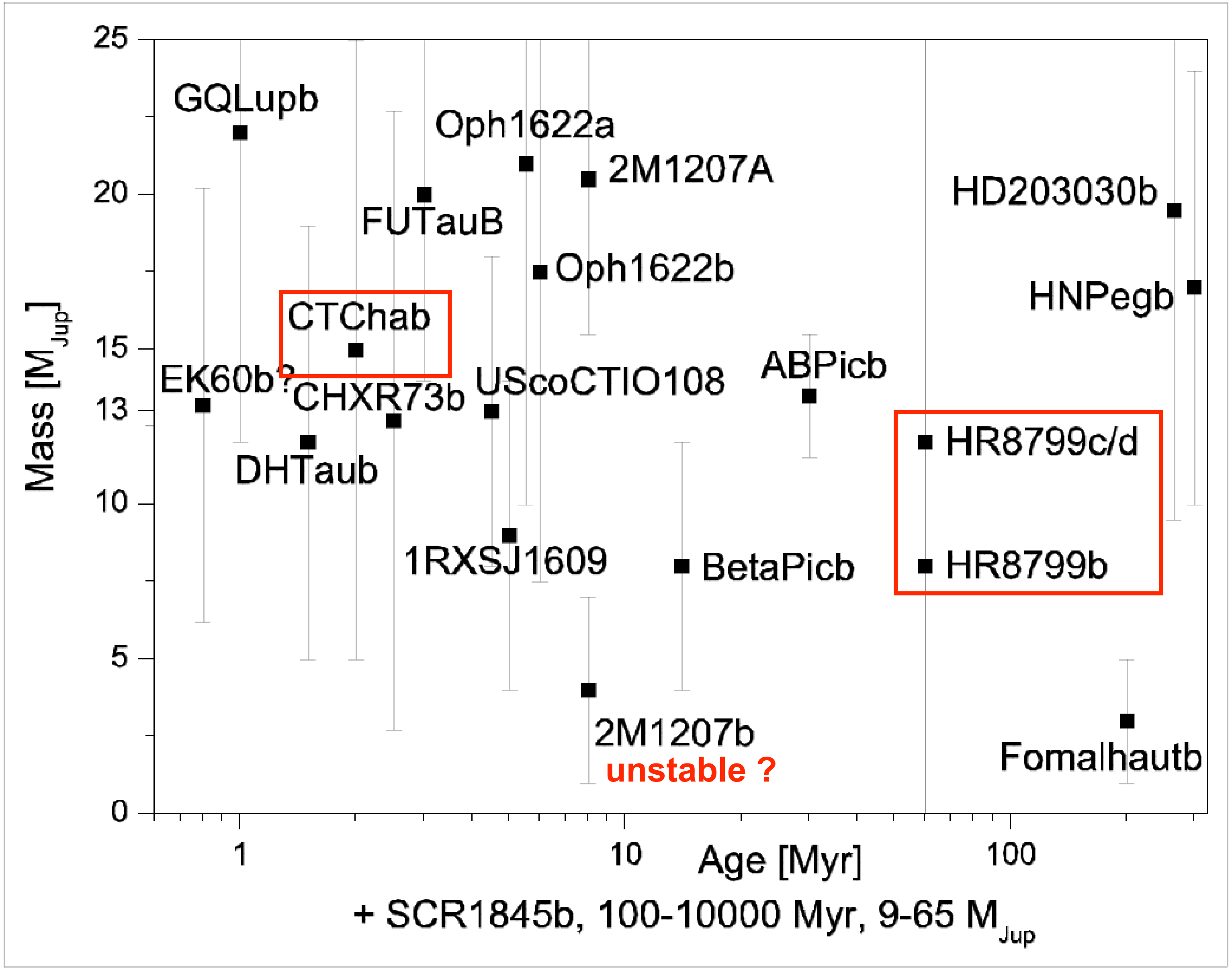


Inner ring at 3 to 15 AU.

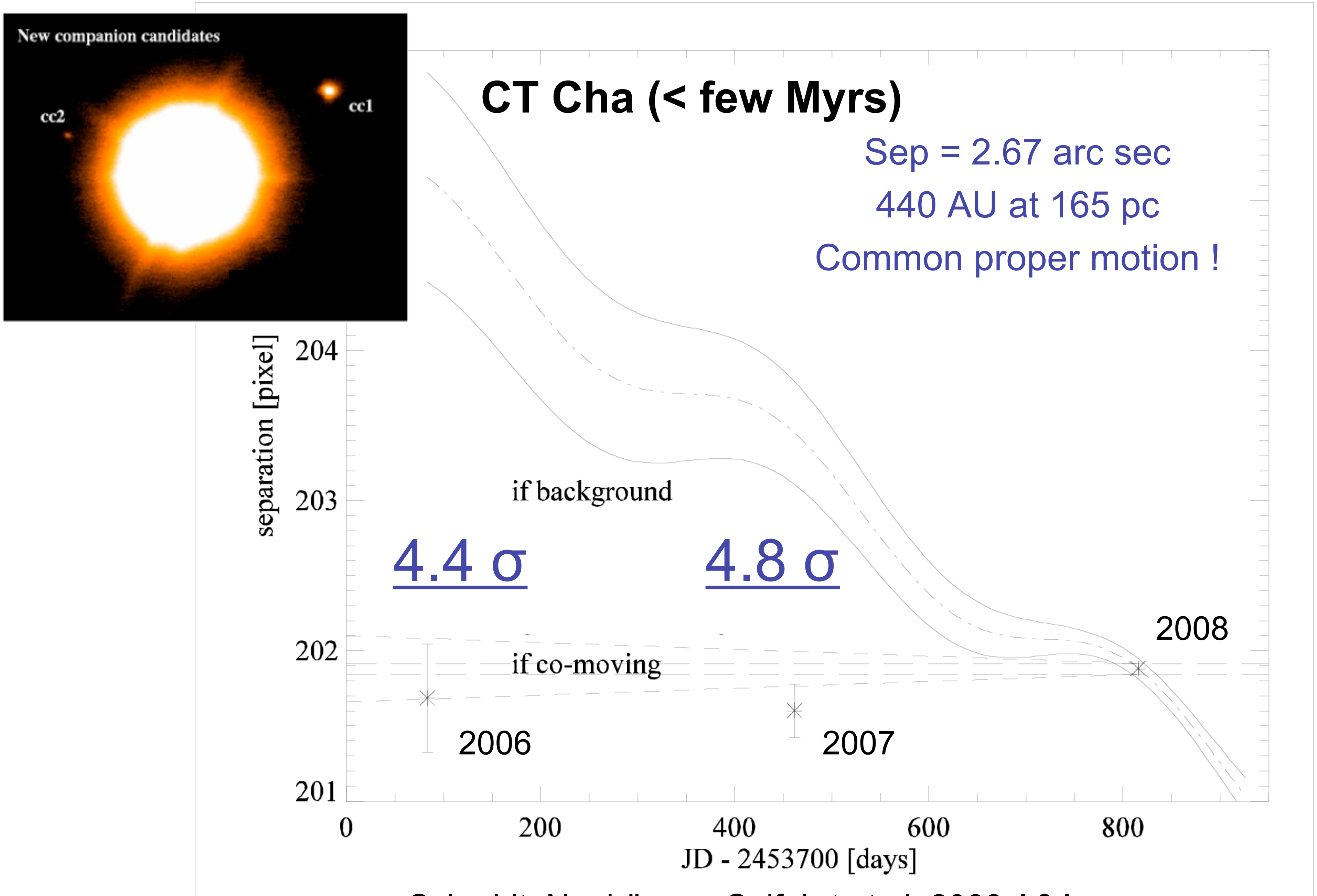
Companions and dust rings stable, only if masses are low, hence planets.

(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
(Close et al. 2007)
M_{tot} (M_1 + M_2) Solar Masses
Separation (AU)
10
1
0.1
1
10
100
1000
10000
10^5



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



Schmidt, Neuhäuser, Seifahrt et al. 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:

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

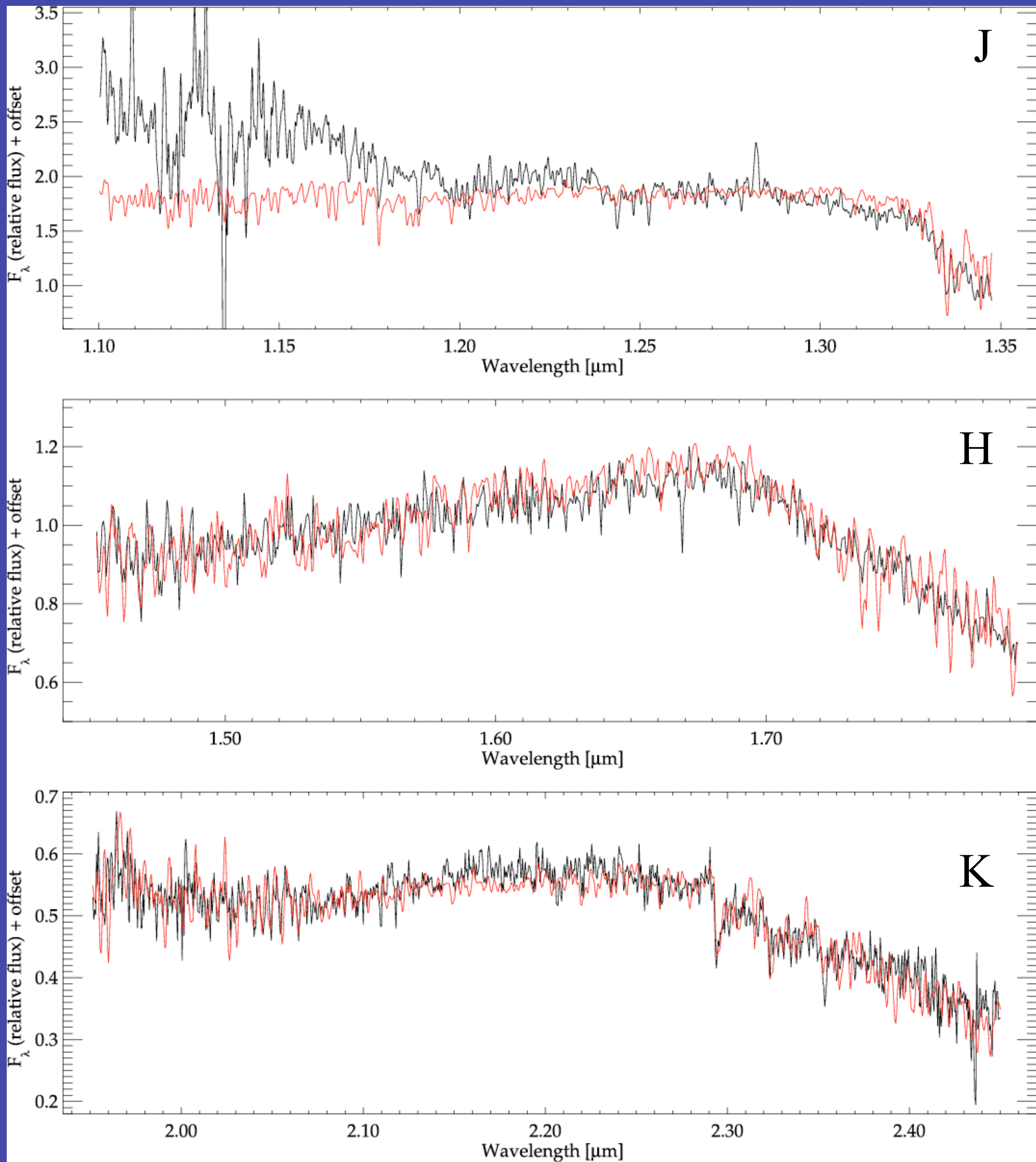
➔ L and T give radius (~ 2.2 ± 0.7 R_jup)

➔ **L, T, R, and g give mass:**

~ 17 ± 6 M_jup

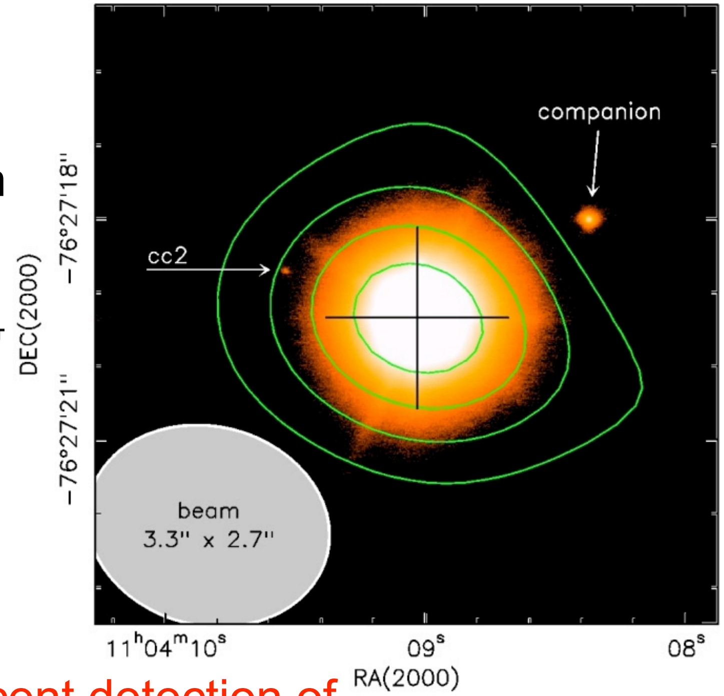
(planet or BD ?)

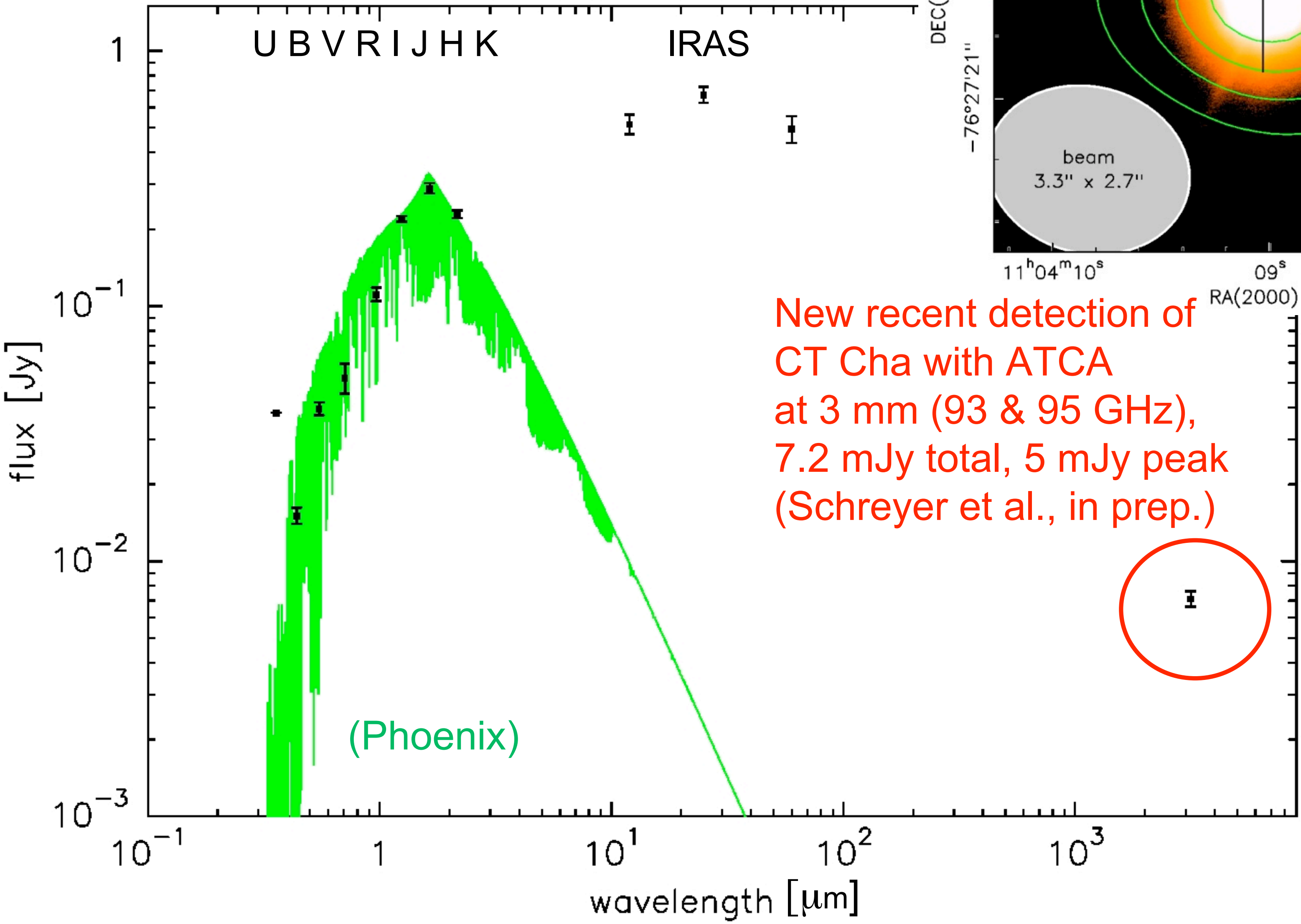
VLT Sinfoni spectra



Schmidt, Neuhäuser, Seifahrt et al. 2008 A&A

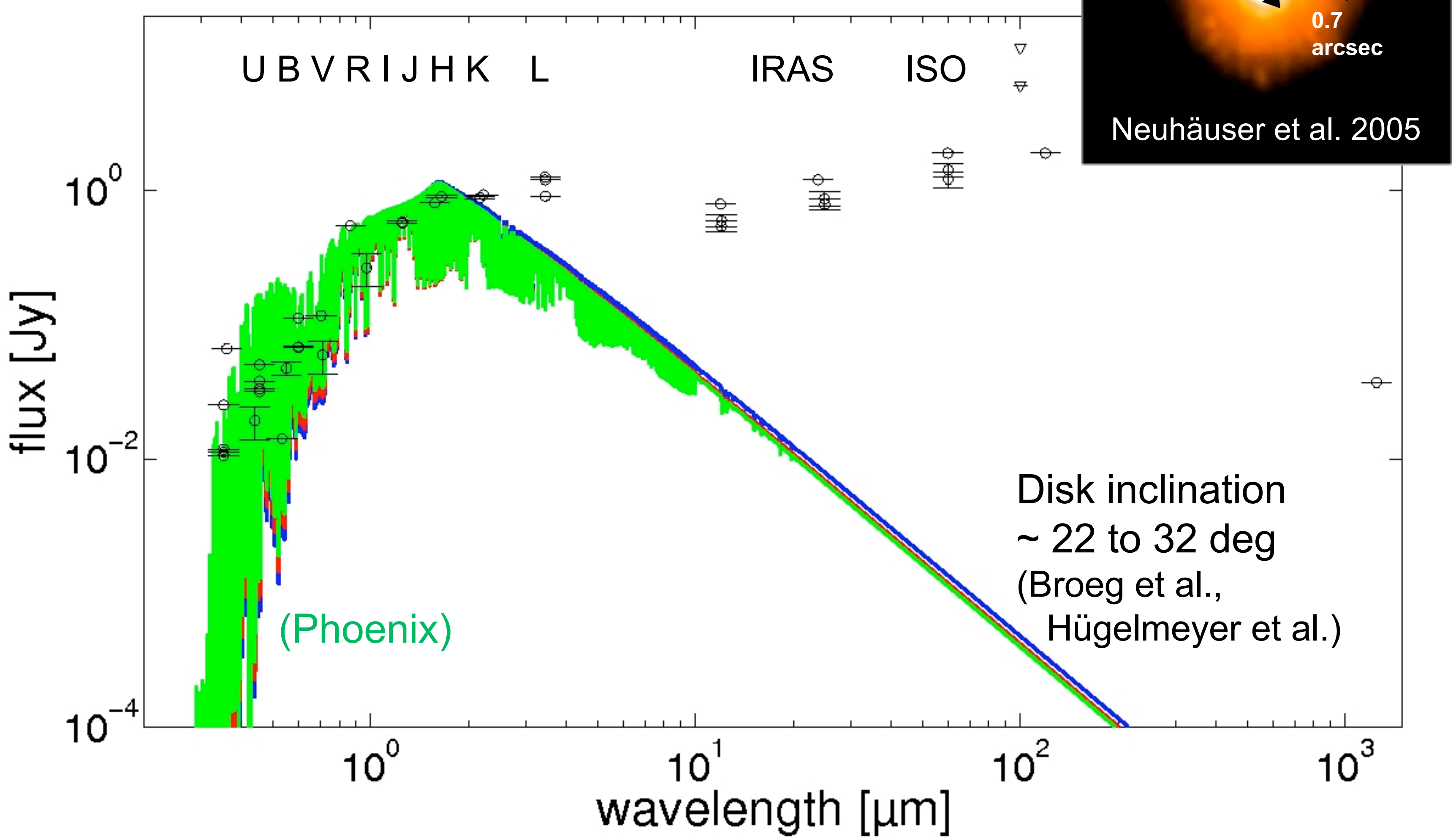
The disk around
classical T Tauri star CT Cha
(companion at 440 AU separation





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 (?)

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)

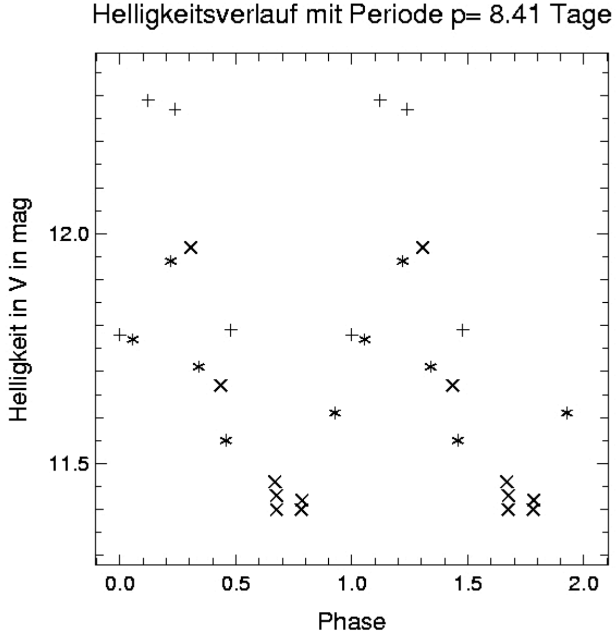
Direct imaging planets can constrain and probe

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

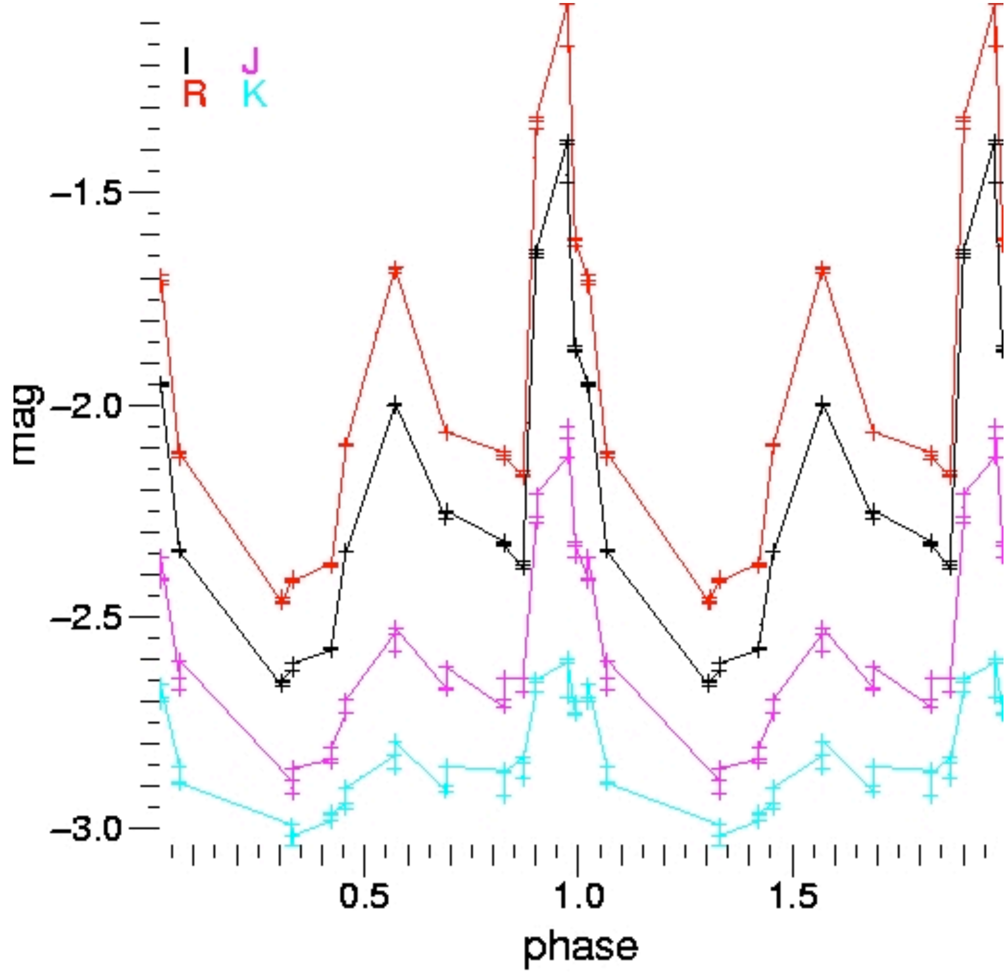
Rotation period of GQ Lup A

4 week monitoring with 8 min/night at CTIO (2005)

(data from Schwartz & Noah, Appenzeller et al., Bertout et al., 1977/78)



8.41 day period, but only one spot.



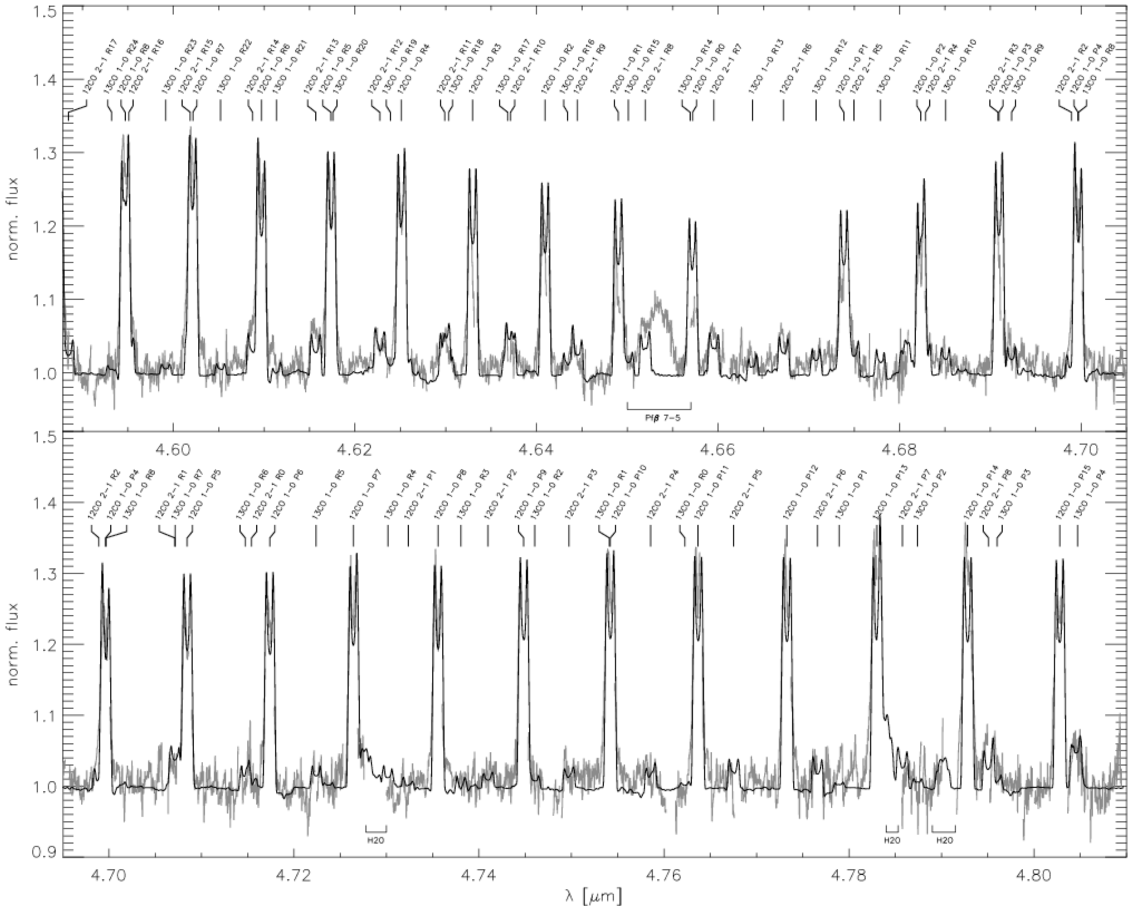
8.41 day rotation period with two bright spots !

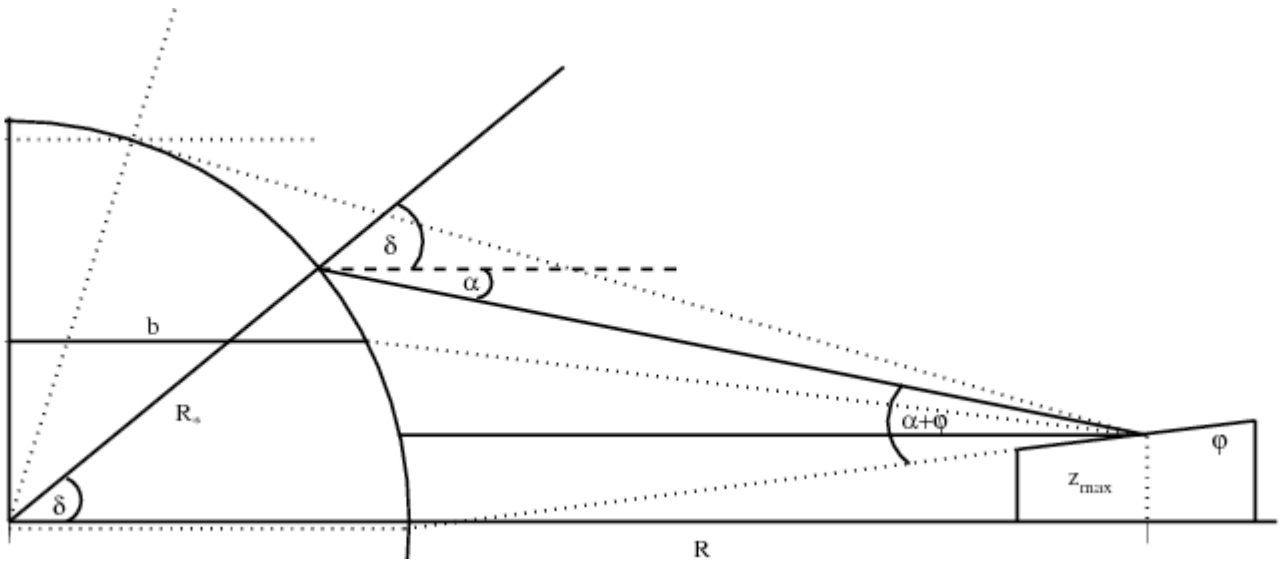
Rotation period, v sin i, and radius
(from Stefan-Boltzmann law with luminosity and temperature)
yield inclination of GQ Lup A (and its disk) to be ~ 27 5 degrees from pole-on
(26 to 39 deg, if up to half the luminosity is from disk accretion).

(Broeg, Schmidt, Guenther, Gaedke, Bedalov, Neuhäuser, Walter, 2007, A&A)

GQ Lup observed with CRIRES,
compared to radiative transfer
Disk model,
gives 22 deg disk inclination
(Hügelmeyer et al. 2009 A&A)

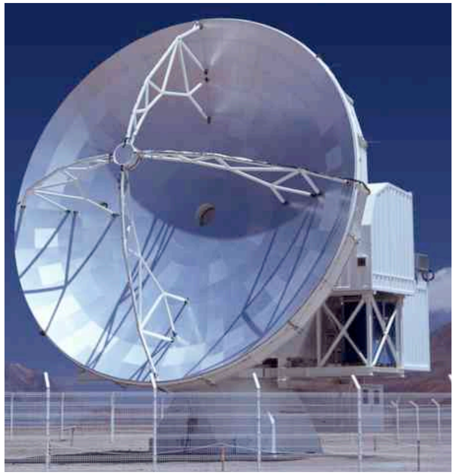
At inner disk at 0.052 to 0.5 AU,
Accretion rate 3e-9 Msun / yr

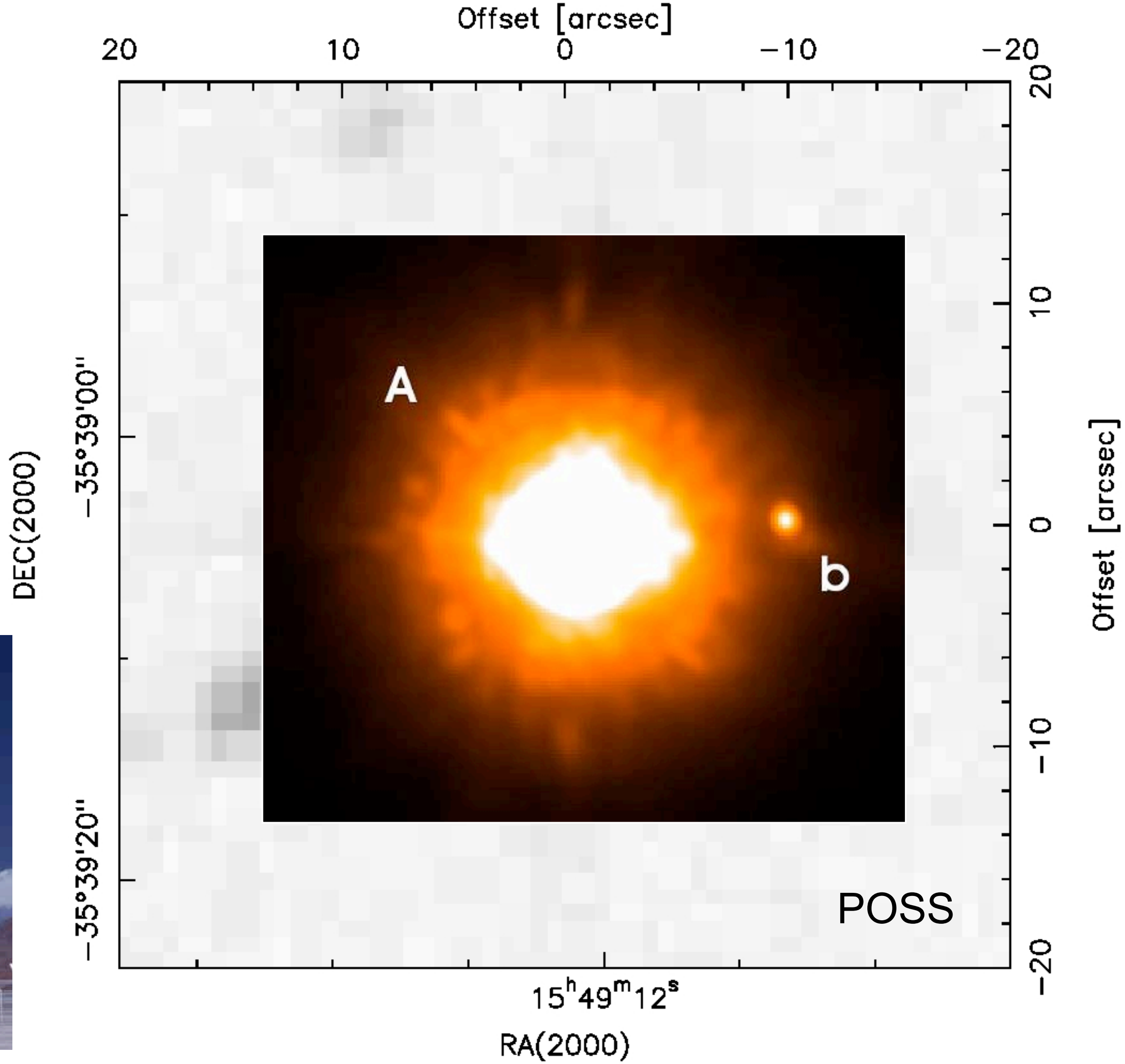




Large radio beams

The beam size of APEX: 18″ !





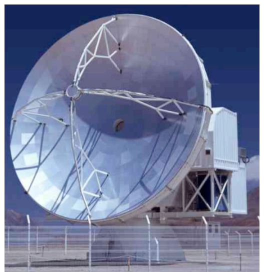
Results

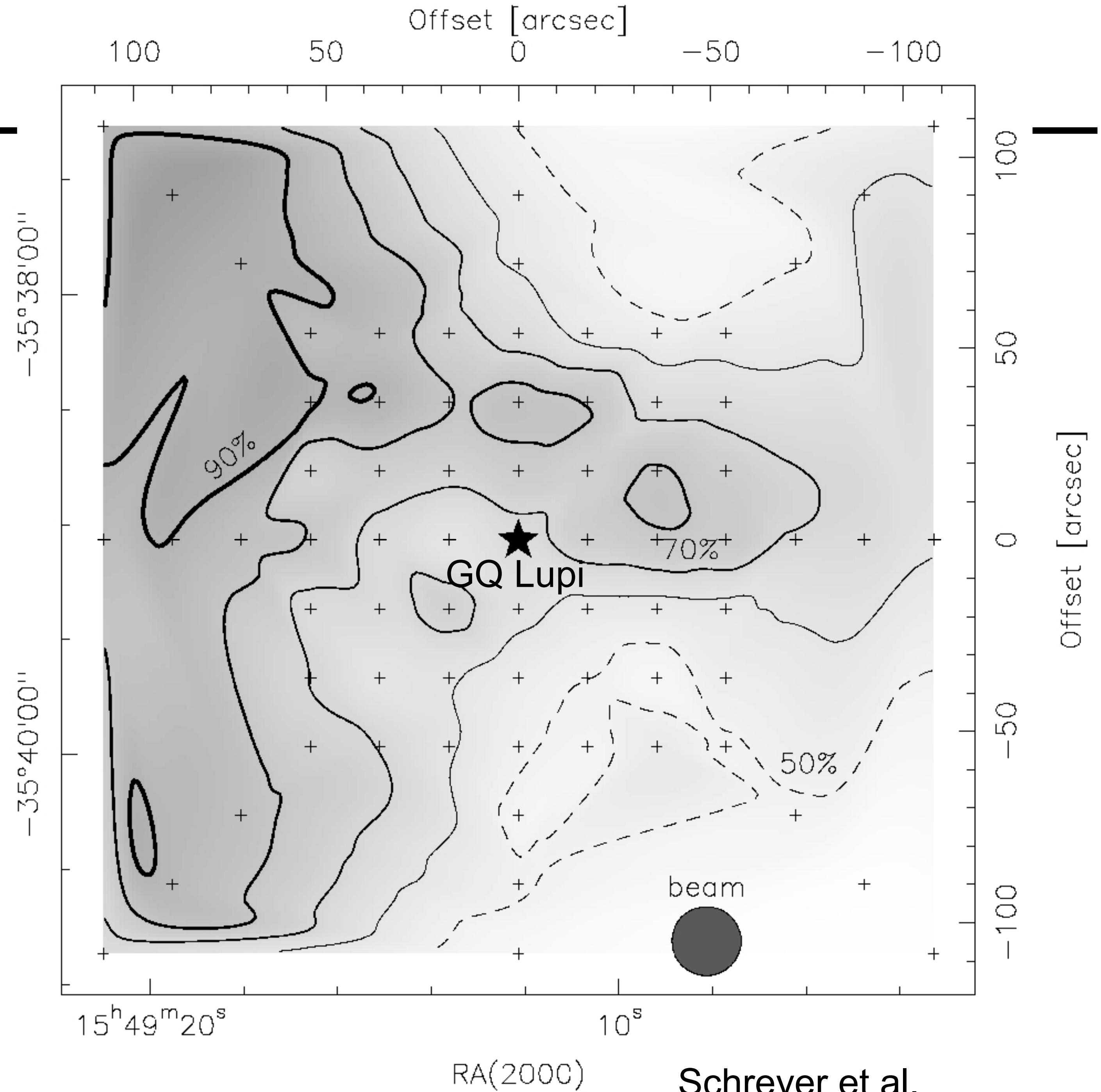
(1) APEX

Map in CO 3-2 (total integrated line emission)

with:
$CO/H_2 = 10^{-4}$,
T_{ex} = 15…25 K,
τ ≈ 1..10,
D = 140 pc

$\Rightarrow M_{gas} \approx 0.15\ M_\odot$

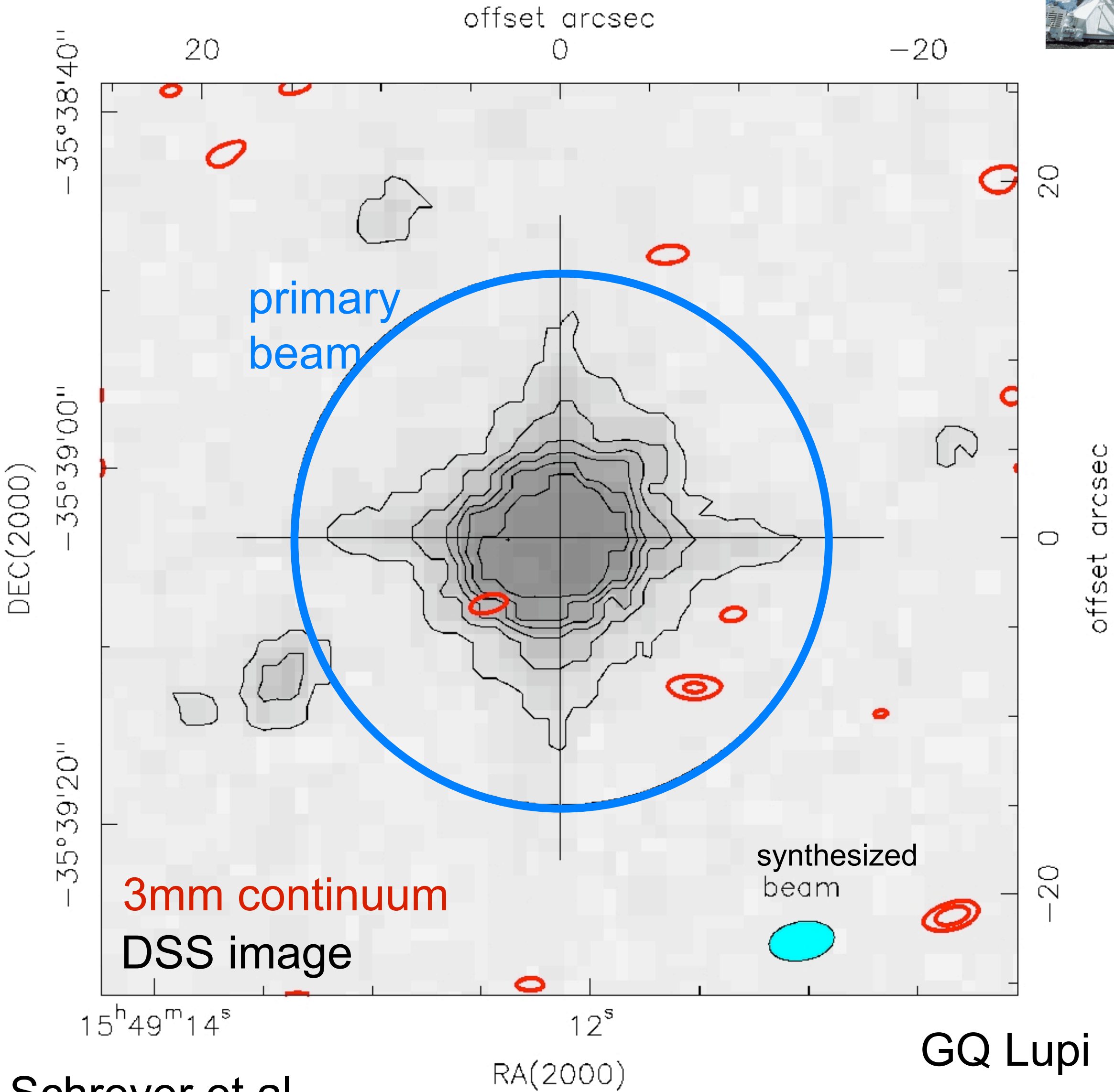




Schreyer et al.

Result

(2) ATCA



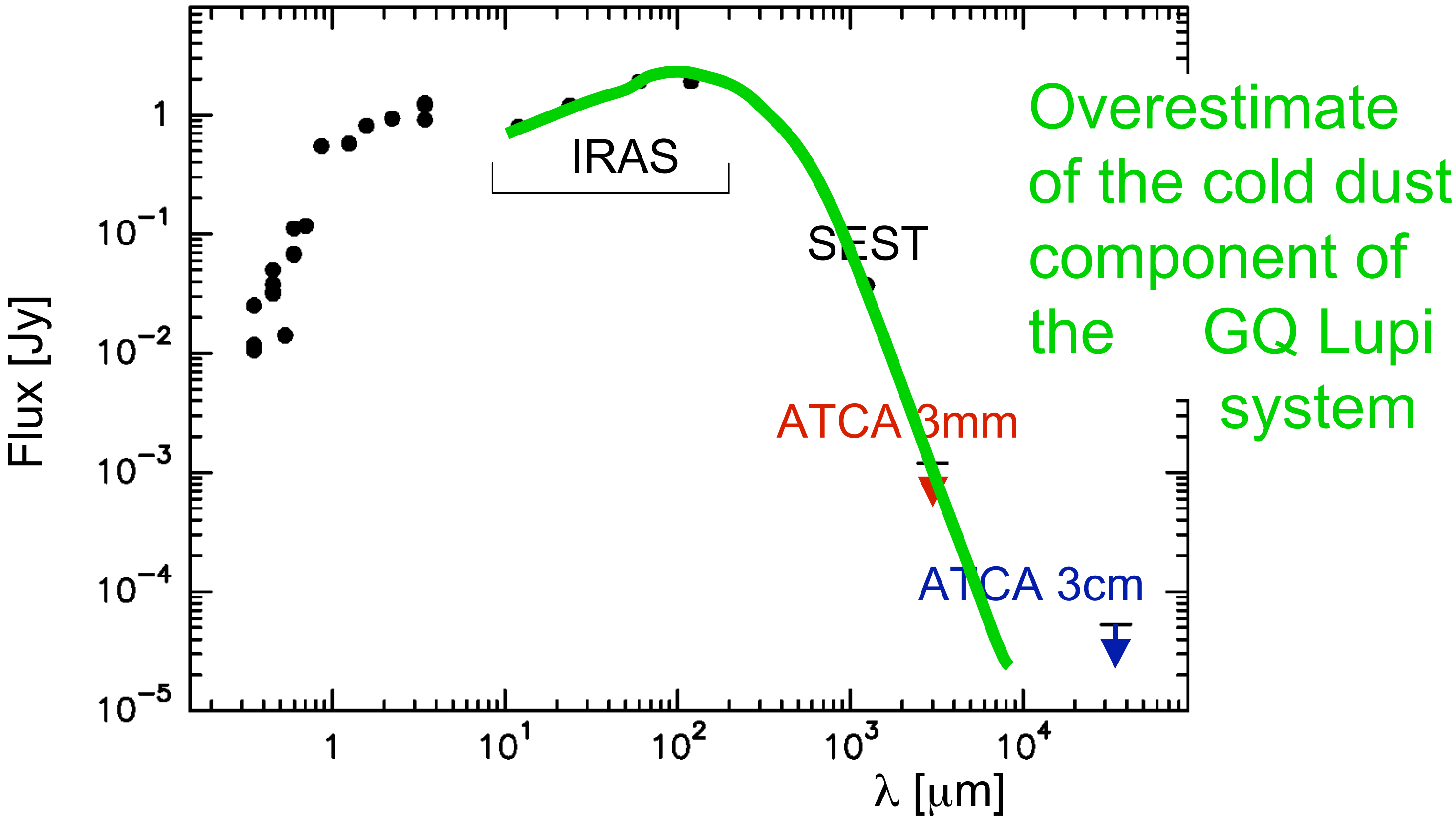
Red contours:
3σ & 4σ rms

Schreyer et al.

GQ Lupi

Results: SED

SED GQ Lupi System



Result: The 38mJy by D. Nürnberger

- does not stem from the GQ Lupi System.
- but is the total integrated cloud emission as in case of the IRAS measurements

Schreyer et al.