OBSERVATIONAL CONSTRAINTS
on the
FORMATION
of
VERY LOW MASS STARS & BROWN DWARFS

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Question: How do Brown Dwarfs Form?

- Sub-stellar objects (Mass < 80 Jupiters [<0.08 $M_\odot$])

- Common in the field and star-forming regions: # densities similar to those of low mass stars (~0.1 / pc^3)

(Kirkpatrick et al. 1999, 2000; Gizis et al. 2000; Burgasser 2001; Chabrier 2003)

- Some orbit stars, but vast majority are free-floating bodies, some with masses ≲10 Jupiters

(Lucas & Roche 2000; Zapatero Osorio et al. 2000, 2002; Mohanty et al. 2003a, b)

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How do all these isolated brown dwarfs form?

↑

(Answer important for general understanding of star & planet formation)

Formation Scenarios

- **`Ejection' (competitive accretion) :**

  'stellar embryos' tossed out of multiple proto-stellar systems before forming full-fledged stars

  - very small disks, compared to stellar ones (≤ 10-20 AU)
  - classical T Tauri (cTT) phase is rare
  - no isolated Class-0 phase
  - wide binaries rare

  (Reipurth & Clarke 2001; Bate, et al. 2002, 2003)

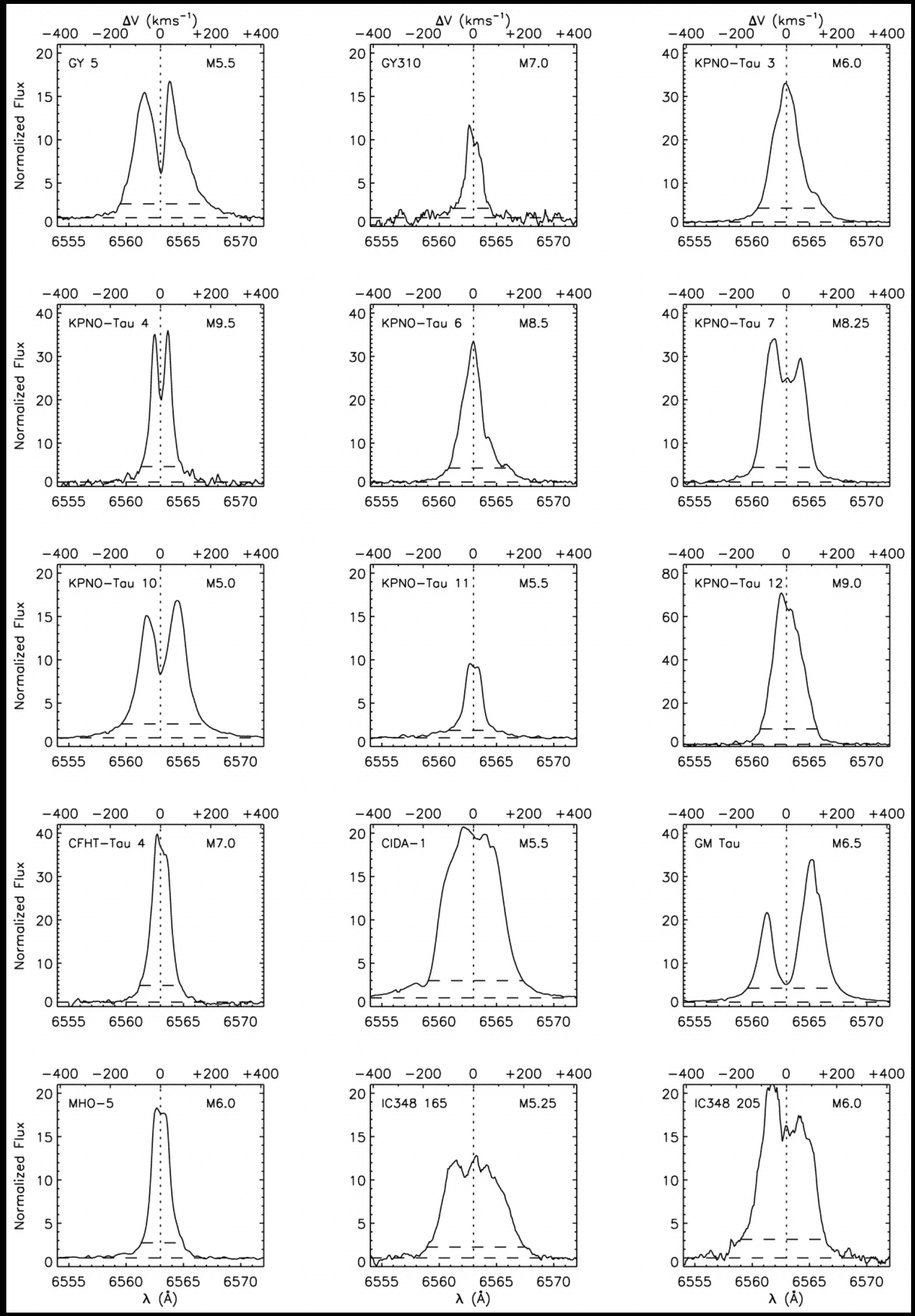
- **`Turbulent Fragmentation' (core accretion):**

  BDs formed directly out of ultra-low mass cores

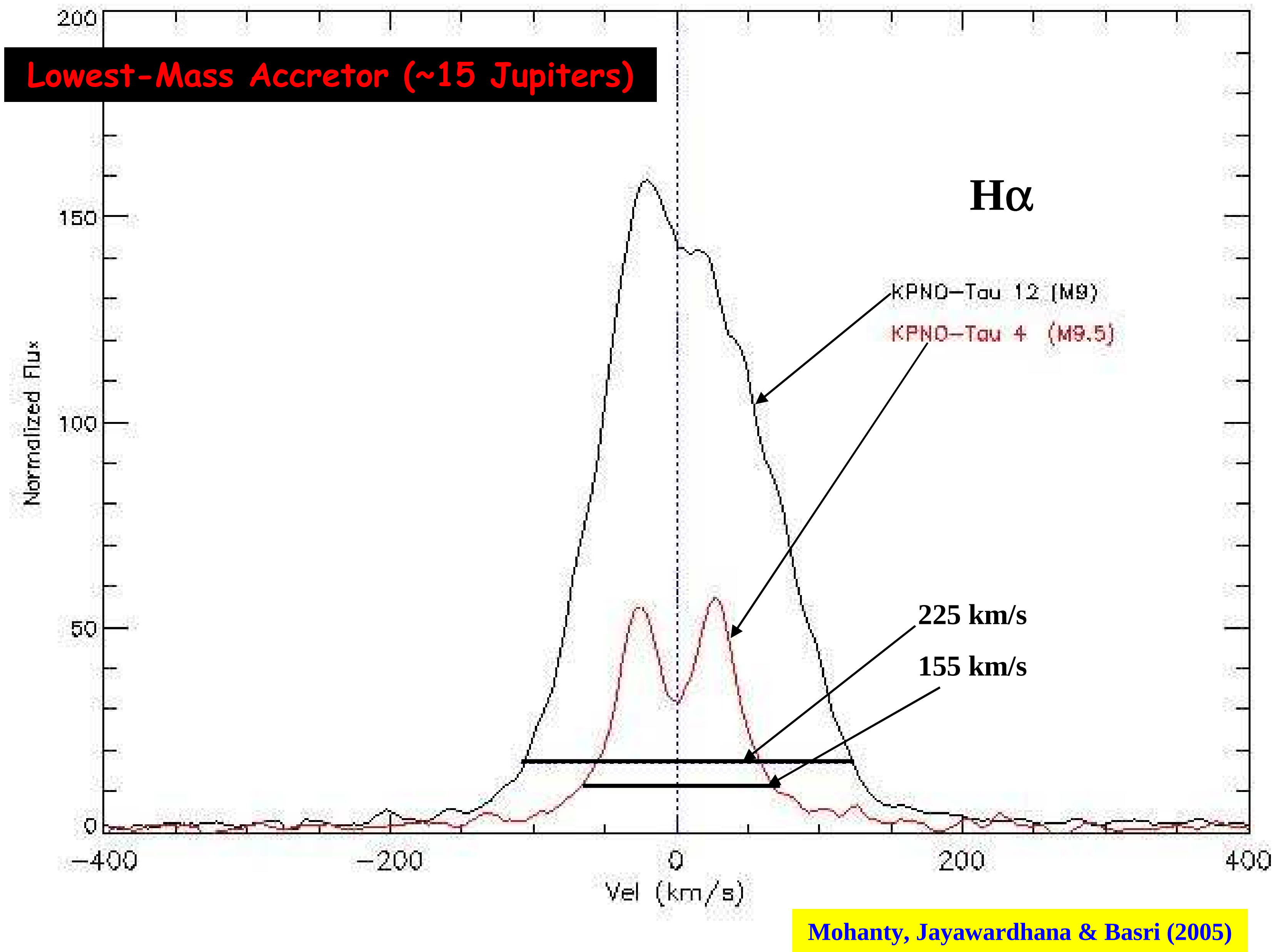
  - common formation mechanism for stars and brown dwarfs
  - disks, classical T Tauri phase, & isolated Class-0 phase common
  - wide binaries not disrupted (but may not form due to other reasons)

  (Padoan & Nordlund 2002, 2004)

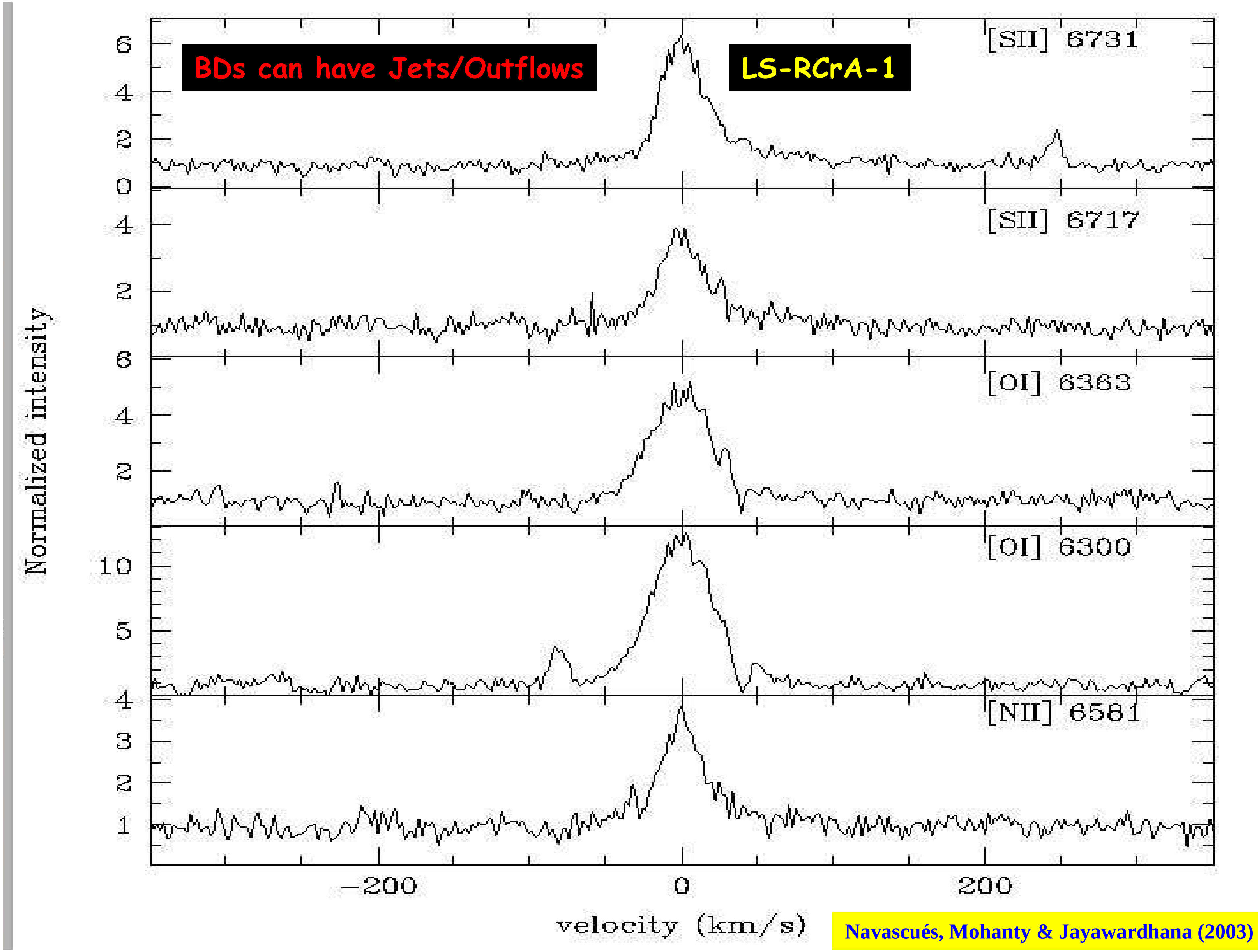
BD Accretors...



Mohanty, Jayawardhana & Basri (2005)

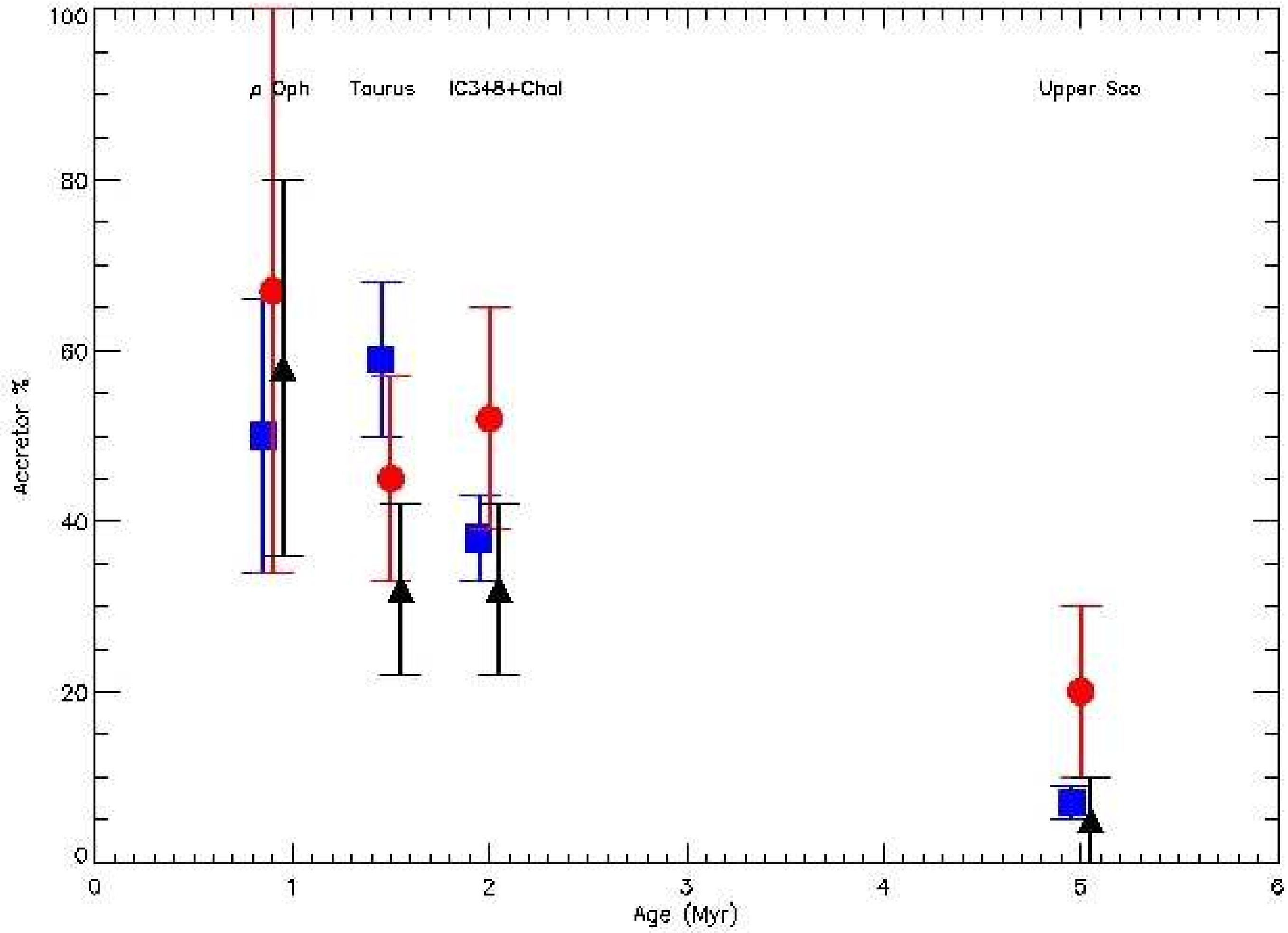


Lowest-Mass Accretor (~15 Jupiters)
Hα
KPNO–Tau 12 (M9)
KPNO–Tau 4 (M9.5)
225 km/s
155 km/s
Normalized Flux
Vel (km/s)
200
150
100
50
0
−400
−200
0
200
400
Mohanty, Jayawardhana & Basri (2005)

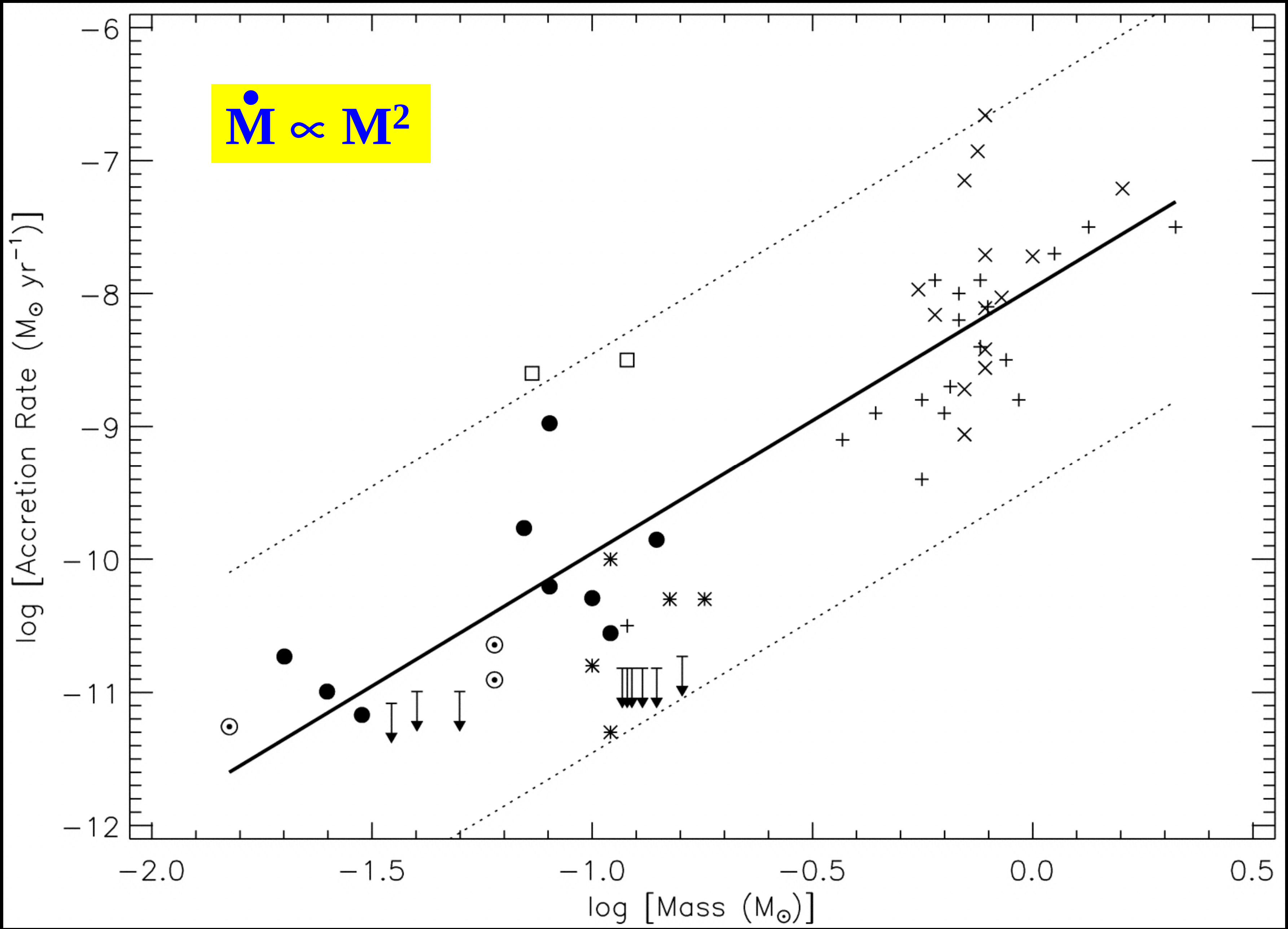


BDs can have Jets/Outflows
LS-RCrA-1
[SII] 6731
[SII] 6717
[OI] 6363
[OI] 6300
[NII] 6581
Normalized intensity
velocity (km/s)
−200
0
200
Navascués, Mohanty & Jayawardhana (2003)

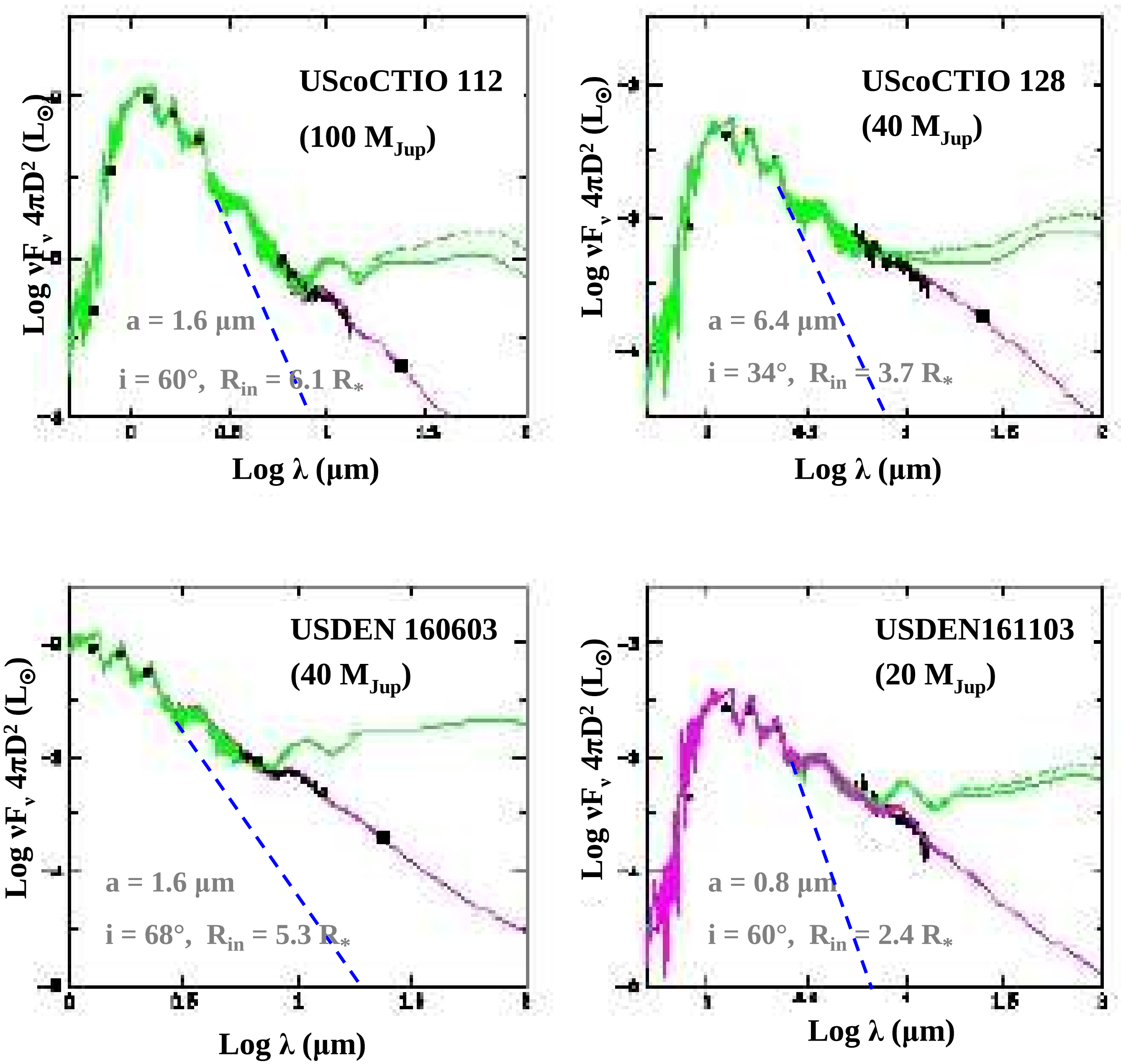
Accretor Fraction with Age: BDs versus Solar-Type Stars



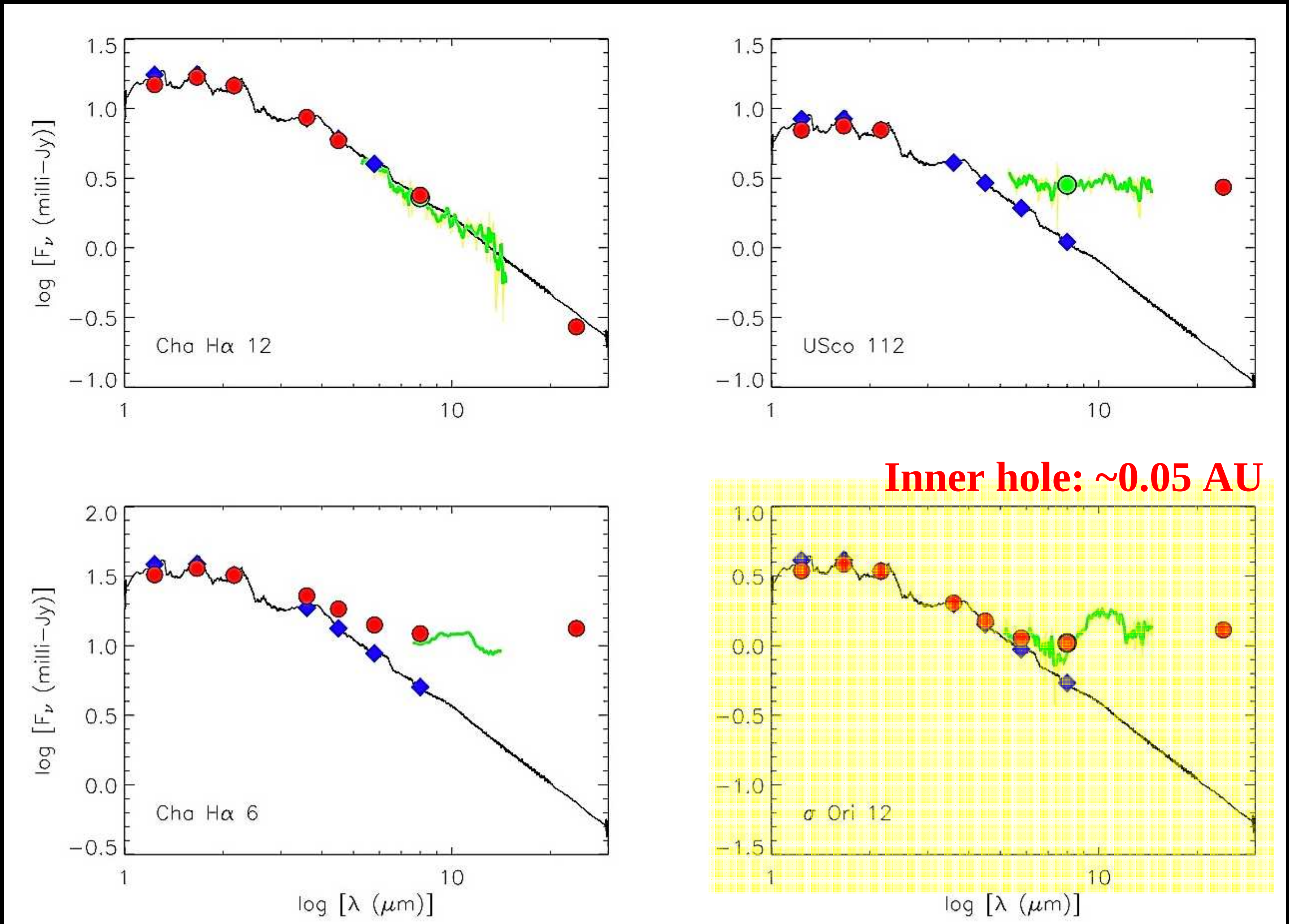
Mohanty, Jayawardhana & Basri (2005)



Mohanty, Jayawardhana & Basri 2005 **(also Muzerolle et al. 2003, 2005; Natta et al. 2004)**



Mohanty et al. in prep



Mohanty et al. 2007, submitted

FORMATION CONCLUSIONS

1) Brown dwarfs of all masses down to the D-burning limit pass through a classical T Tauri-phase; both infall and outflow observed; accretion-timescale and CTT fraction is comparable to that in stars; physical mechanisms involved appear similar (magnetospheric; mass vs. accretion-rate).

2) Brown dwarfs and stars have similar disk fractions; the disk properties and evolution appear similar in both.

⇓

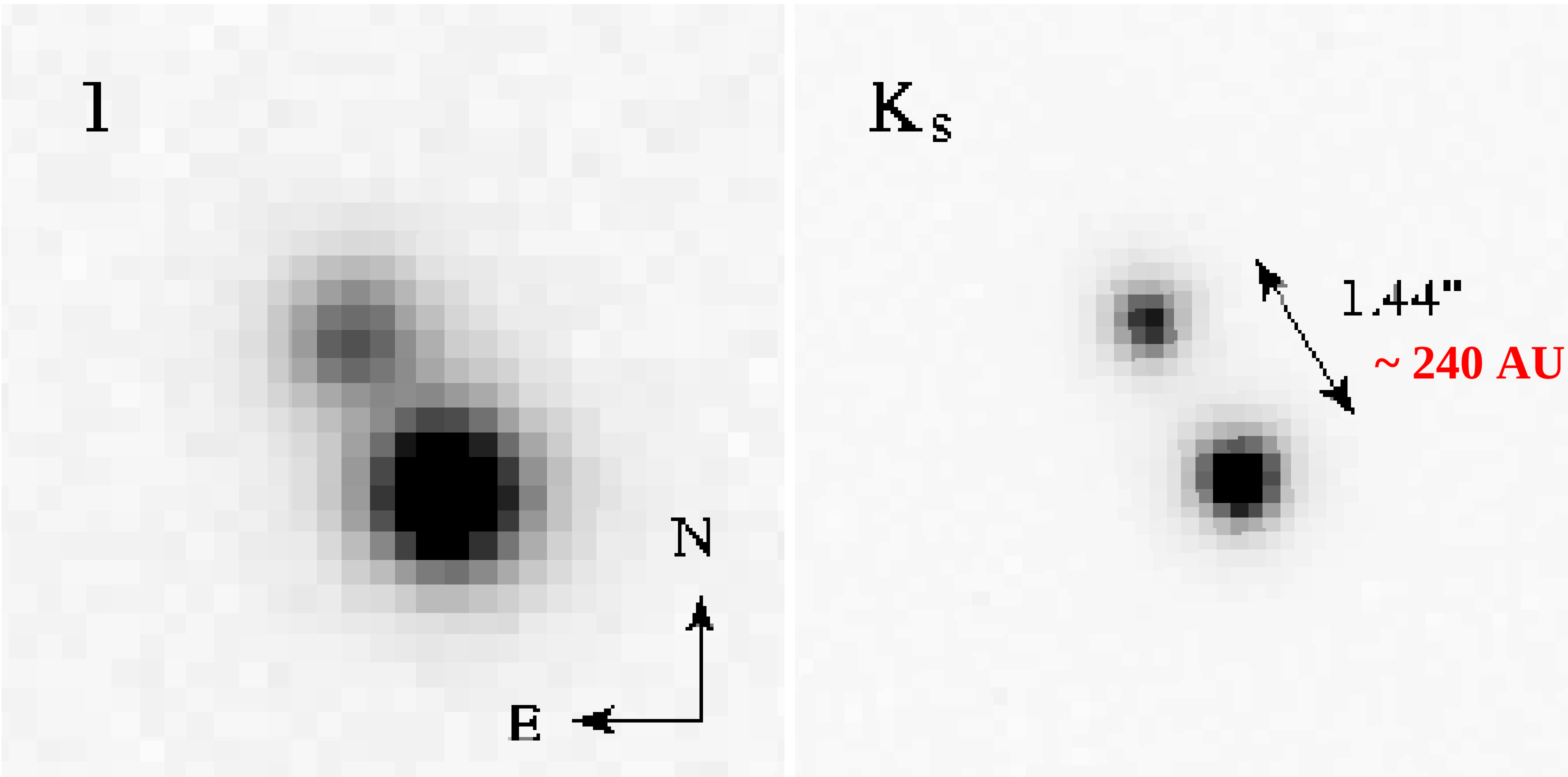
Brown dwarfs and stars have very similar infancies

⇓

common formation mechanism ???

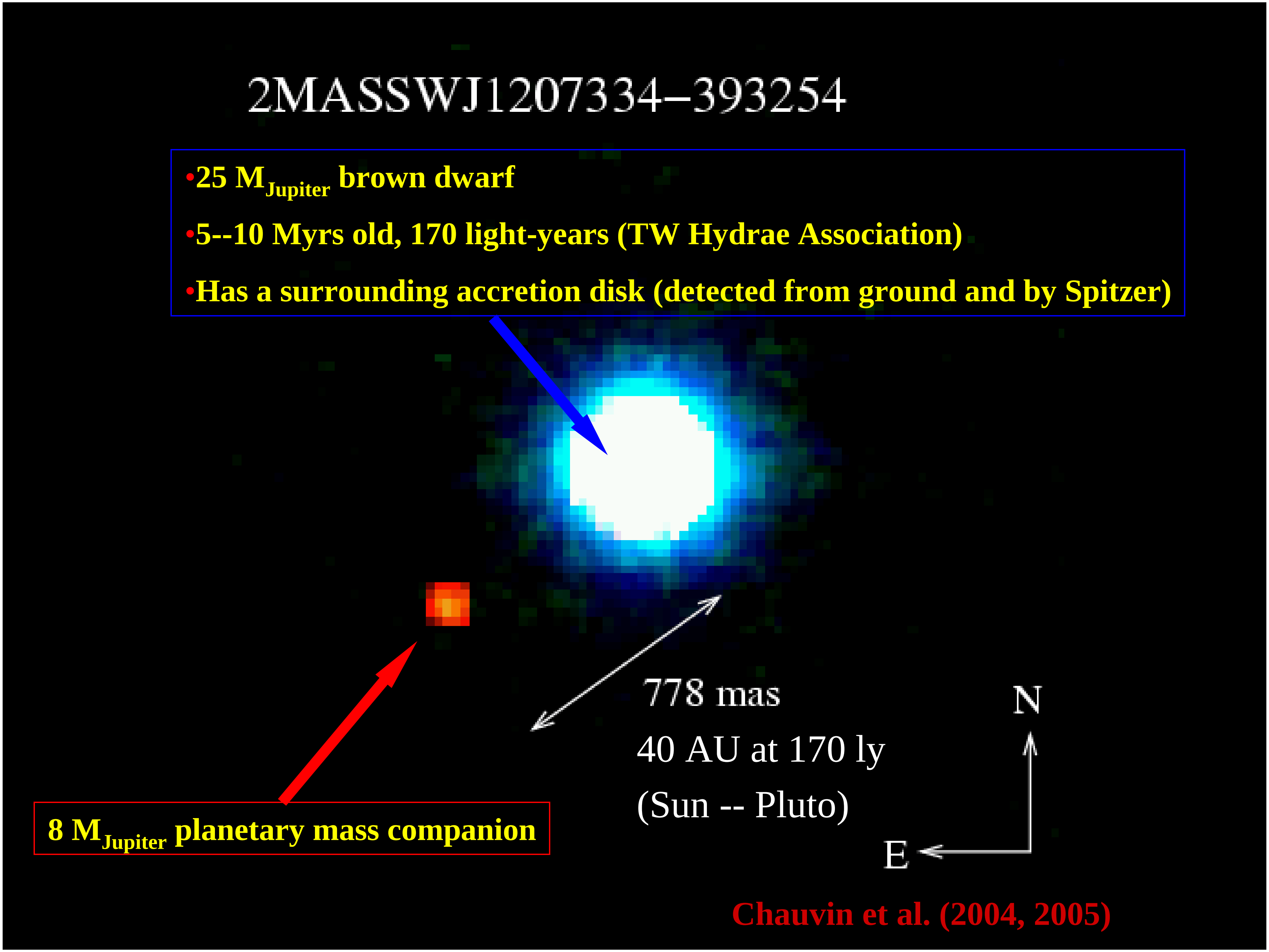
(mostly inner disk diagnostics examined so far; need:
large sub-mm/mm surveys, binarity surveys, direct disk-imaging)

Brown Dwarfs can form Wide Binaries

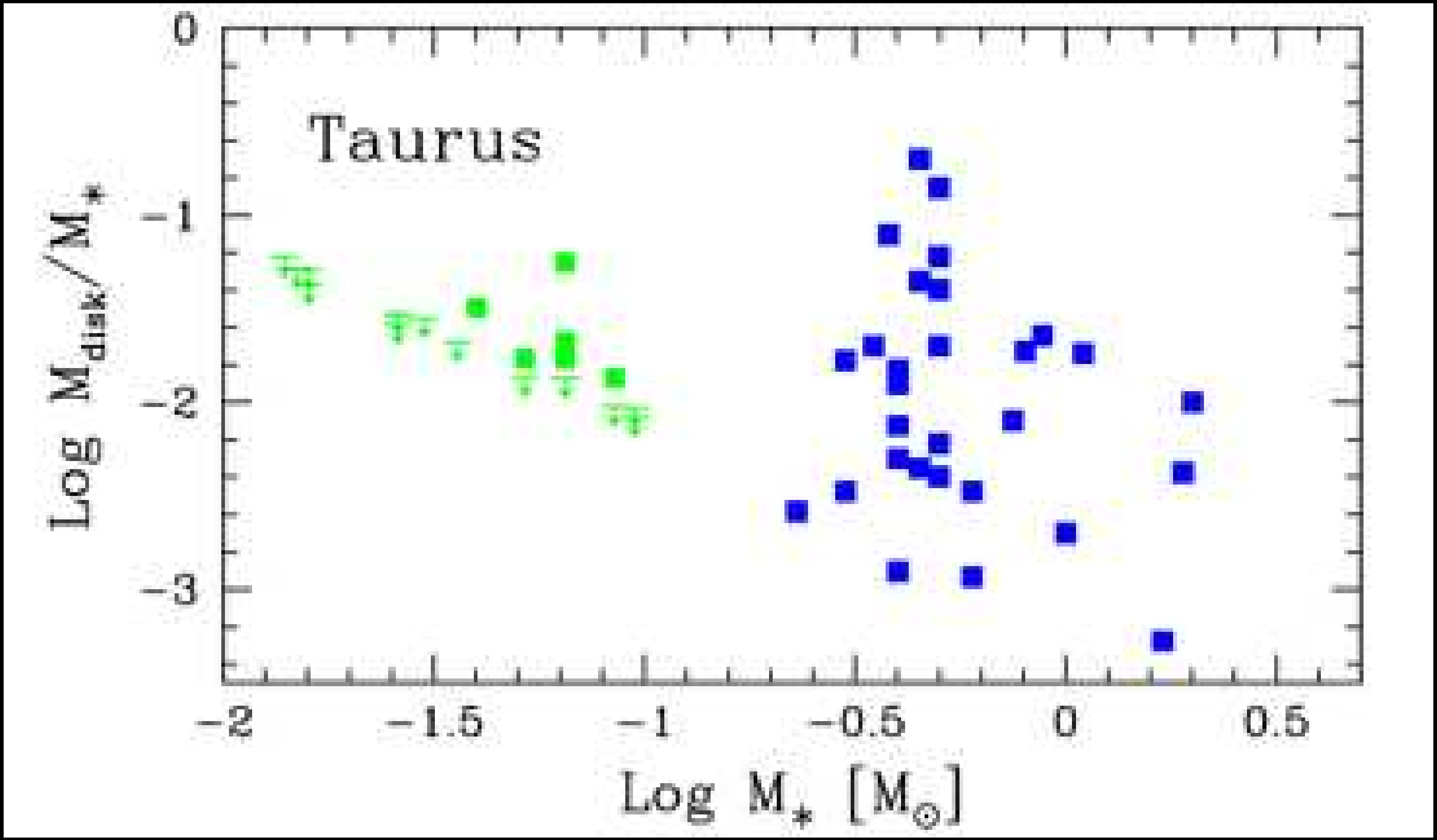


Images of the binary system 2M1101-7732AB at *I* and K_S (FWHM=0".85 and 0".39). Each image is 3" on a side and is displayed linearly from the background level to half of the peak flux of the primary.

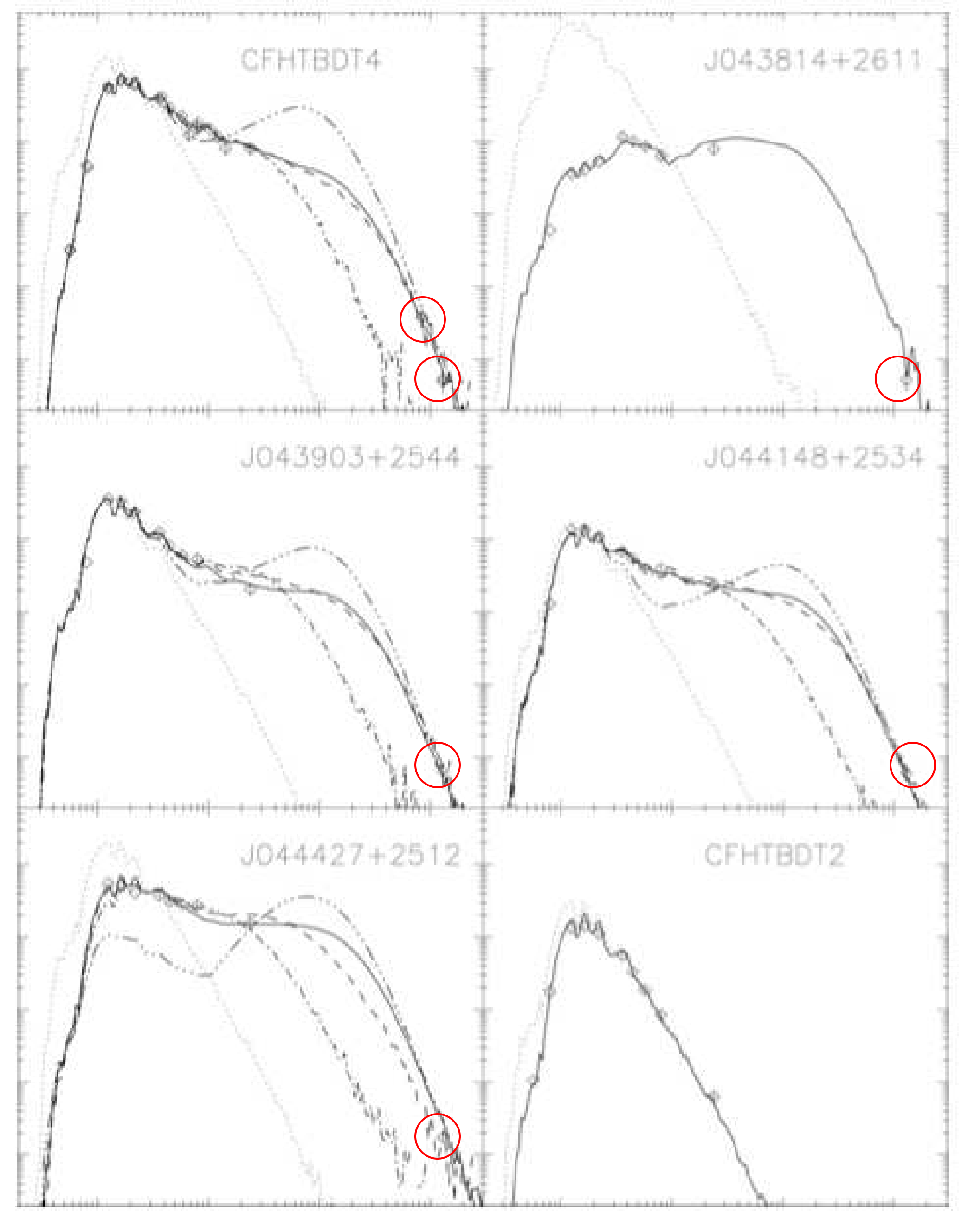
Luhman 2004


2MASSWJ1207334–393254
•25 $M_{Jupiter}$ brown dwarf
•5--10 Myrs old, 170 light-years (TW Hydrae Association)
•Has a surrounding accretion disk (detected from ground and by Spitzer)
778 mas
40 AU at 170 ly
(Sun -- Pluto)
N
E
8 $M_{Jupiter}$ planetary mass companion
Chauvin et al. (2004, 2005)

Disk Masses: M_{disk}/M_{star} ~ CONSTANT ~ few %



Scholz et al. in 2006



BD Disk Radii

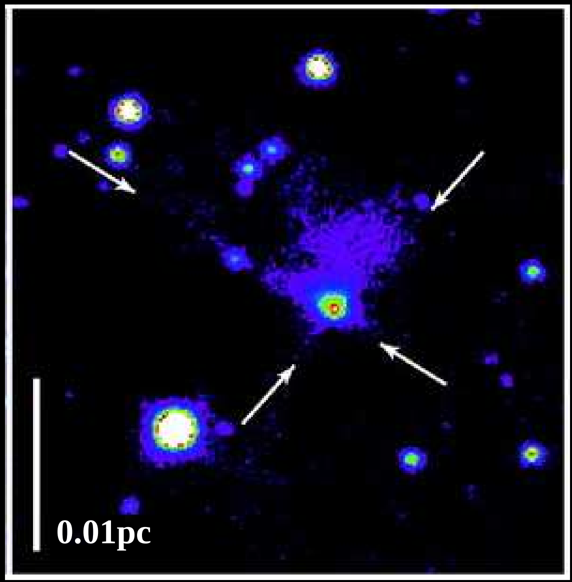
>> 1 AU….

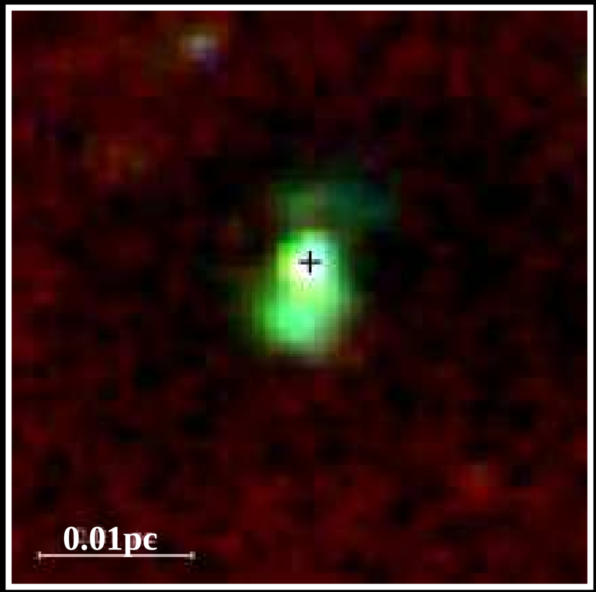
≥ 10 AU

But HOW big?

Scholz et al. in 2006

VeLLOs: Proto-Brown Dwarfs ?



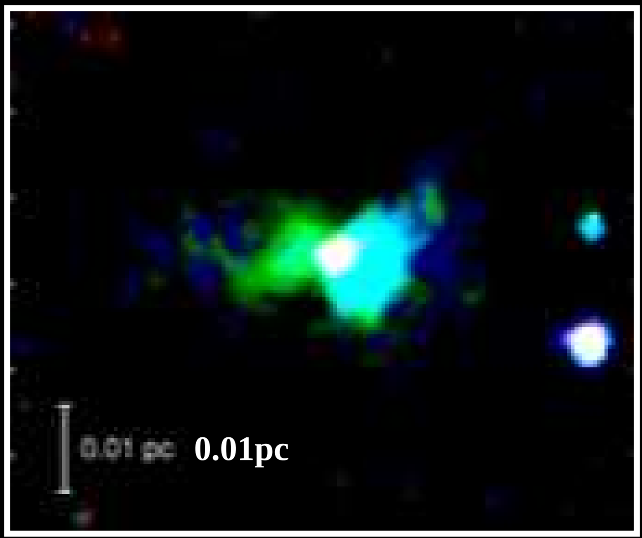


L ~ 0.1 Lsun

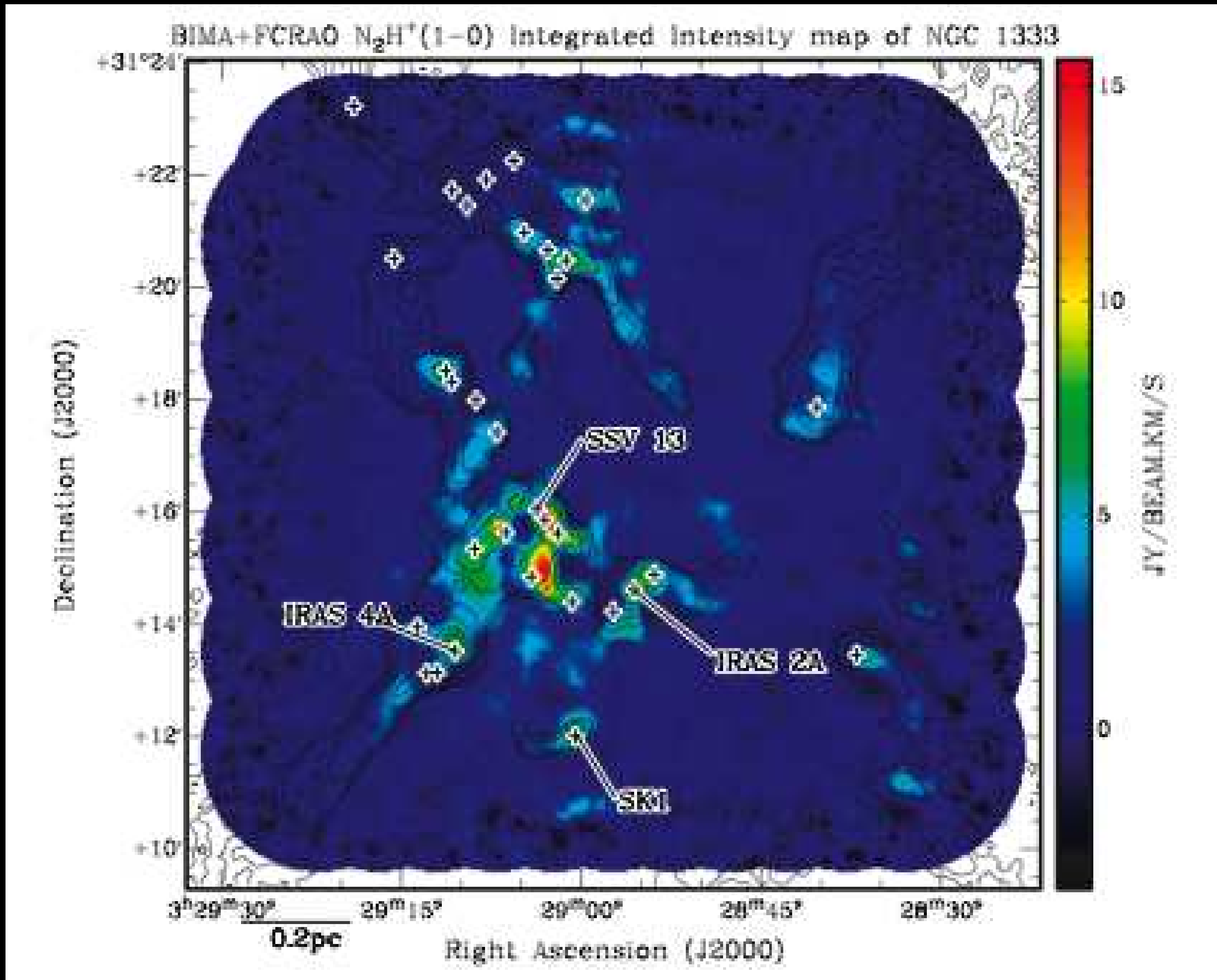
M ~ 0.01Msun

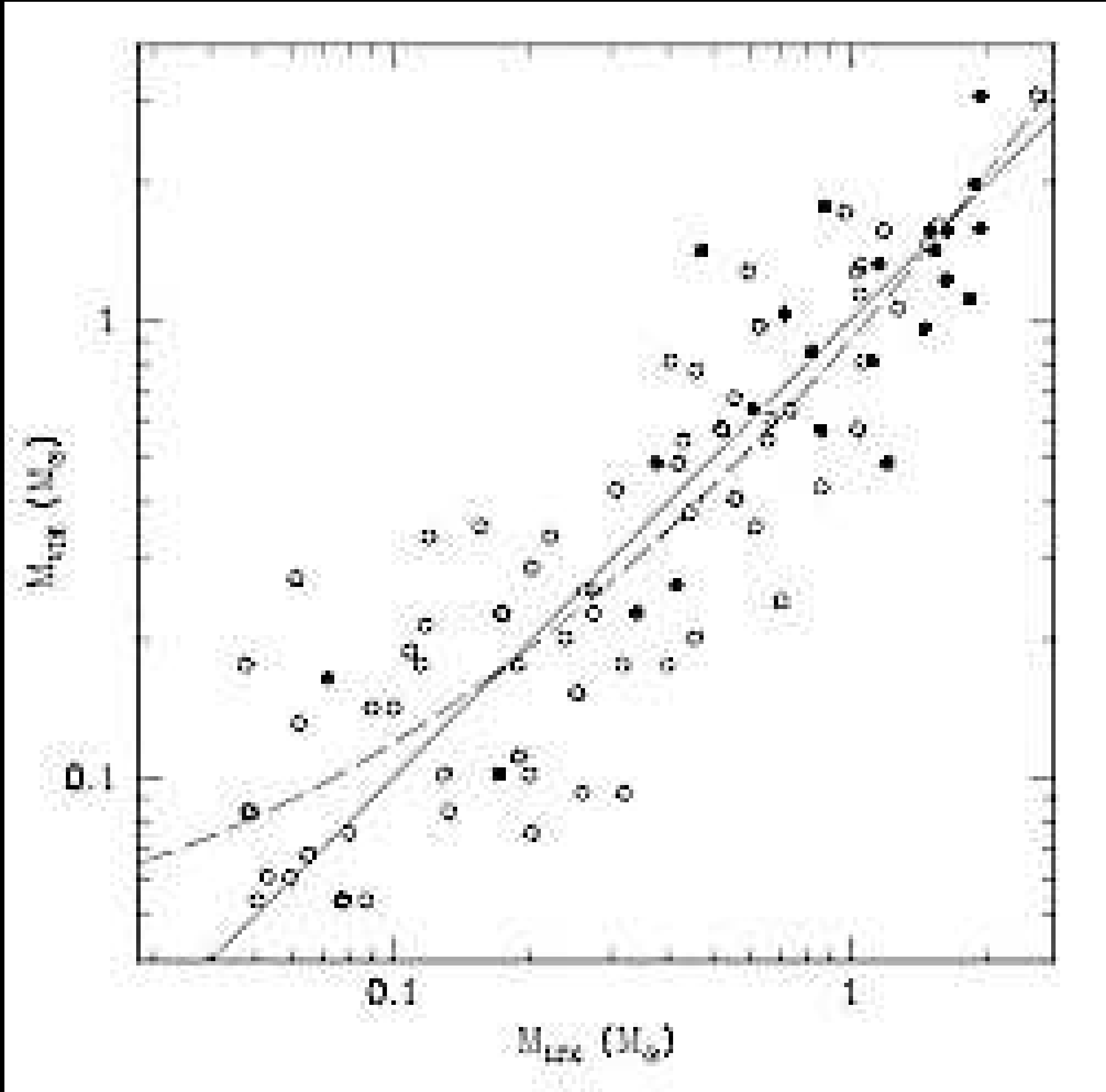
But

Mcore ~ few Msun

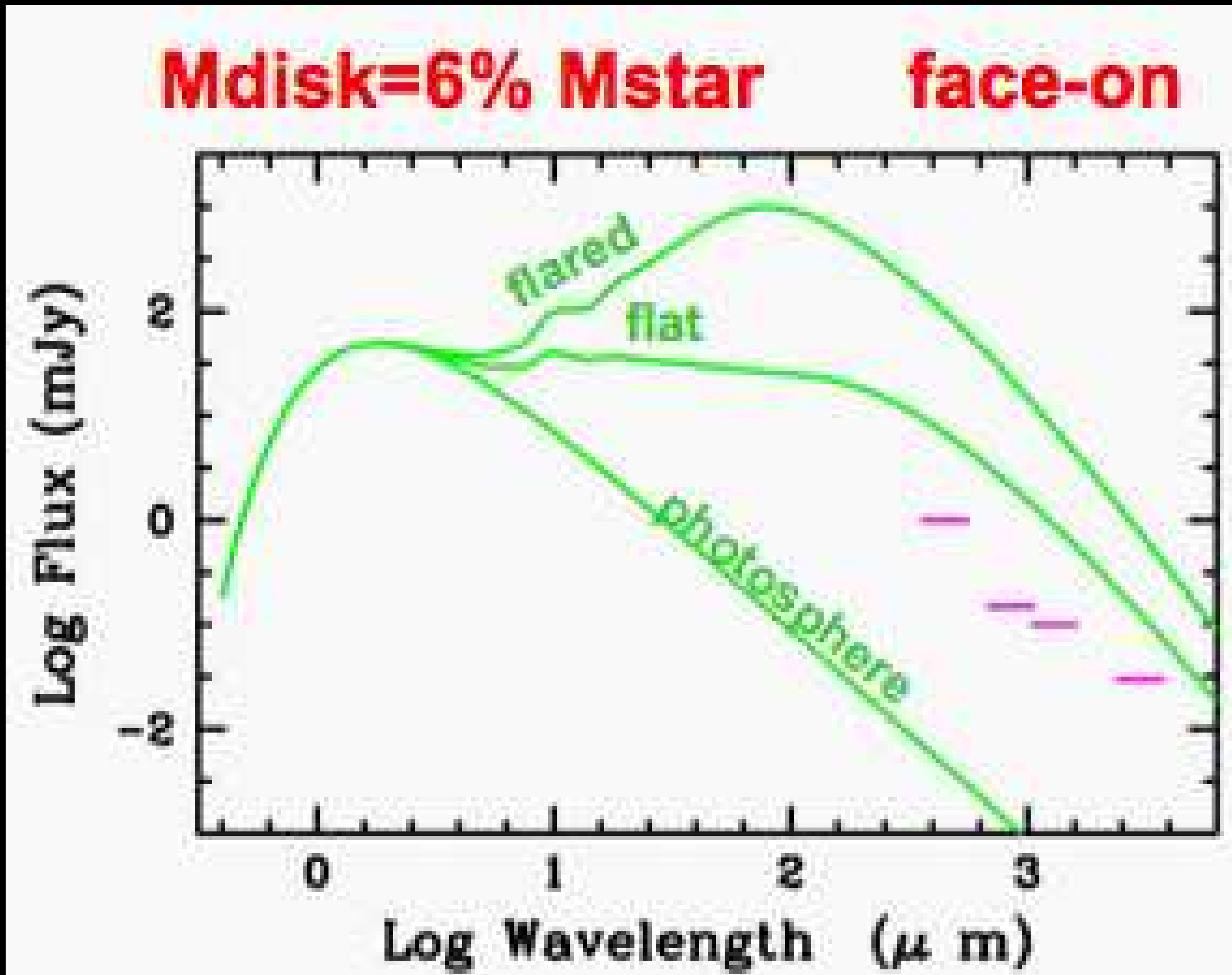


L1014: Huard et al. 2006,
L1521: Bourke et al. 2006.
IRAM 04191: Dunham et al. 2006

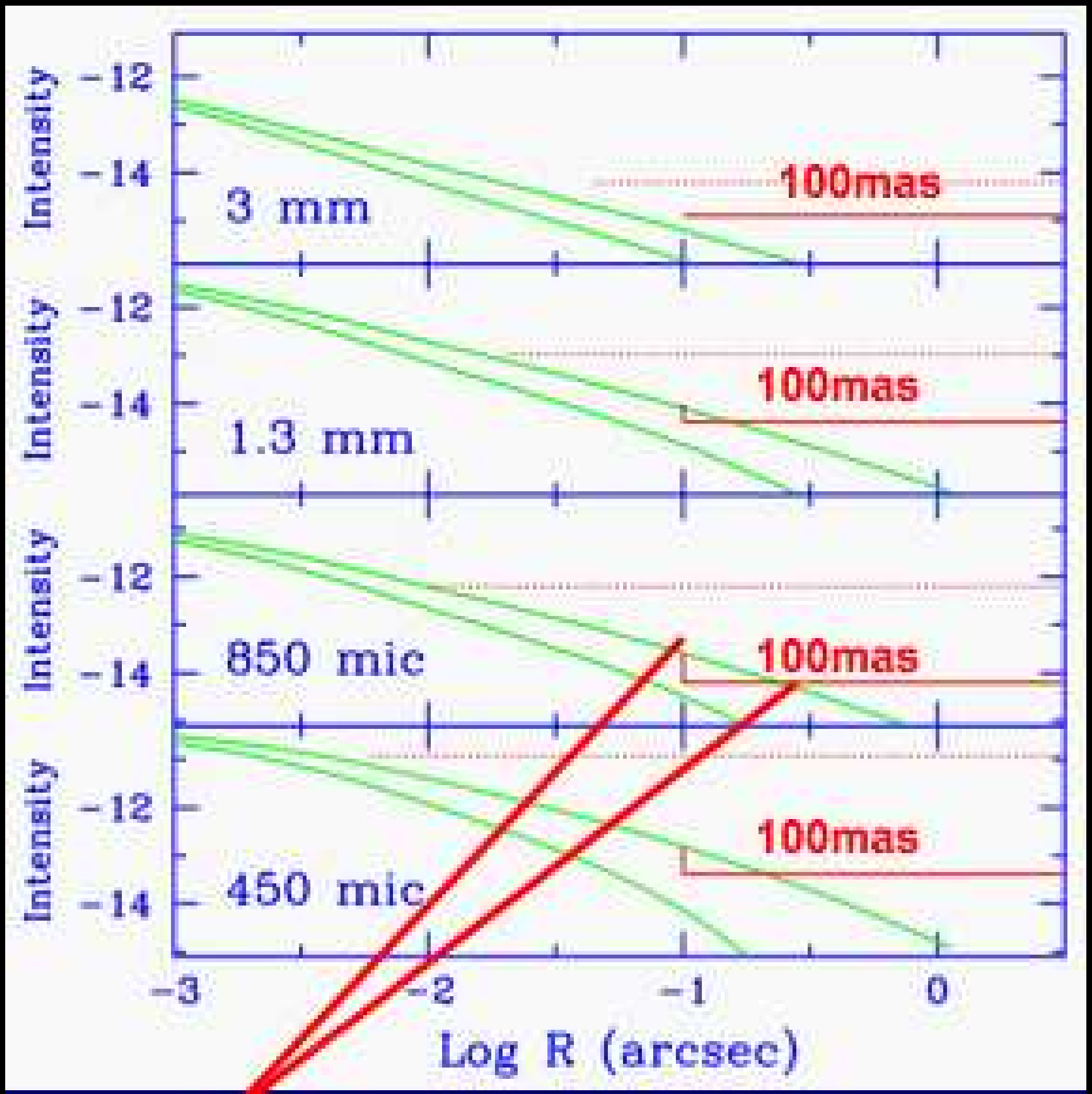

BIMA+FCRAO N_2H^+(1-0) Integrated Intensity map of NGC 1333
+31°24'
+22'
+20'
+18'
+16'
+14'
+12'
+10'
Declination (J2000)
SSV 13
IRAS 4A
IRAS 2A
SK1
3h29m30s
29m15s
29m00s
28m45s
28m30s
0.2pc
Right Ascension (J2000)
15
10
5
0
JY/BEAM.KM/S



1
0.1
0.1
1



Mdisk=6% Mstar
face-on
flared
flat
photosphere
Log Flux (mJy)
Log Wavelength (μ m)
2
0
-2
0
1
2
3



10-30 AU in dust

FUTURE WORK

- **What are the true sizes, and masses, of brown dwarf disks?**

Large sub-mm/mm surveys (ongoing….),
AO-imaging & Interferometry to spatially resolve the disks

- **Can turbulent fragmentation really work?**

Theory: more detailed numerical simulations…

Observations: find ultra-low-mass gravitationally bound cores & embedded proto-brown dwarfs (Spitzer, SMA)

- **Do brown dwarf disks form planetesimals/planetary systems?**

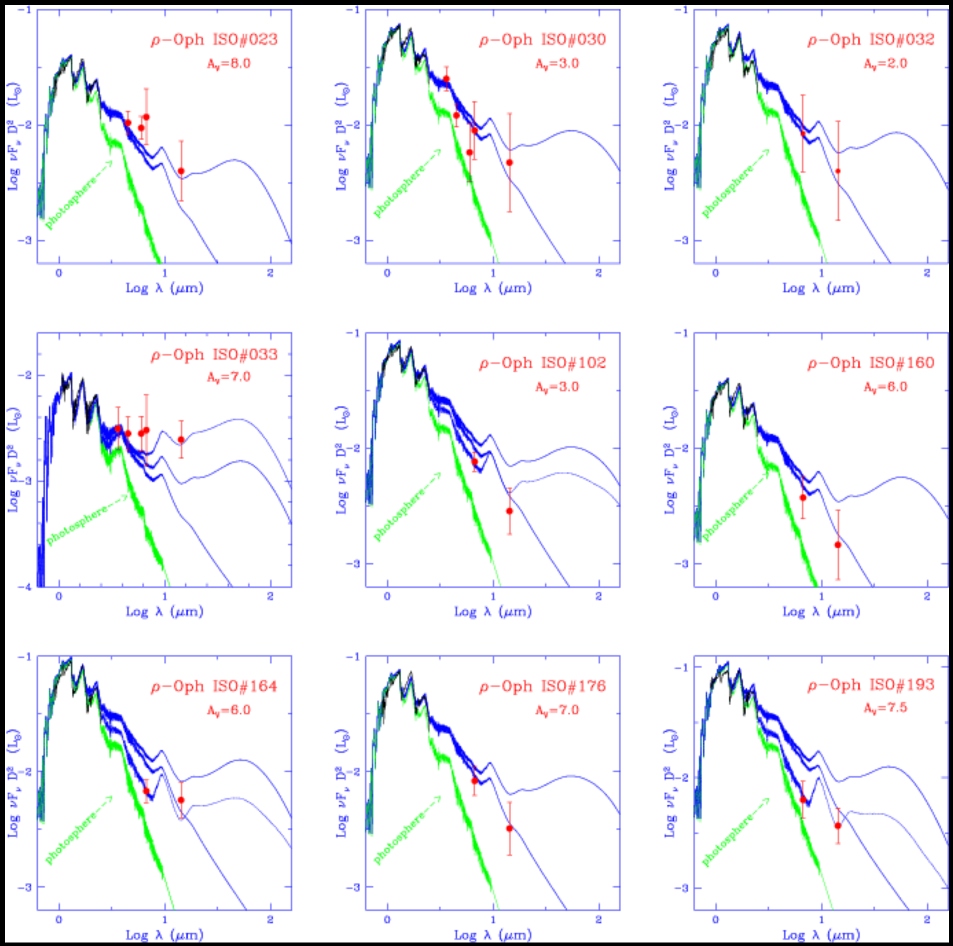
AO-imaging, Radial-velocity surveys, SIM, TPF, Darwin

THE END

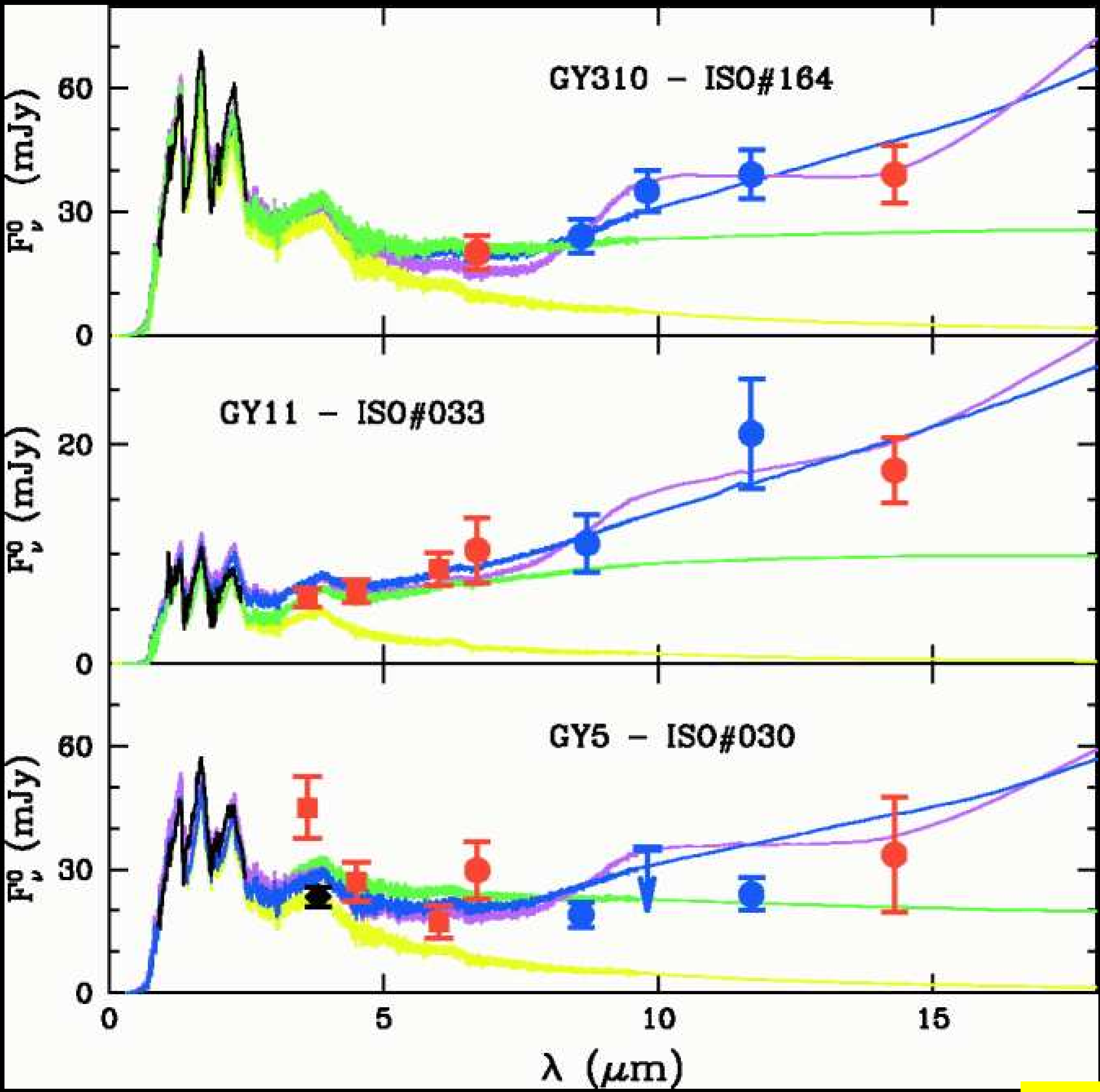
Disk Excess Measurements

ISO Measurements of MIR Disk Excess

At 7μm and 14μm: ρ Oph

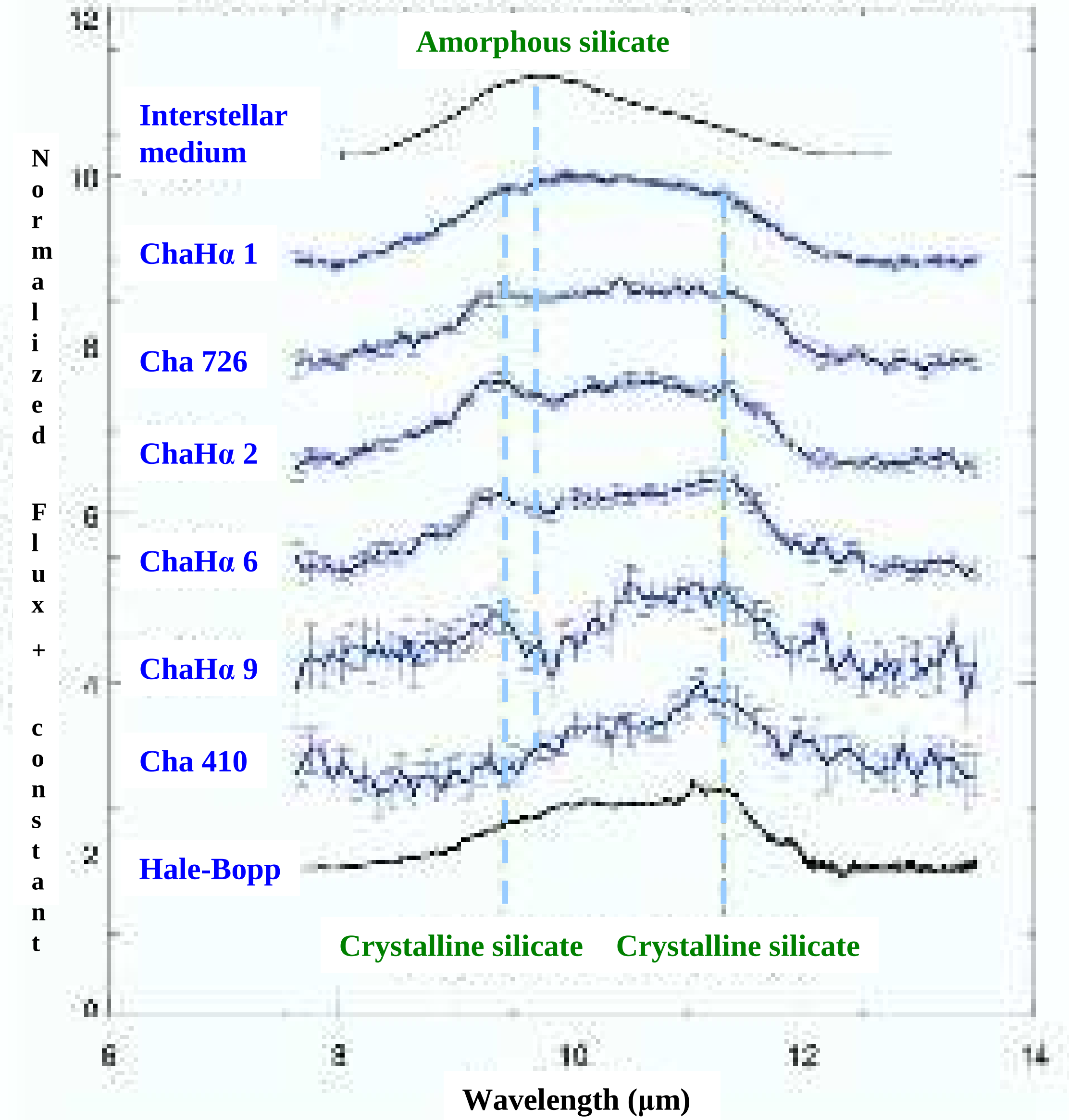


Natta et al. (2002)



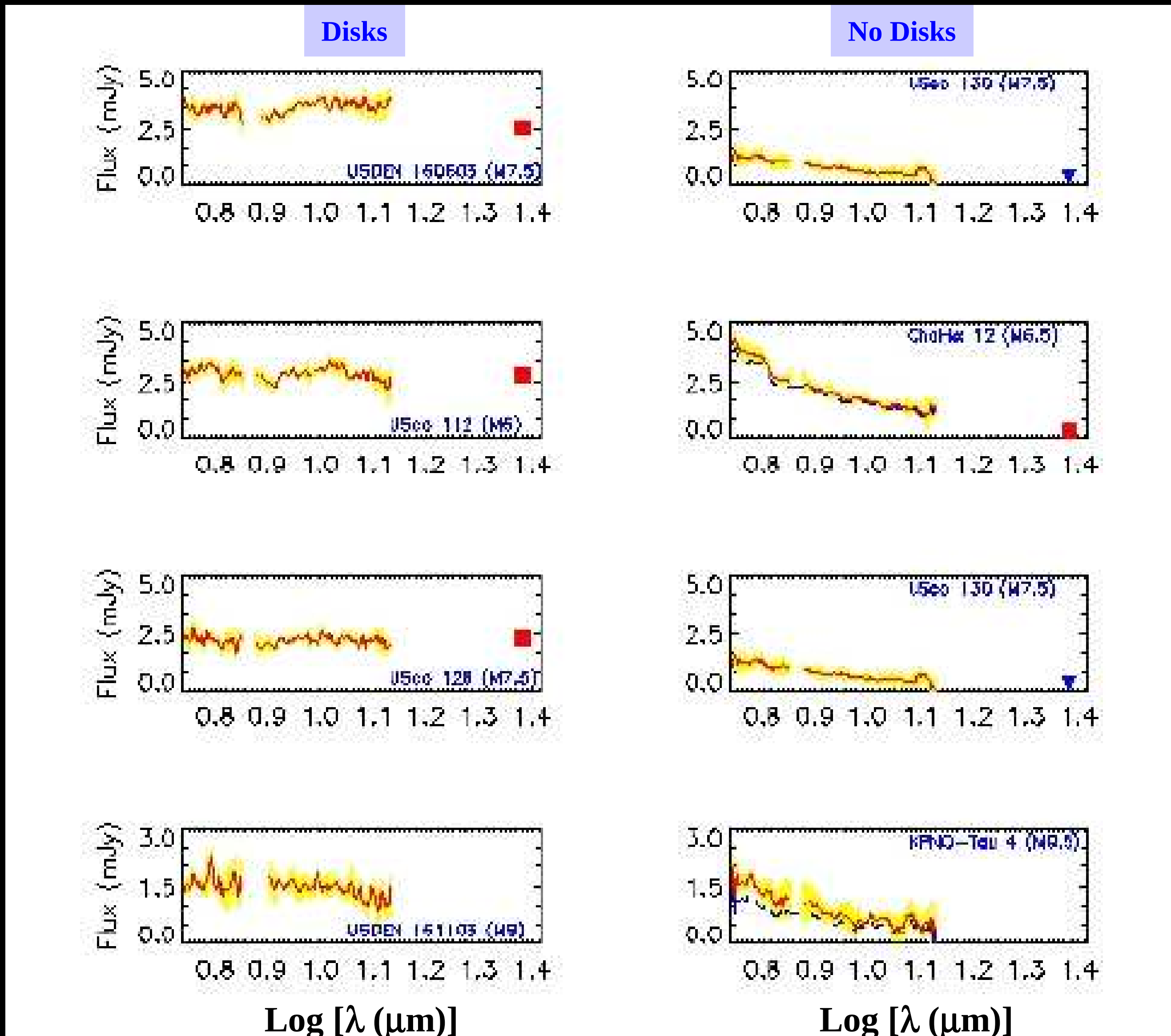
Mohanty et al. (2004)

Silicate Emission Features from Brown Dwarf Disks



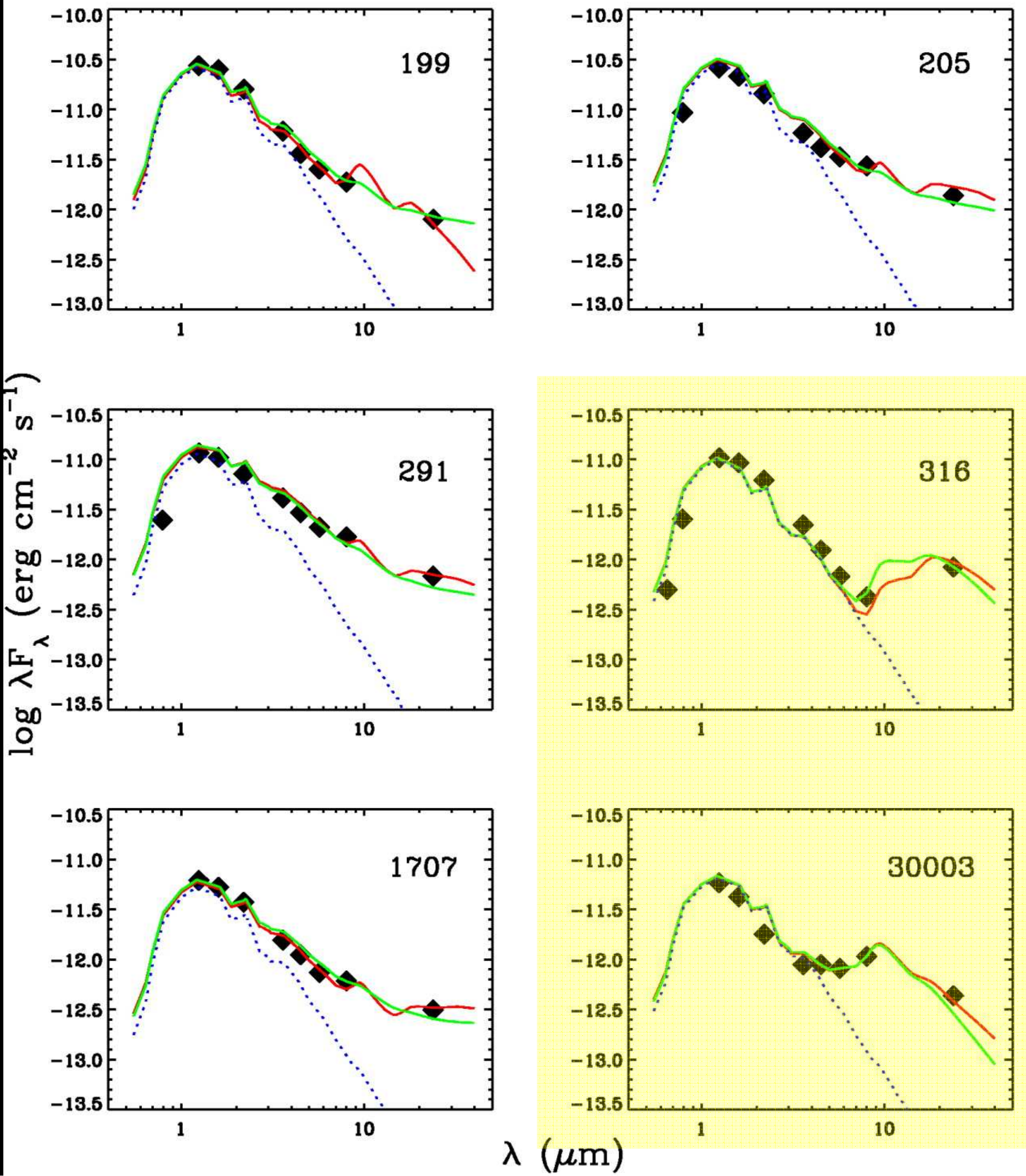
Apai et al. (2005)

Disks around weak-/post-accretion young BDs (IRS +MIPS)



Mohanty et al. in prep

Muzerolle et al. 2006



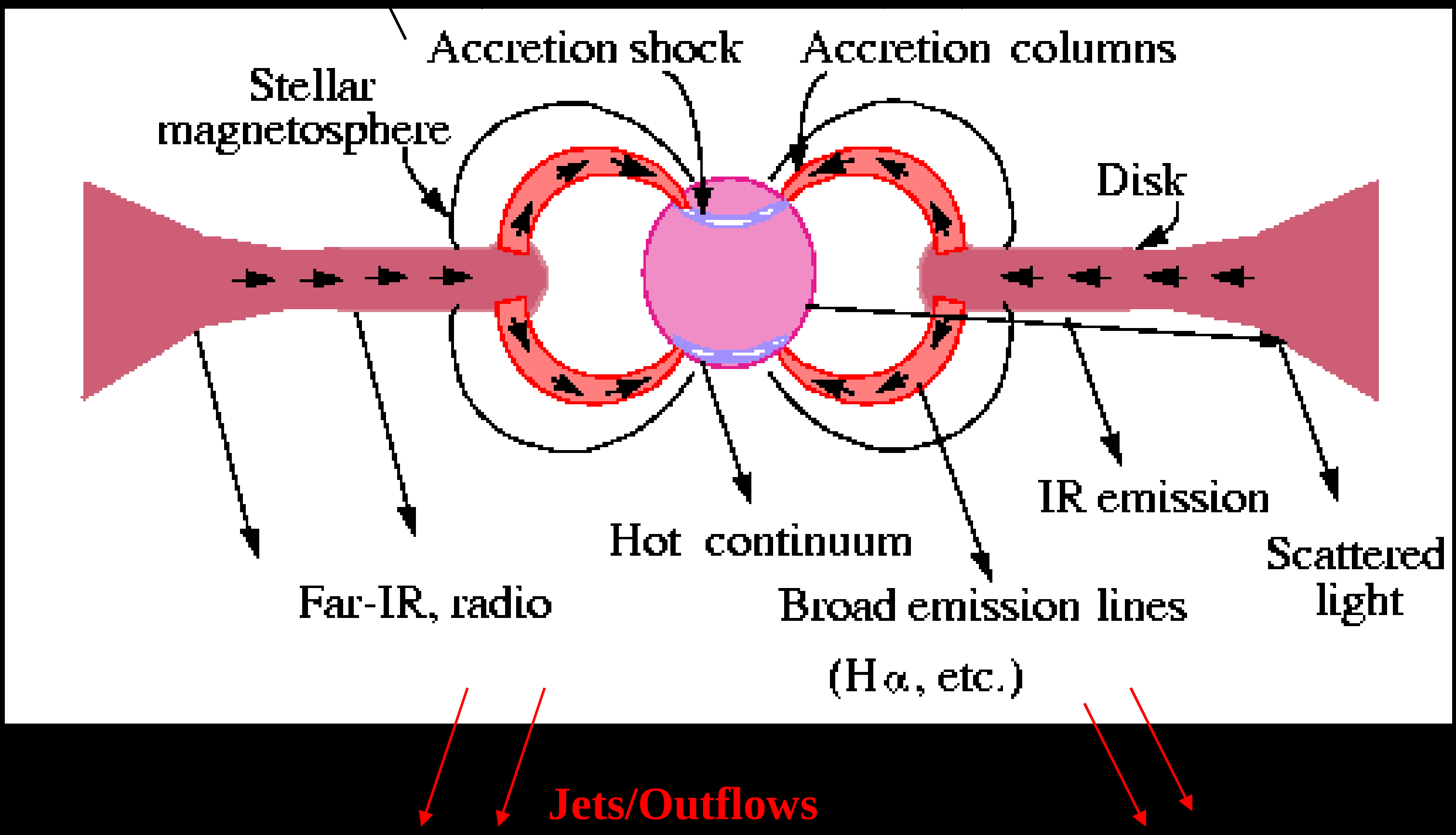
Inner hole: ~1 AU

(Dust Sublimation

Radius: ~ 0.005 AU)

Inner hole: ~0.1 AU

Classical T Tauri Phase in Stars



Spectroscopic Signatures of Accretion

Sample

Objects with *known spectral types later than M5* in Upper Scorpius, ρ Ophiuchus, IC 348, Taurus, Chamaeleon I, and TW Hydrae

Total ~ 80 (also Muzerolle et al. 2003, 2005: total ~120)

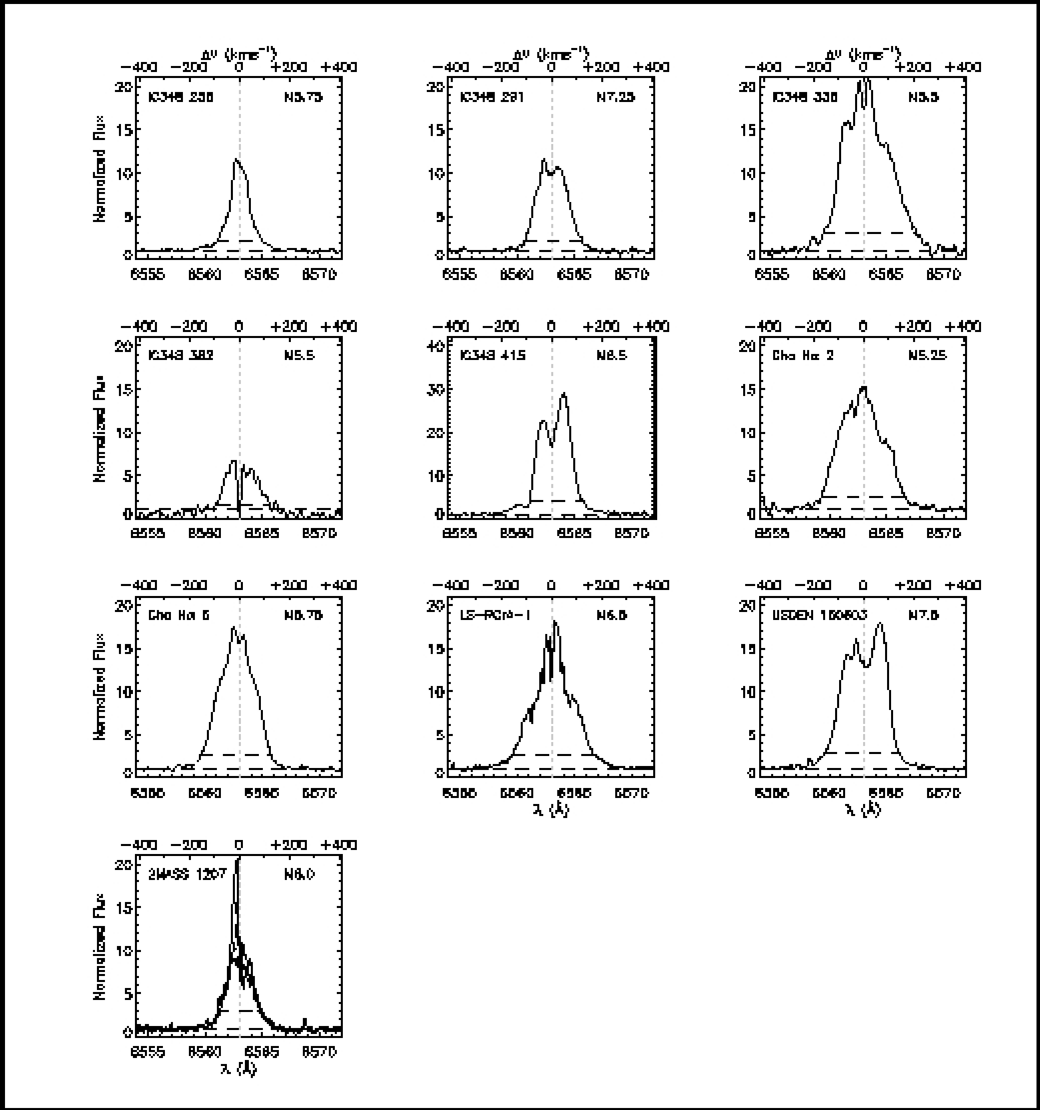
Observations

High-resolution optical spectra at Keck and Magellan

R~33,000 (HIRES), R~20,000 (MIKE)

Hα line profiles in high-resolution spectra are a good diagnostic of accretion (+ OI, HeI, CaII …)

More BD Accretors...



Mohanty, Jayawardhana & Basri (2005)

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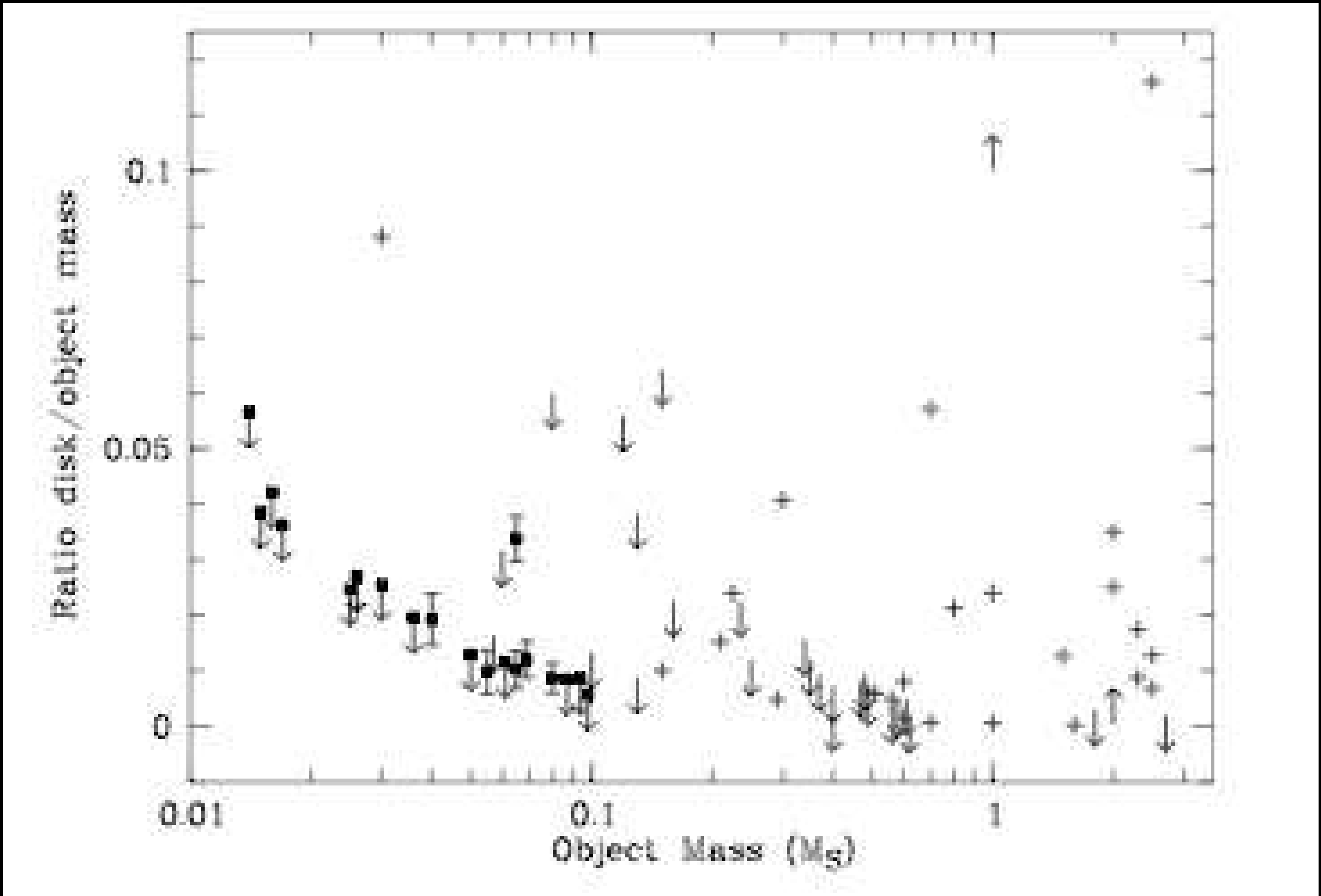

Scholz et al. in 2006

- **Existence of 2M1207AB system -- wide separation binary -- argues strongly against ejection; star-like formation preferred**

- **Stellar binary formation mechanisms, when carried into the substellar regime, can form planetary mass companions (which may have their *own* disks and perhaps form asteroids/moons)**