Studies of the substellar population of Taurus

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Formation and Evolution
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Outline

Motivations to study Taurus

12 years of searches for BD in Taurus

Wider and wider optical surveys

Spectral type distribution and the IMF of Taurus

Are brown dwarfs missing in Taurus ?

Accretion / outflows signatures in Taurus brown dwarfs

Xray properties of Taurus brown dwarfs

Spatial distribution of Taurus brown dwarfs

Implications for substellar formation models

Summary and Conclusion

Why study brown dwarf population in Taurus ?

Proto-typical low mass star formation region

Young : 1-3 Myr : limited dynamical effects

Loose: 1-10 stars/pc^3 (very different from Trapezium)

Large extension (≈ 100 deg^2) Non clustered star formation

No bright stars to irradiate & disturb their surroundings

Nearby (140 pc)

Relatively modest extinction <AV≈3>

Stellar population complete down to I ~ 12
(Kenyon & Hartmann 1995, ApJS 101, 117)

With known spatial distribution (Gomez et al. 1993, AJ 105, 1927)

... Peculiar ? Excess of binaries (eg. Duchêne 1999)

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12 Years of Searches for very low mass stars and brown dwarfs in Taurus

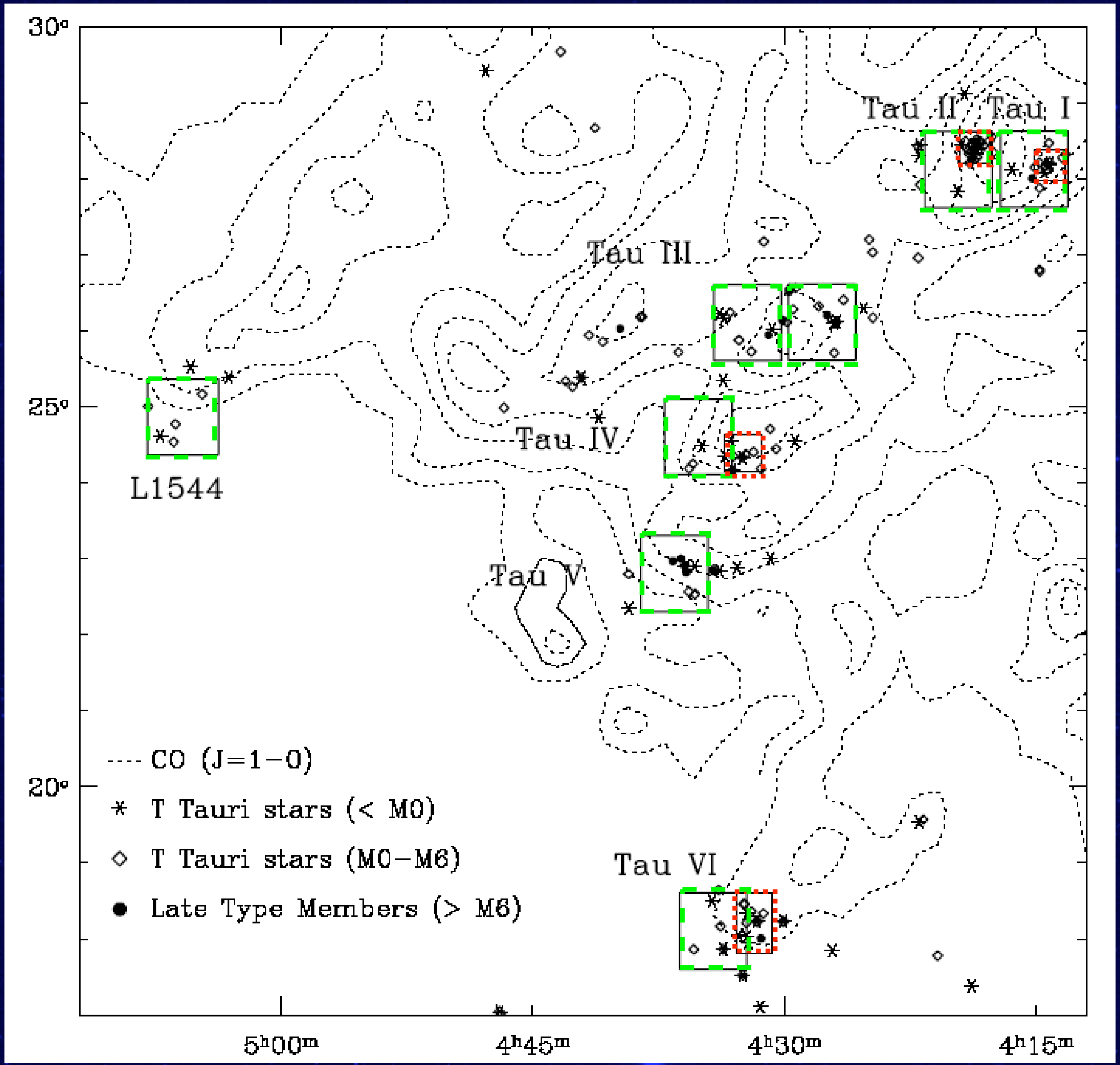
Stellar/substellar boundary: M6-M6.5V for ages 1-10 Myr (Baraffe et al. 1998, Chabrier et al. 2000)

- Pioneering studies: L1495 E — Strom & Strom 1994, ApJ 424, 237; Luhman & Rieke 1998, ApJ 497, 354
- Wide-field deep optical imaging surveys:

	comp. limit	ext.
Briceno et al 1998, Luhman 2000	$I_C=19$, $R_C=21.5$	0.7 deg^2
Briceno et al 2002, Luhman et al 2003	I_C = 19-20, z'=18	7.7 deg^2
Luhman 2004	$I_C=19$, z'=18	4 deg^2
Martin et al 2001, Guieu et al 2005	$I_C=21.8$, z' = 20.9	28 deg^2

To date: 35 deg^2 (≈30%) surveyed down to 30 M_{JUP}, Av < 4

12 Years of Searches for very low mass stars and brown dwarfs in Taurus



12CO contour map:
Ungerechts & Thaddeus, 87

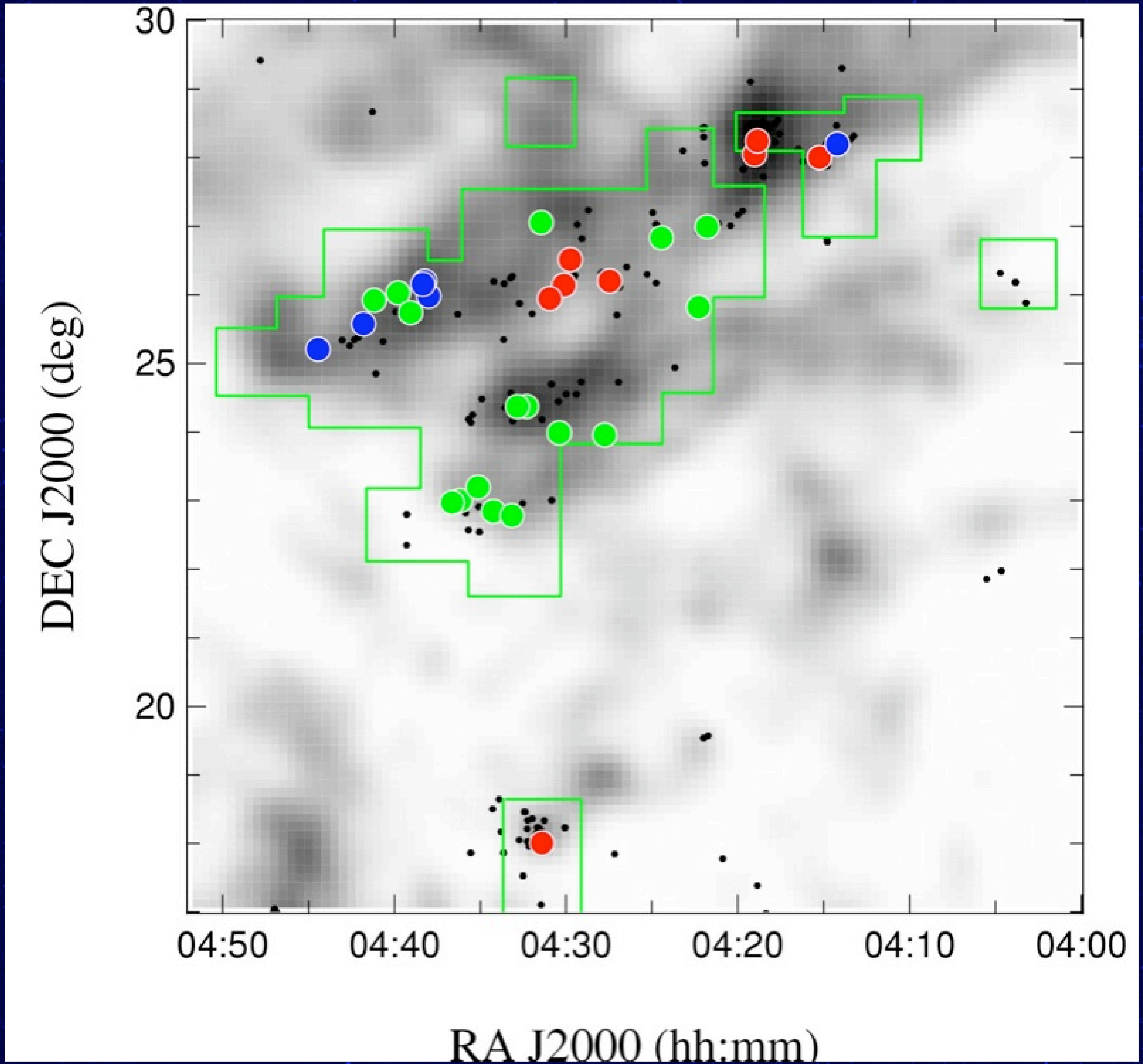
Tau I-VI Aggregates: 0.5-1 pc proj radius
Gomez et al. 93

Red boxes:
Briceno et al. 1998, Luhman 2000

Green boxes:
Briceno et al. 2002

All searches began centered on the aggregates

Wider and wider optical surveys ...



Luhman 2000

Martin et al. 2001

Briceno et al. 2002

Luhman et al. 2003

Luhman 2004

Guieu et al. 2005

Current census of brown dwarfs in Taurus

To date 35 square degrees surveyed in the optical domain down to the substellar regime (I,z' ≈ 22-21)

≈ 30 % of total cloud surface
encompassing 84 % of known Taurus stellar population

! Strong galactic contamination → optical candidate selection requires combination with near-IR photometry (currently 2MASS) (50 % contamination remain) + spectroscopic follow-up.

- Mass completeness set by 2MASS and optical spectroscopy
  30 (20?) Mjup for Av < 4 and ages < 10 Myr

33 currently known BDs in Taurus
(21 published + 12 Guieu et al. submitted ; also this conference)

- Motivations to study Taurus
- 12 years of searches for BD in Taurus
- Wider and wider optical surveys
- **Are brown dwarfs missing in Taurus ?**
- Spectral type distribution and the IMF of Taurus
- Accretion / outflows signatures in Taurus brown dwarfs
- Xray properties of Taurus brown dwarfs
- Spatial distribution of Taurus brown dwarfs
- Implications for substellar formation models
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Are brown dwarfs missing in Taurus ?

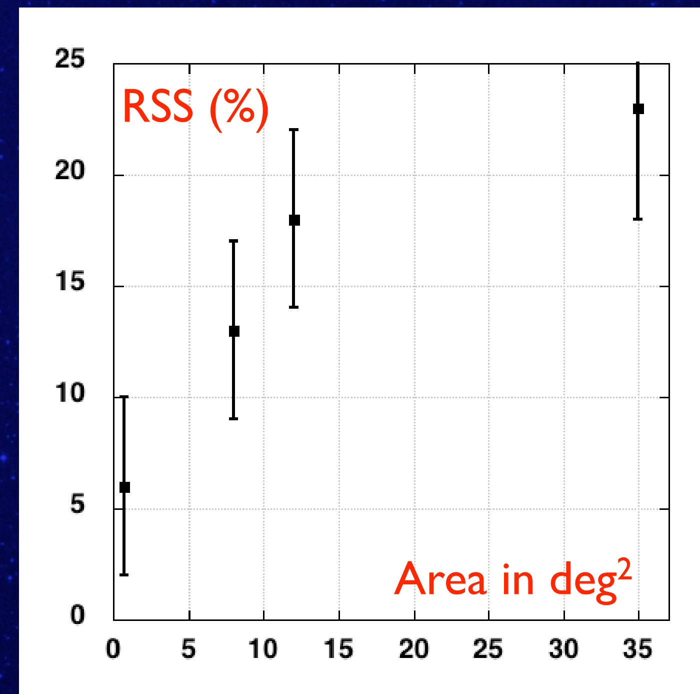
Brown dwarfs to stars ratio:

(adequate for Taurus ?)

$$R_{SS} = \frac{N(0.02 \leq M/Mo \leq 0.08)}{N(0.08 \leq M/Mo \leq 10)}$$

Rss has kept increasing as spatial coverage increased:

0.06 +/- 0.04	Luhman et al (2000)	0.7	deg^2
0.13 +/- 0.04	+Briceno et al (2002)	8	deg^2
0.18 +/- 0.04	+Luhman (2004)	12	deg^2
0.23 +/- 0.05	+Guieu et al (2005)	35	deg^2

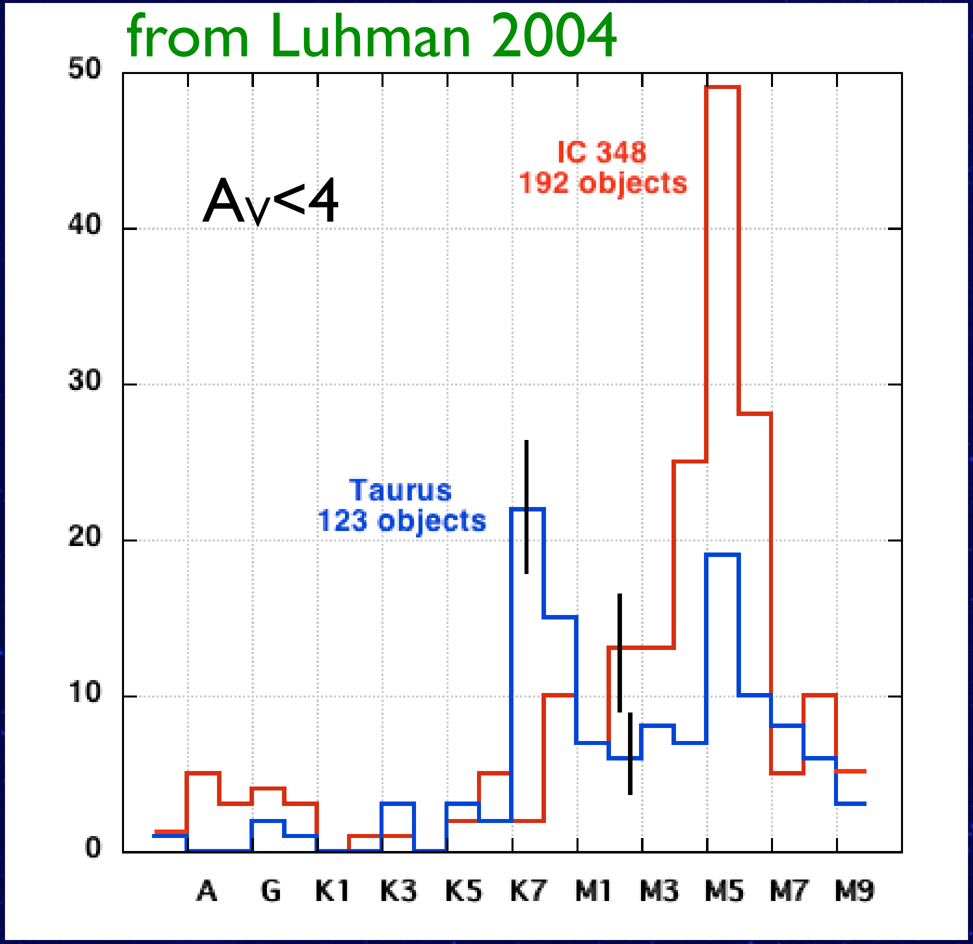


Caveat: Possible incompleteness in Taurus at SpT M2-M4 V

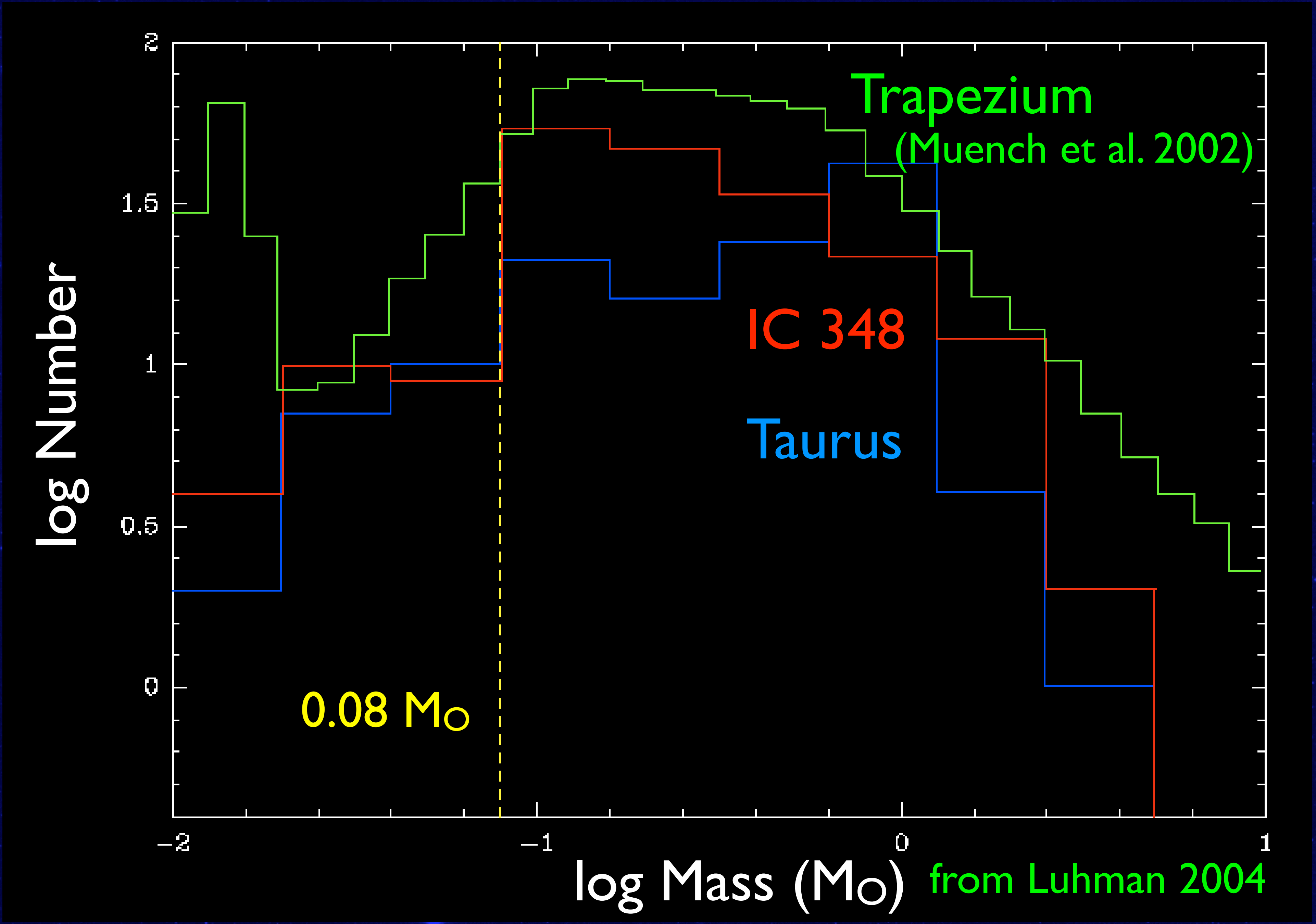
However:
- affects all surveys in Taurus
- If number of stars in this SpT range doubled, Rss will change by 17 %.

Spectral type distribution and the IMF of Taurus

Spectral type distributions in Taurus vs. IC 348



The peculiar substellar IMF of Taurus ?



see Guieu et al., in 15 mn

Are brown dwarfs *really* missing in Taurus ?

Brown dwarfs to stars ratio:
a universal 20-25 % value down to 30 M_{JUP} ?

Taurus: 0.23 (Guieu et al. 2005, submitted)

IC 348: 0.13 (Slesnick et al 2004)

Orion: 0.26 +/- 0.04 (Briceno et al 1998), 0.20 (Slesnick et al 2004)

Pleiades: 0.18 (Moraux et al. 2003)

Disk system field IMF: 0.20 (Chabrier 2004)

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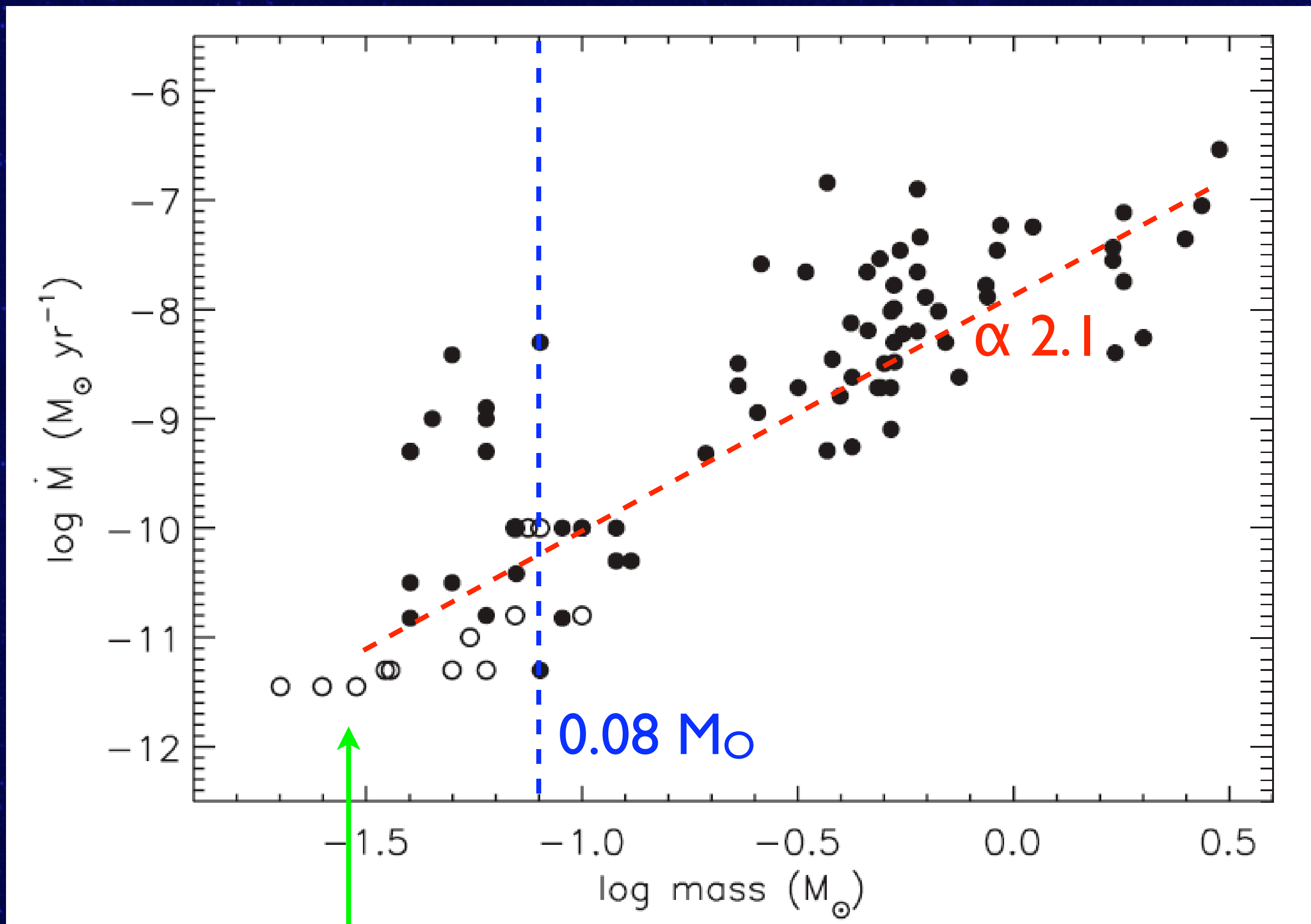
Accretion / outflow signatures in Taurus brown dwarfs

There is evidence that Taurus BD experience a 'TTauri' phase:
(see Jayawardhana; Mohanty; Scholz, this conference !)

- Broad asymmetric Hα emission profile characteristic of accretion:
  Jayawardhana et al. 2002, 2003; White & Basri 2003;
  Muzerolle et al 2000, 2003, 2005; Mohanty et al 2005
- L band excesses: disk frequency 5/9 (> 50 %) in Taurus substellar sources
  Liu, Najita & Tokunaga 2003; Jayawardhana et al. 2003 [id. IC348 (3/6=50%)]
- Level of Hα emission above chromospheric activity
  Barrado y Navascues & Martin 2003, Guieu et al 2005
  ~ 40-50 % undergoing active accretion
- Outflow resolved in a BD (Whelan et al. 2005, Nature 435)
- X ray activity at the stellar/substellar limit:
  Neuhauser et al. 1999; Stelzer & Neuhauser 2001; Mokler & Stelzer 2002; Grosso et al. 2005 in prep

Accretion / outflow signatures in Taurus brown dwarfs



(Taurus + other SFR)

[
Gullbring et al. 98
White & Ghez 01
White & Basri 03
Muzerolle et al. 03
Calvet et al. 04
Natta et al 04
]

Muzerolle et al. 2005: ≥20M_{JUP} objects harbor magnetic fields ≈ 100-200 Gauss
(Tau + Cha I)   cf. Xray activities, Grosso et al. 2005, in prep.

Continuous M/Ṁ relation through the stellar / substellar boundary

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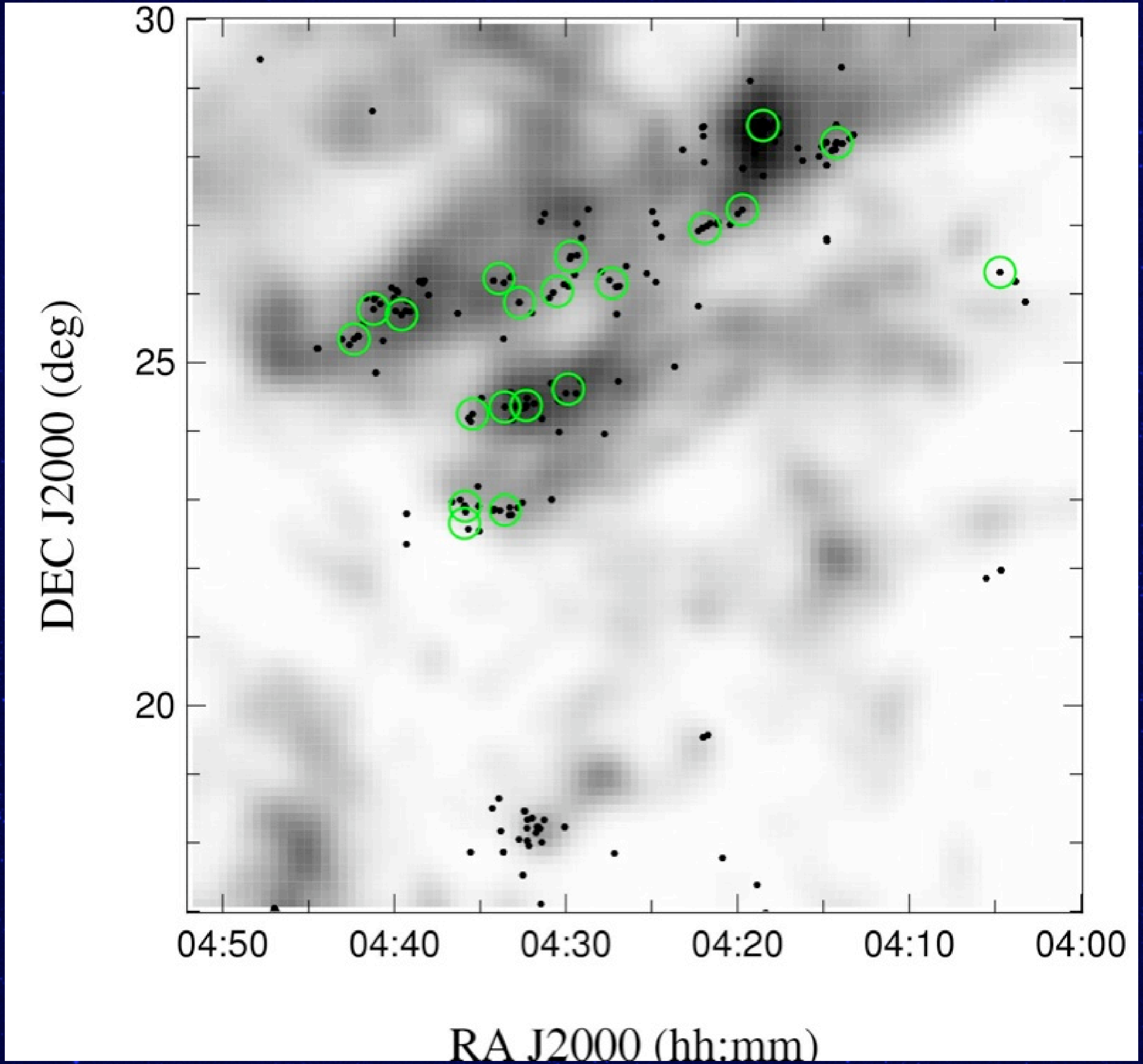
Xray properties of brown dwarfs in Taurus

XMM survey of 19 fields centered on known TTS (PI. Manuel Guedel)



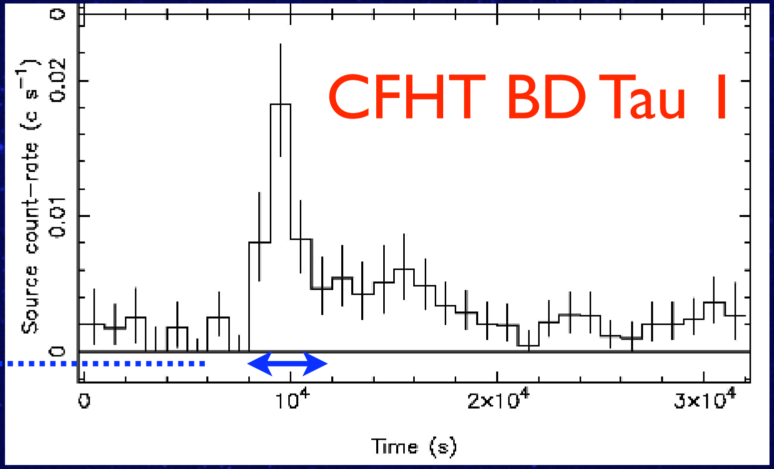
Xray properties of brown dwarfs in Taurus

X ray emission from young brown dwarfs (Grosso et al., in prep.)

17 previously known brown dwarfs in XMM fields
9 brown dwarfs detected (50 %)

Some brown dwarfs display flares →

Variability over period ≈ few hours
(cf Scholz, this conference)



- X ray properties in Taurus appear similar to that in Orion (50% for A_V<5) Preibisch et al. 2005, astro-ph 0506049

- Tendency to detect earlier (hot) BDs (≤ M7-M8)

→ Similar to small TTS with a hot corona ? No evidence for a magnetic activity change at the stellar / substellar boundary.

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Models of brown dwarf formation in Taurus

Certainly no photo-erosion ! (Whitworth, this conference)

• BDs form like stars (standard formation scenario)
gravitational collapse and fragmentation of turbulent cores
→ substellar IMF reflects initial conditions in the molecular cloud (density, temperature, level of turbulence).

• supersonic turbulence at large scale
Padoan & Nordlun 2004; Delgado-Donate et al. 2003

• subsonic turbulence at smaller scales Goodwin et al 2004a,b

Taurus *is* filamentary

• BDs form ... via ejection (ejection scenario)
→ Dynamically unstable multiple systems (*embryo* ejection model)
Reipurth & Clarke 2001; Bate et al. 2002, 2003
ejection BD velocities similar to lo-mass stars
→ Secular decay in clusters
Sterzik & Durisen 2003; Kroupa & Bouvier 2003a,b

• BDs form through both paths (turbulent cores + ejection)
→ Taurus IMF comes from its peculiar core mass function.
Goodwin et al 2004a,b; 2005

IMF peak and R_{SS} : implication for BD formation models

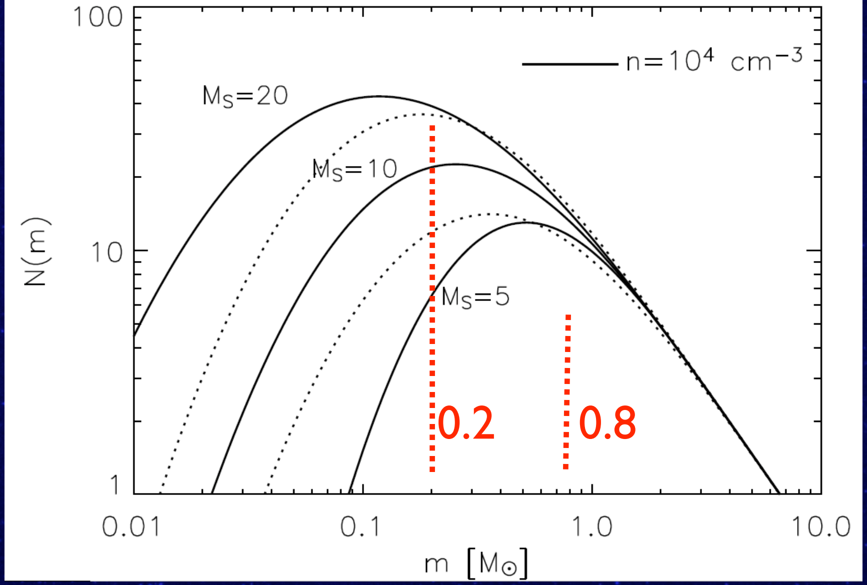
- Difference in (stellar) mass distribution peaks Taurus / Orion:

  → supersonic turbulence fragmentation models

  Padoan & Nordlun 2004; Delgado-Donate et al. 2003

- Similarity of Taurus and ONC R_{SS}:

  → not explained by supersonic turbulence fragmentation models (only)



- Uniformity of R_{SS} values among SFR:

  → more compatible with sub-sonic turbulence fragmentation models: predict $R_{SS} \approx 0.2$ independent of level of turbulence (Goodwin et al 2004a,b)

Spatial distribution of brown dwarfs in Taurus: implications...

in ≈ 30% of Taurus :

• Initial Surveys (12.4 deg^2) → brown dwarfs correlated with stars.
Briceno et al. 2002; Luhman 2004. (however see Martin et al 2001)

• More extended survey (30 deg^2) → relative abundance of BDs with respect to stars is lower (by a factor ≈2) in the center of the aggregates (scale ≈ 0.5 pc), with respect to the distributed population

but also :

• No clear spatial segregation between stars and BDs at large scale
Guieu et al 2005 ; cf. Goodwin 2005, this conference

→ test spatial distribution vs spectral types ?

Spatial distribution of brown dwarfs in Taurus: implications...

Fragmentation models predict M_{JEANS} decreases with increasing (central) density

→ Evidence for BD ejection from central high density regions ?

(BD travel 1 degree in 2 Myr at 1 $km.s^{-1}$ @ 140 pc)

• Observations at large scale seem to suggest ejection velocities similar between VLM stars and BDs (see Guieu et al., this conference, in 10 mn !)

→ Consistent with predictions from recent embryo-ejection models:
Bate et al. 2003; Goodwin et al. 2004; Kroupa & Bouvier 2003b
(secular decay too slow?)

Accretion / outflow signatures in Taurus brown dwarfs: implications ...

Evidence that BD form like stars ? Not quite so!

Even truncated disks can

- survive for a few Myr: Viscous timescale τ_{visc} scales as $M^{-1/2}$

For R_{OUT} = 10 AU, τ_{visc} ~ 2 Myr around a 50 M_{JUP} BD

- with $\dot{M} \approx 5\,10^{-11} M_O.yr^{-1}$ & $M_{disk} \approx 5\,10^{-4}\ M_O$ → τ_{disk} ≈ few Myr ≥ age of Taurus
- drive an outflow: with ionisation ≈ 10^{-7} (from external radiation)

NB. in TTS, disk winds driven within inner few (one) AU

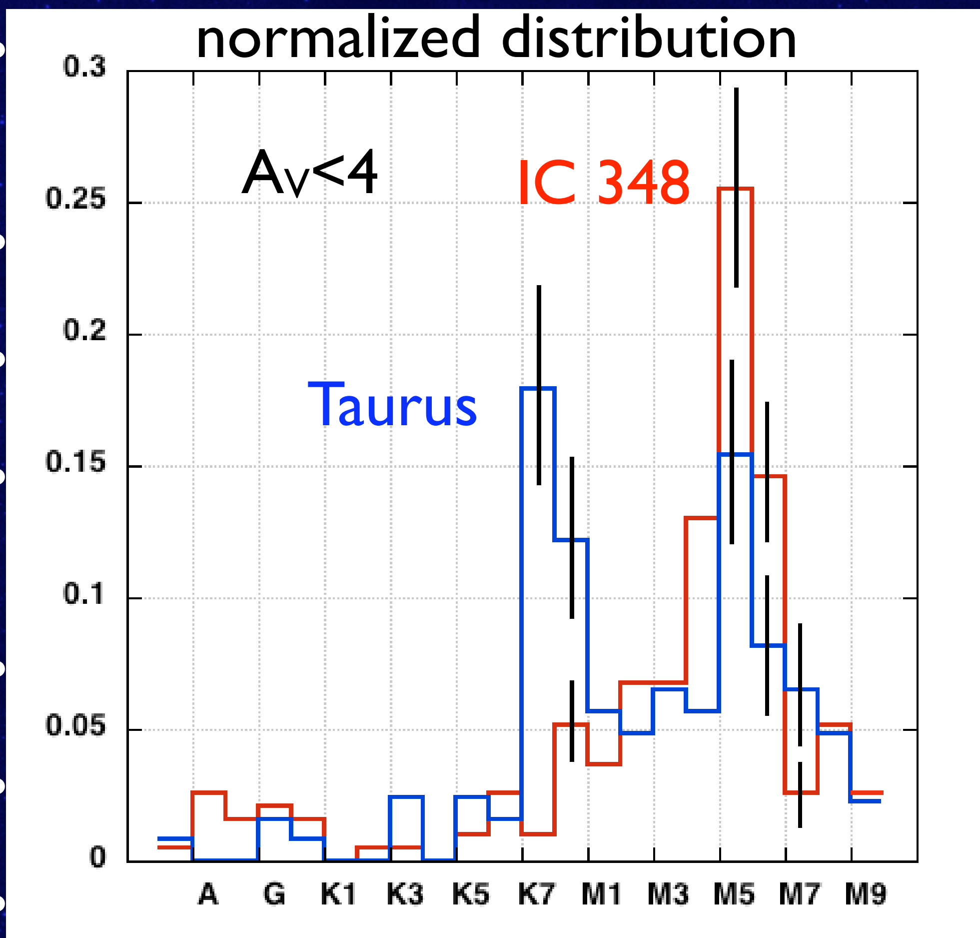
Garcia et al. 2001a,b

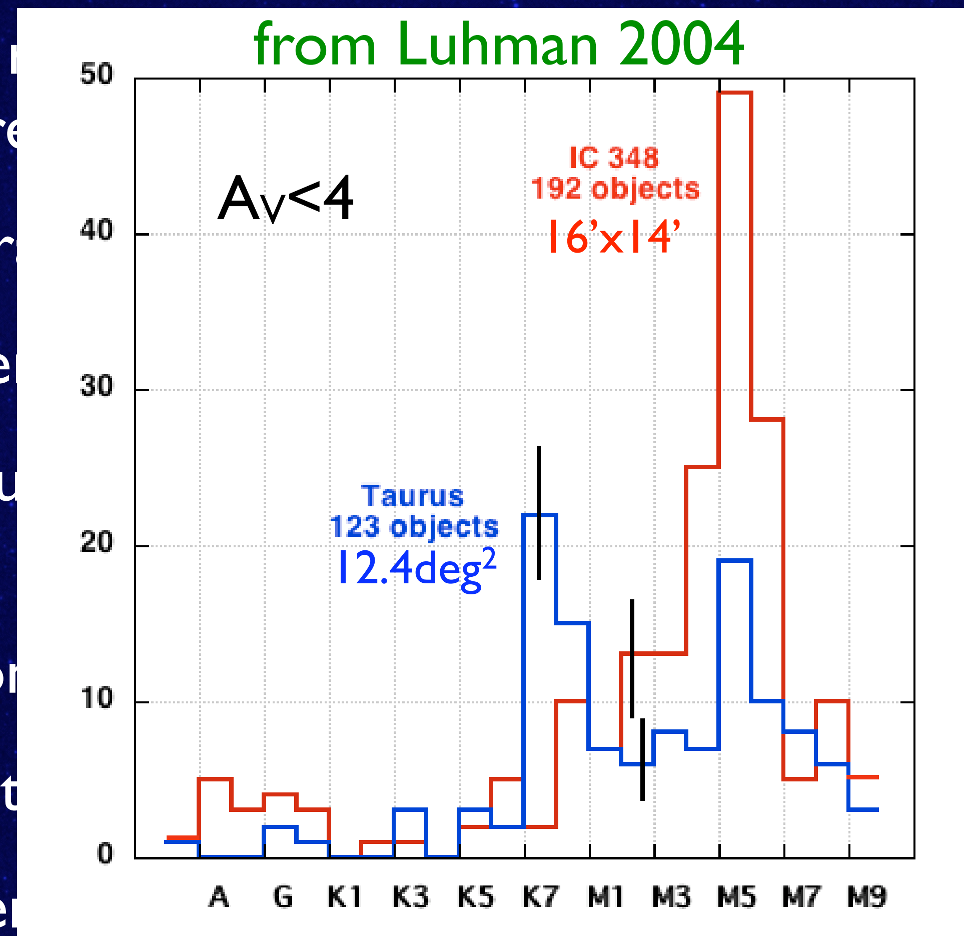
Test: detection of extended outer disk (mm emission).
can we measure sizes ?

So far, only 2 BDs (CFHT-Tau 4, IC 348 613) detected
In mm continuum (Klein et al 2003; Pascucci et al. 2003)
→ inferred disk masses ~ a few M_{JUP} ≈ a few 10^{-3} Mo
(computations cf. Beckwith et al. 90)

SUMMARY and CONCLUSION

- The relative abundance of BDs/stars in Taurus is 23 %, similar to Orion, Pleiades and the field (system disk).





- Uniformity of R_{SS} consistent with core sub-sonic turbulence models