First results from the UKIDSS Galactic Cluster Survey

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in collaboration with N. C. Hambly and R. F. Jameson

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Collaborators

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Outline of my talk

1. What are in brown dwarfs?
2. Overview of techniques and searches to find brown dwarfs
3. Why do we study the substellar IMF?
4. Quick overview of the UKIDSS Galactic Cluster Survey
5. The Upper Scorpius association
6. The Alpha Per open cluster
7. The Pleiades
8. Future work and perspectives

The realms of brown dwarfs

- Brown dwarfs have masses < 0.072 $M_\odot$ at solar metallicity (*Baraffe et al. 1998)*
- Core temperature and pressure insufficient to ignite hydrogen
- Luminosity and temperature decrease inexorably with time
- Radii of extrasolar planets larger than those of brown dwarfs

0.03 $M_\odot$	L ($L_\odot$)	T_{eff} (K)	R (R_{jup})
1 Myr	10^{-2}	2800	4.3
1 Gyr	6×10^{-6}	1900	1.0

- If M > 0.013 $M_\odot$ brown dwarfs burn deuterium
- If M > 0.065 $M_\odot$ brown dwarfs burn lithium shortly
- Atmospheres composed of H, He, C, O, N

The formation of brown dwarfs

- Controversy over the formation mechanisms of brown dwarfs
  - Jeans mass in molecular clouds larger than the mass of a brown dwarf
  - Accretion should be interrupted to keep the mass below 0.072 $M_\odot$
- Proposed formation mechanisms
  - Turbulence in molecular clouds *Klessen (2001); Padoan & Nordlund (2002)*
  - Irradiated pre-stellar cores *Whitworth & Zinnecker (2003)*
  - Disk instabilities *Boss (1998, 2000); Li (2002); Watkins et al. (1998a, 1998b); Boffin et al. (1998)*
  - Ejection of the least massive component from multiple systems *Reipurth & Clarke (2001)*
  - Formation in circumstellar disks *Papaloizou & Terquem (2001) Armitage & Bonnell (2002)*
- Observational tests
  - Brown dwarfs and stars share the same formation mechanism in disagreement with N-body simulations *(Kroupa 2001)*

Searches for brown dwarfs I

- First unambiguous brown dwarfs discovered in 1995

Nakajima et al. (1995)
Rebolo et al. (1995)

- Isolated brown dwarfs in the field
  - All-sky surveys:
    - 2MASS *(Kirkpatrick et al. (2000)*
    - DENIS *(Delfosse et al. 1997, 1999)*
    - SDSS (*Fan et al. 2002; Schneider et al. 2002)*
    - UKIDSS ...
  - Proper motion surveys:
    - LHS and NLTT catalogues *(Luyten 1979, 1980)*
    - Solar vicinity within 8 pc *(Reid and collaborators)*
    - Extension of the NLTT catalogue *(Lépine and collaborators)*
    - Calán-ESO database *(Ruiz et al. 1997)*
    - Liverpool-Edinburgh catalogue *(Pokorny, Jones & Hambly 2003)*
    - Our proper motion survey *(Scholz et al. 2000; Lodieu et al. 2005)*
  - Serendipitous discoveries:
    - *Cuby et al. 1999; Liu et al. 2002; Kendall et al. 2003*

Searches for brown dwarfs II

- Brown dwarfs as companions to stars
  - High-resolution imaging with adaptive optics

    Close et al. (2002, 2003); Freed et al. (2003); McCaughrean et al. (2004)

  - High-resolution imaging with the *Hubble* space telescope

    Martín et al. (1999); Reid et al. (2001); Burgasser et al. (2003); Gizis et al. (2003); Bouy et al. (2003)

    - Binary fraction ~20%
    - Separations < 20 AU with a peak around 8 AU
    - Mass ratios around unity

  - Radial velocity surveys

    Mayor et al. (1992); Tokovinin et al. (1994); Mazeh et al. (1996) Marcy et al. (1999), Udry et al. (2002)

    => Less than 0.5% of solar type stars have BD companions

Searches for brown dwarfs III

- Brown dwarfs in star-forming regions:
  - Trapezium Cluster *(Muench et al. 2002; Slesnick et al. 2004)*
  - Sigma Orionis *(Béjar et al. 2001; Barrado y Navascués et al. 2004a)*
  - IC 348 *(Luhman et al. 2003)*
  - Taurus *(Briceño et al. 2002)*
  - Rho Ophiuchus *(Luhman et al. 2000)*
  - Chameleon *(Comerón et al. 1999, 2000)*
  - Serpens *(Lodieu et al. 2002; Klotz et al. 2004)*

- Brown dwarfs in young open clusters:
  - Pleiades *(Martín et al. 1998; Dobbie et al. 2002; Moraux et al. 2003)*
  - Alpha Per *(Barrado y Navascués et al. 2002)*
  - IC 2391 *(Barrado y Navascués et al. 2004b)*
  - NGC 2547 *(Jeffries et al. 2004)*
  - IC 4665 *(de Wit et al. 2005)*
  - Collinder 359 *(Lodieu et al. 2005)*

=> Determination of the IMF in the substellar regime

The Initial Mass Function

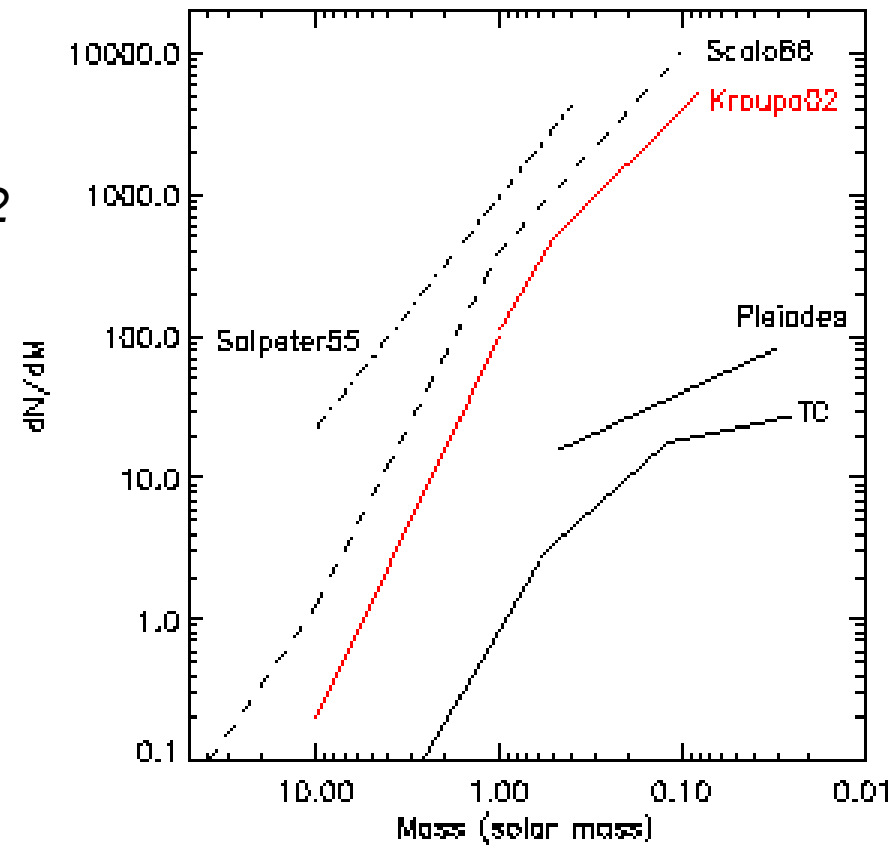
- Understand the origin of stars and brown dwarfs
- Definition of the IMF:

  Salpeter definition: $\xi(\log M) = dN / d\log M \propto M^{-x}$

  Mass spectrum definition $\xi(m) = dN / dM \propto M^{-\alpha}$

- Determination of the IMF: *Kroupa 2002*

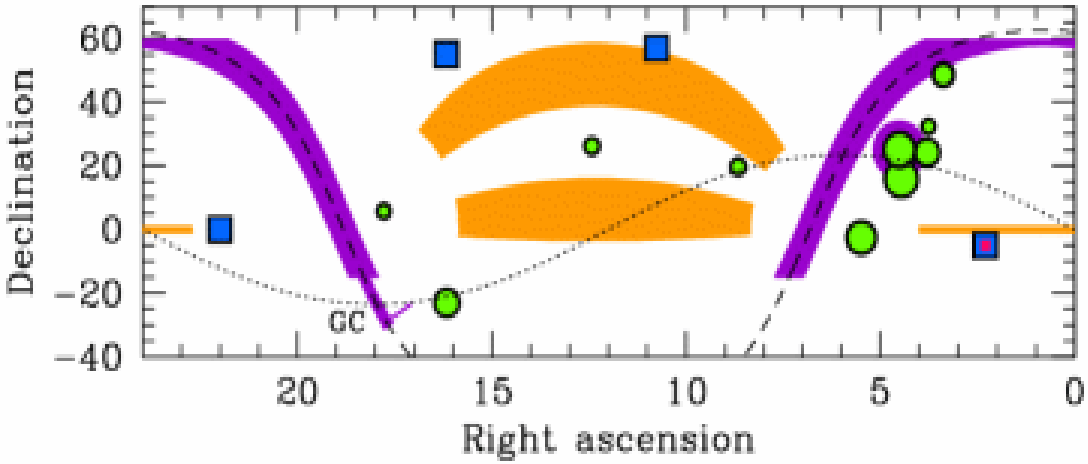
  - $M > 1\ M_\odot$ $\alpha = 2.7$
  - $M = 1\text{-}0.5\ M_\odot$ $\alpha = 2.2$
  - $M = 0.5\text{-}0.08\ M_\odot$ $\alpha = 1.3$
  - $M < 0.08\ M_\odot$ $\alpha = 0.5\text{-}1.0$



UKIDSS

- ➔ New wide-field NIR survey with WFCAM on UKIRT *(Lawrence et al. 2006)*
- ➔ Pipeline-processed by CASU in Cambridge *(Irwin et al. 2006, in prep)*
- ➔ WFCAM Science Archive *(Hambly et al. 2006, in prep)*
- ➔ 5 components: LAS, GCS, GPS, DXS, and UDS
- ➔ Typical 5 sigma completeness limit is *K* = 18.1 mag (Vega)
- ➔ EDR on 10 Feb 2006 *(Dye et al. 2006, MNRAS, in press)*
- ➔ DR1 on 21 July 2006 *(Warren et al. 2006, MNRAS)*

➢ Galactic Cluster Survey (GCS)



- ➔ *ZYJHK* observations
- ➔ 1000 square degrees
- ➔ 10 star-forming regions and open clusters
- ➔ 2 epochs in the K-band
- ➔ 5 sigma completeness limits: *Z*=20.0, *J* = 18.6, *K* = 17.5

The Upper Scorpius association

Lodieu, Hambly, & Jameson 2006, MNRAS, in press

Lodieu, Hambly, Jameson, Carraro, Kendall 2006, MNRAS, in press

The Upper Sco cluster

1) Scorpius Centaurus = nearest OB association
- ✗ Upper Scorpius
- ✗ Upper Centaurus Lupus
- ✗ Lower Centaurus Crux

Blaauw (1964)

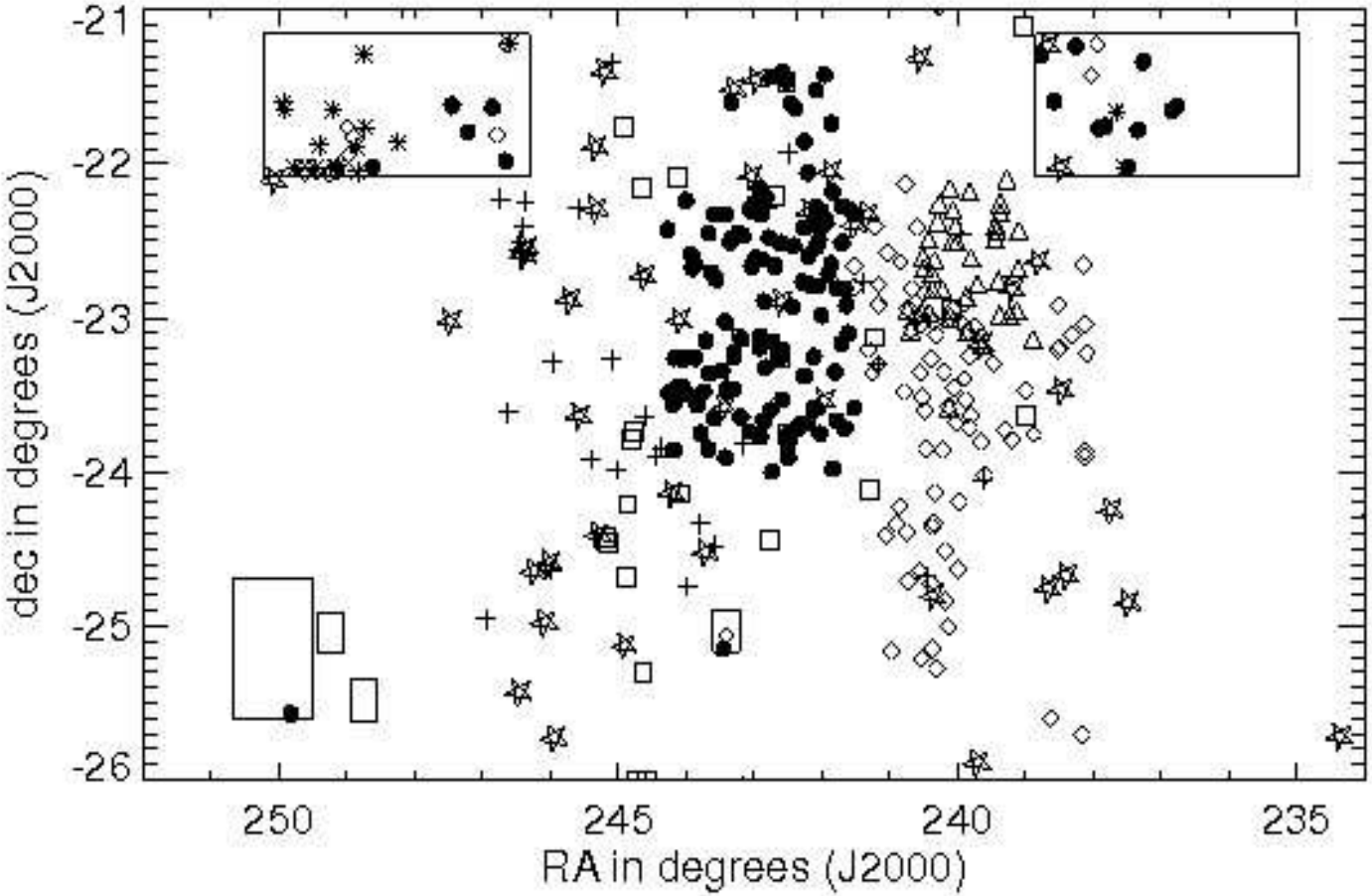
- Area ~ 120 square degrees
- Age = 5 Myr (kinematic + isochrone fitting)
- Distance = 145 pc (Hipparcos)
- Region free of extinction (Av < 2 mag)

2) Previous surveys:

- ✔ X-rays studies *(Walter et al. 1994; Preibisch et al. 1998, Argiroffi et al. 2006)*
- ✔ Hipparcos astrometry *(de Bruijne 1997)*
- ✔ Deep optical (*RI*) surveys *(Ardila et al. 2000, Slesnick et al. 2006)*
- ✔ Optical (*I*) + near-infrared (*JK*) *(Martin et al. 2004)*
- ✔ Near-infrared (*ZYJHK*): UKIDSS GCS SV & EDR *(Lodieu et al. 2006a, b)*

Coverage in Upper Sco

Coverage based on 6.5 deg^2 (SV data) and 9.3 deg^2 (EDR data)



Δ *Preibisch et al. (1998)*

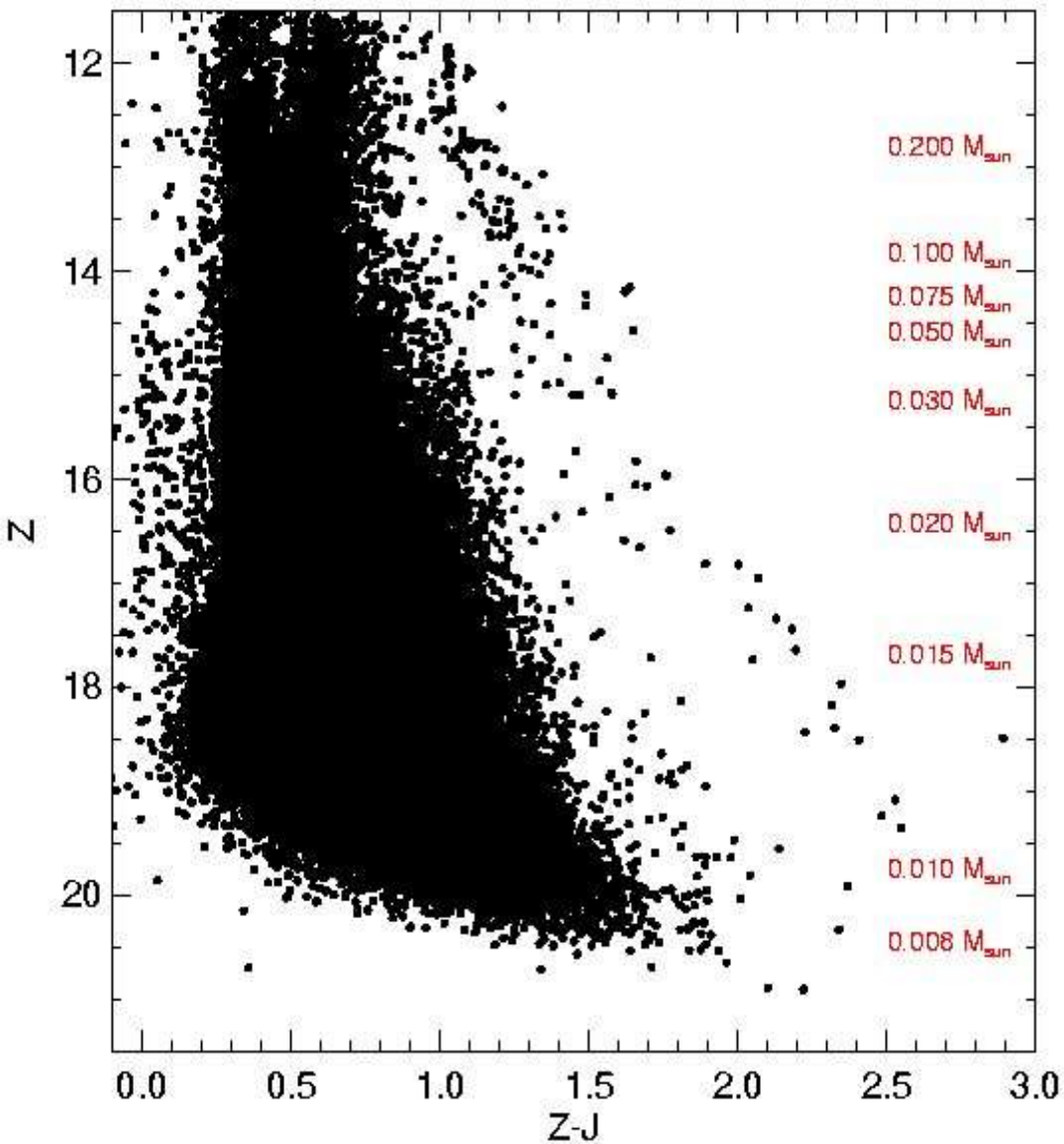
◊ *Ardila et al. (2000)*

□ *Martin et al. (2004)*

* *Slesnick et al. (2006)*

● *Lodieu et al. (2006a, b)*

Selection of members (I)



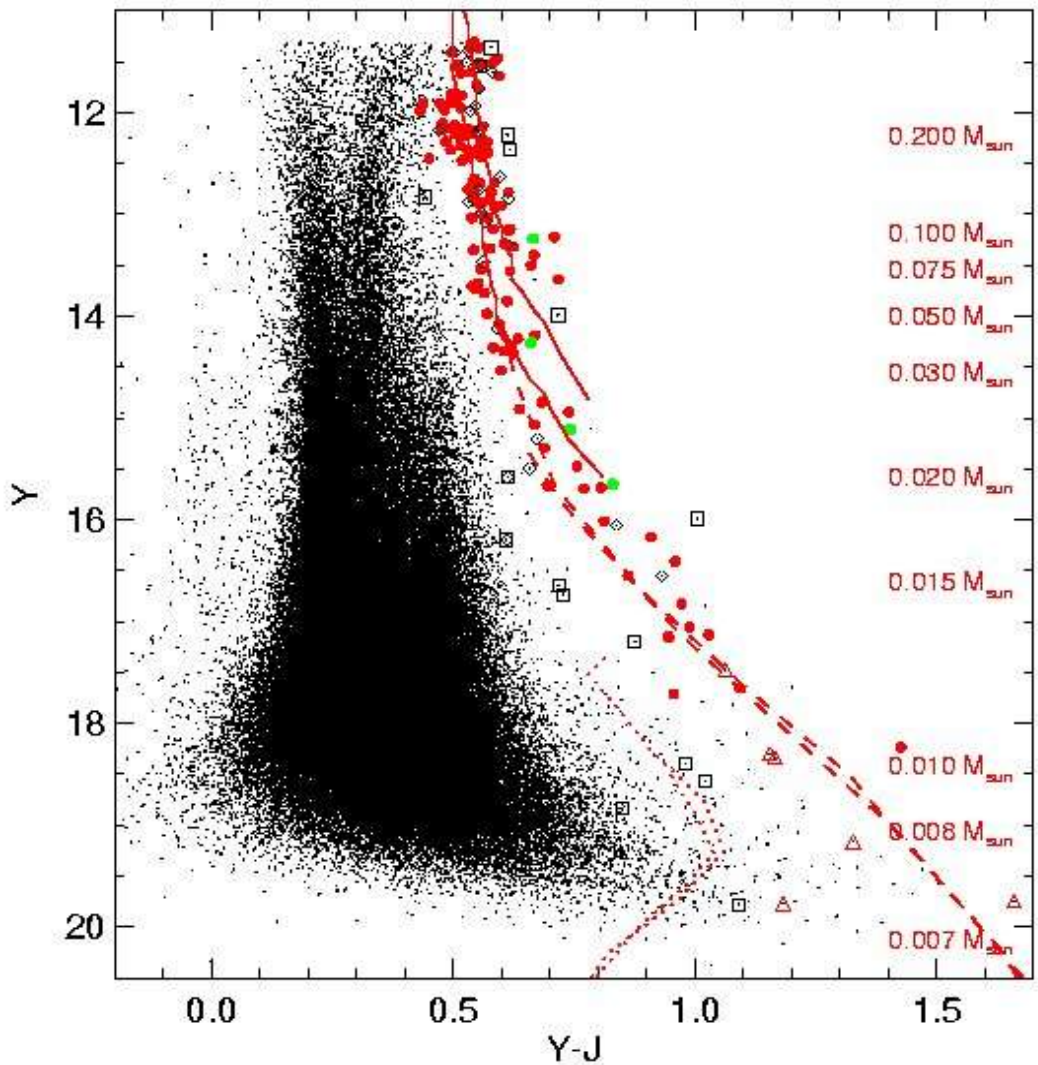
164 sources selected with Z = 11.5-20.5 mag

Cluster sequence well separated from field stars

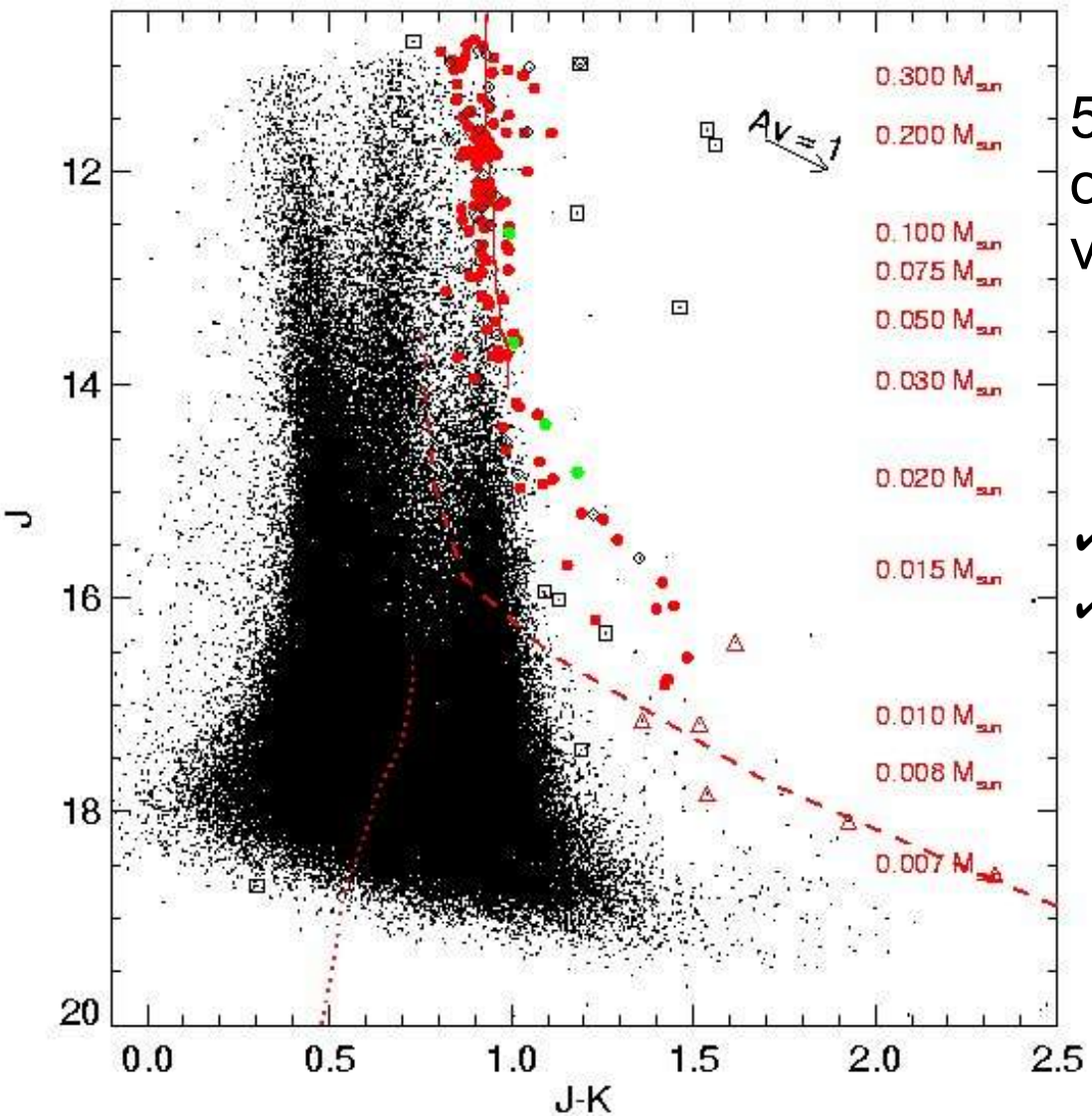
Mass scale from the NextGen and DUSTY models
(Baraffe et al. 1998; Chabrier et al. 2000)

Selection of members (II)

Lower-mass brown dwarfs with no *Z* detection can be selected from this colour-magnitude diagram: 6 new candidates (open red triangles)



Selection of members (III)

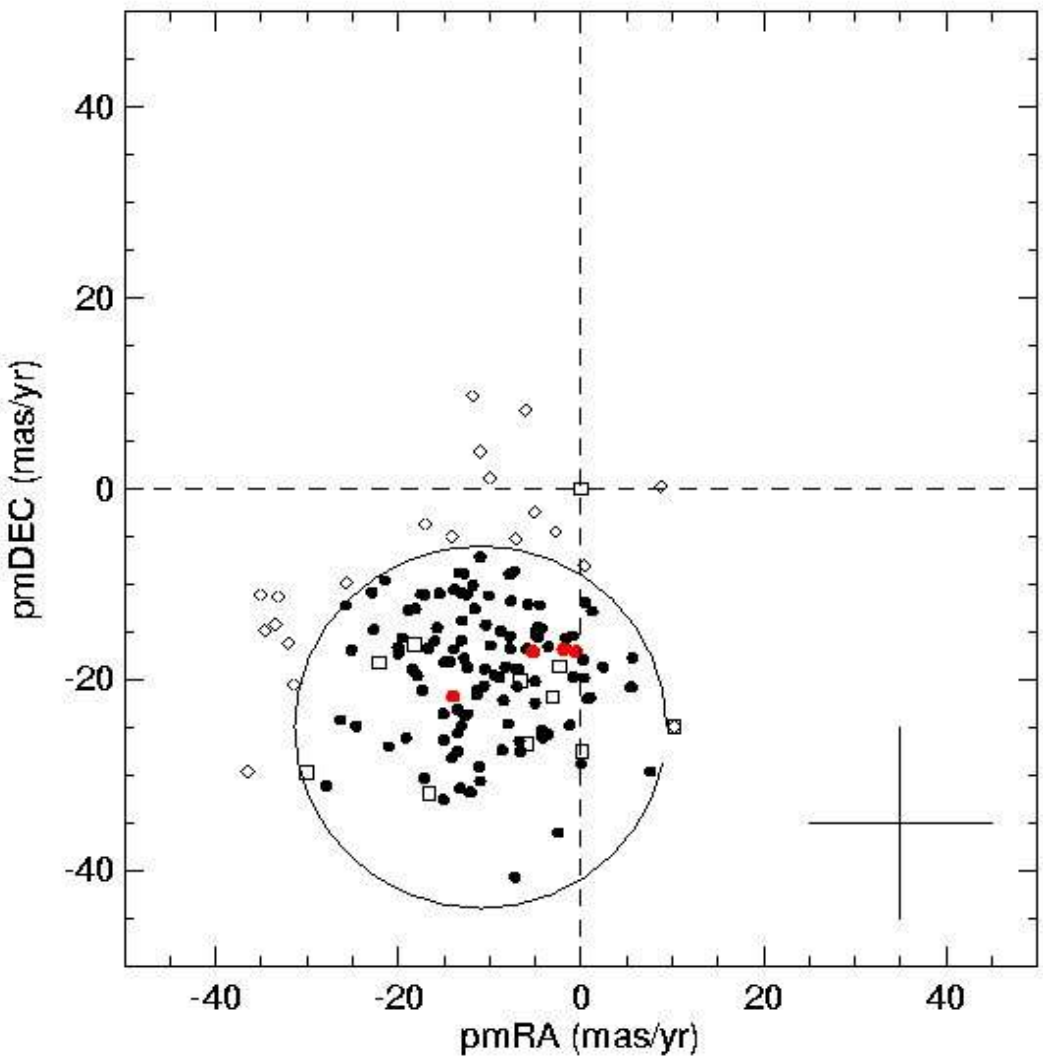


5 filters are available => rejection of photometric candidates from various colour-magnitude diagrams

- ✔ 18 candidates (squares) rejected
- ✔ 146+6 good candidates (red dots)

Proper motion selection

Photometry is usually not enough for membership assessment
=> Proper motion available from the GCS/2MASS cross-correlation



Upper Sco mean PM
(-11, -25) mas/yr

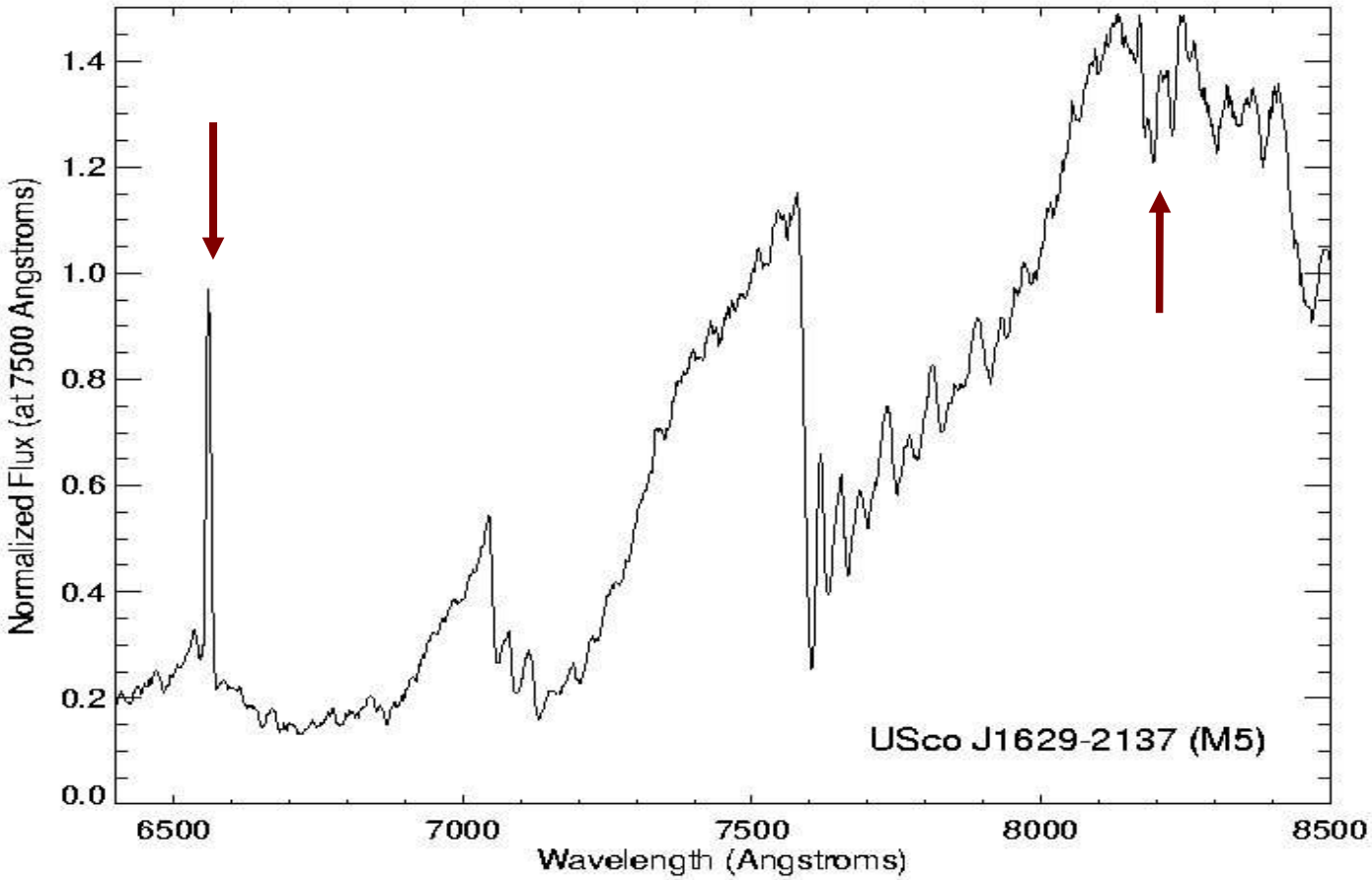
- ✔ Limit @ *J* = 15.8 mag
- ✔ 2 sigma circle selection
- ✔ 23 rejected PM non-members
- ✔ 129 good candidates

Level of contamination = 25%

Optical spectroscopy

Optical spectra (6400-8500 Å) obtained with ESO3.6-m/EFOSC2
18 photometric+proper motion selected candidates in the EDR
15 spectroscopic members and 3 non-members => 83% success

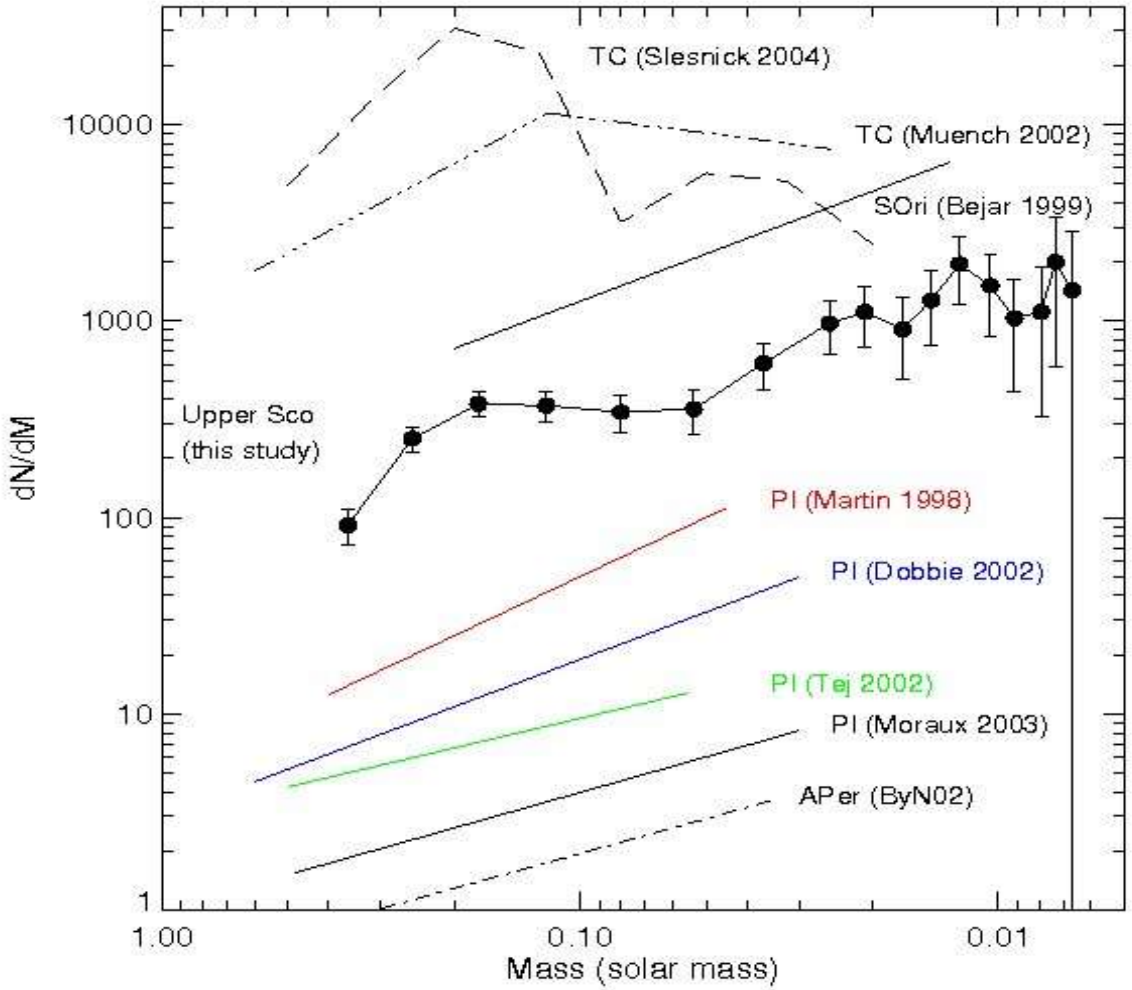
Halpha: EW = -30 to -4 Å => youth indicator
Weak NaI doublets (EW = 2-4 Å) => low gravity indicator



Initial Mass Function

We derived the IMF based on the NextGen and DUSTY models, assuming an age = 5 Myr and a distance of 145 pc

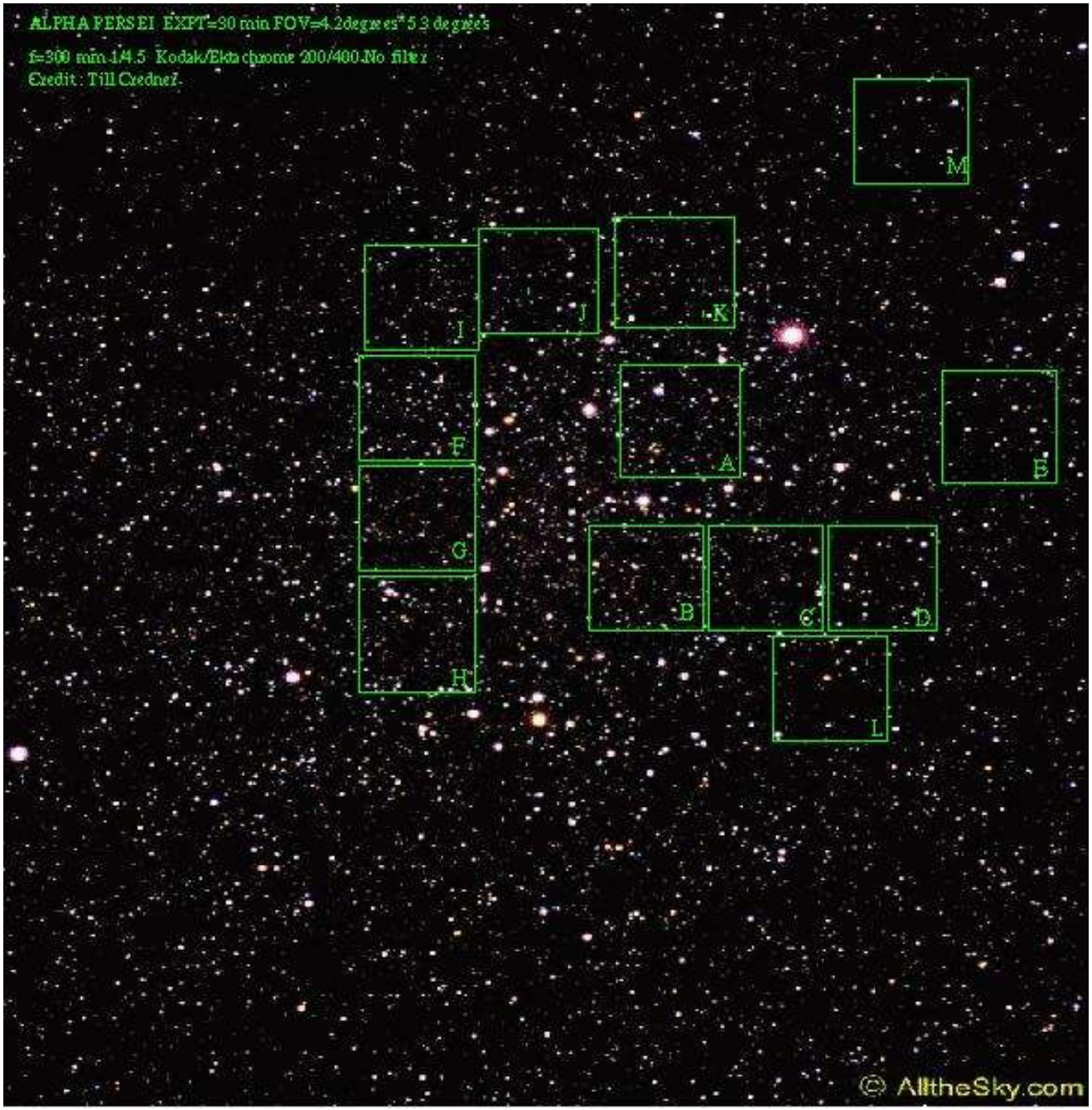
Slope of the power law is alpha = 0.6±0.1 in the 0.3-0.01 $M_{\odot}$ mass range



The Alpha Per open cluster

Lodieu, Dobbie, Hambly, Barrado y Navascués, Jameson 2006, MNRAS, in prep

Properties of Alpha Persei



- Age = 90+/-10 Myr
- Distance = 182 pc
- Extinction < 0.3 mag
- PM = (23,-25.5) mas/yr
- Low galactic latitude
- Extended: 6 deg^2

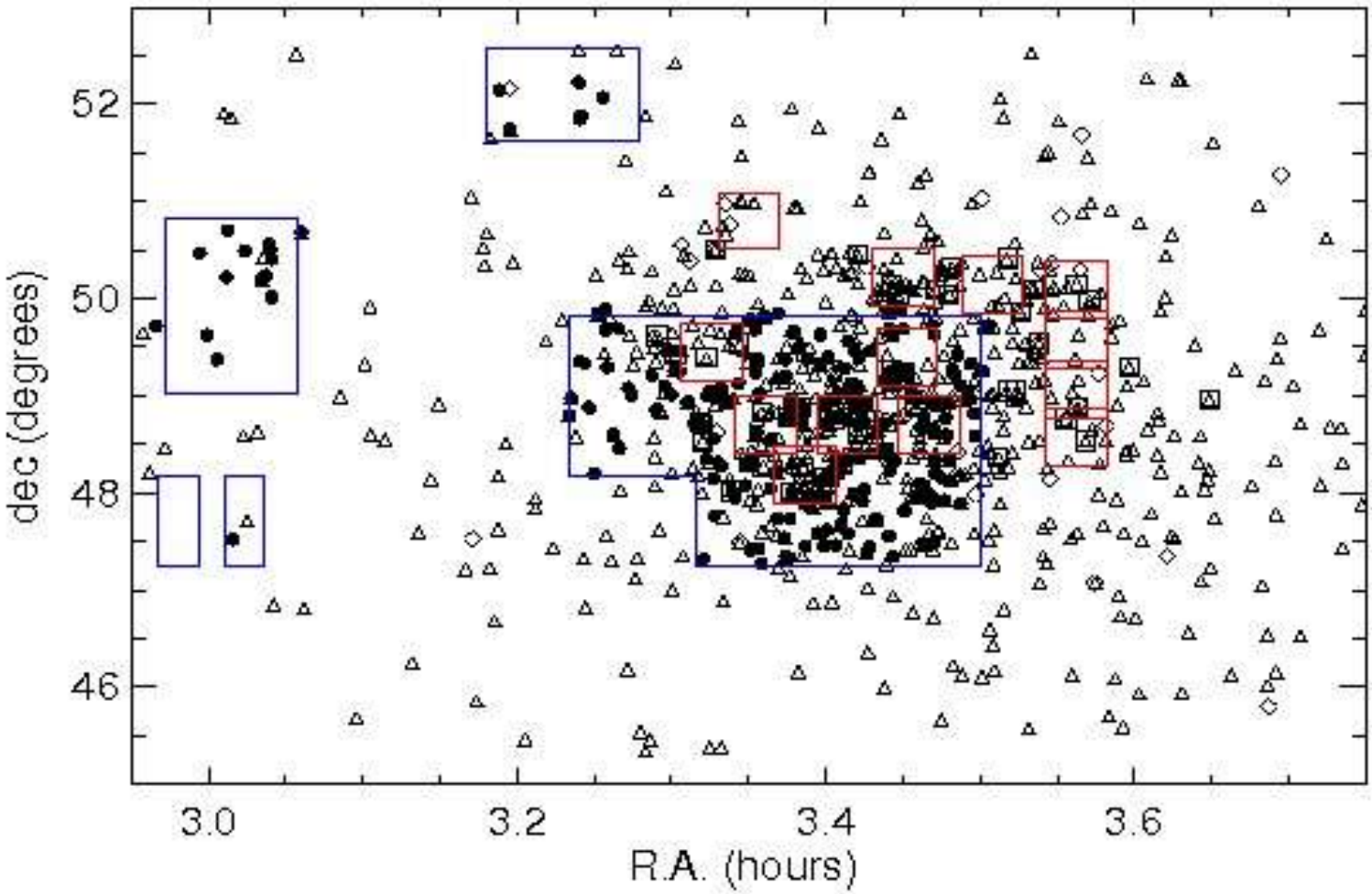
➢ KPNO/MOSA
=> 13 fields in *R, I*
=> ~3 sq. deg.

UKIDSS GCS DR1
=> 9 sq. deg. in *ZYJHK*

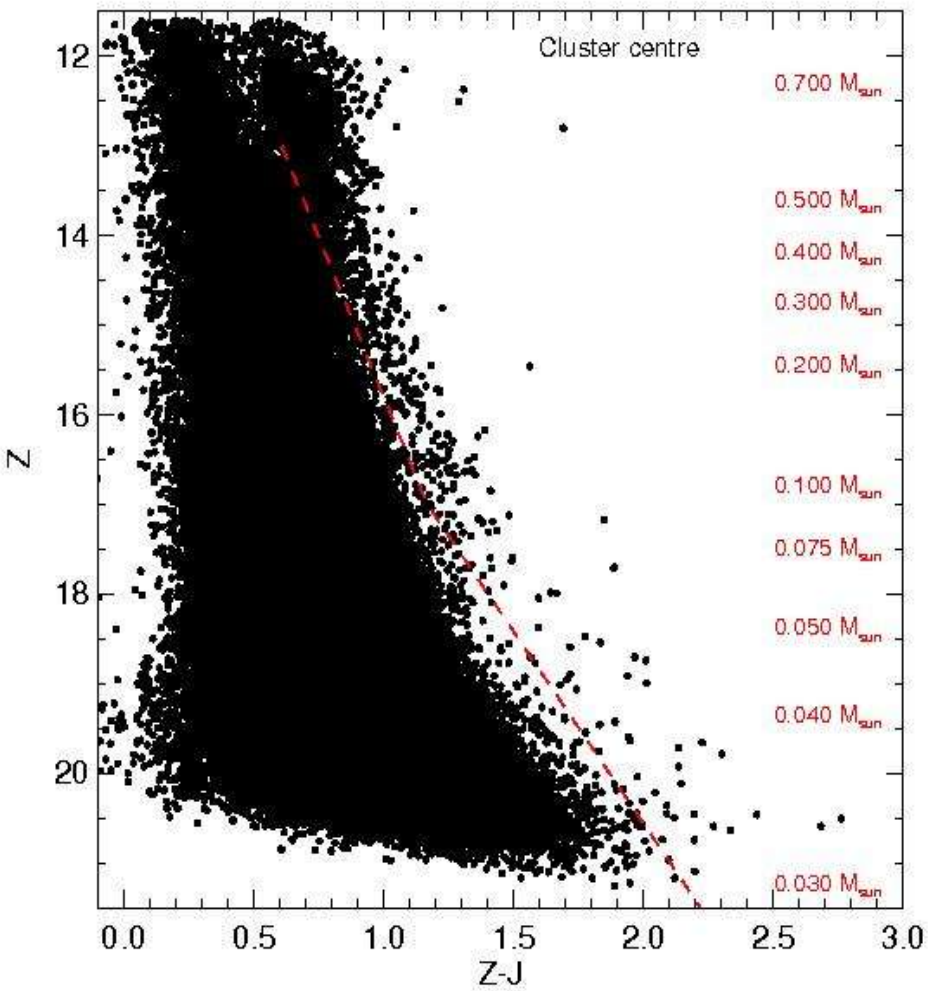
APer: Coverage

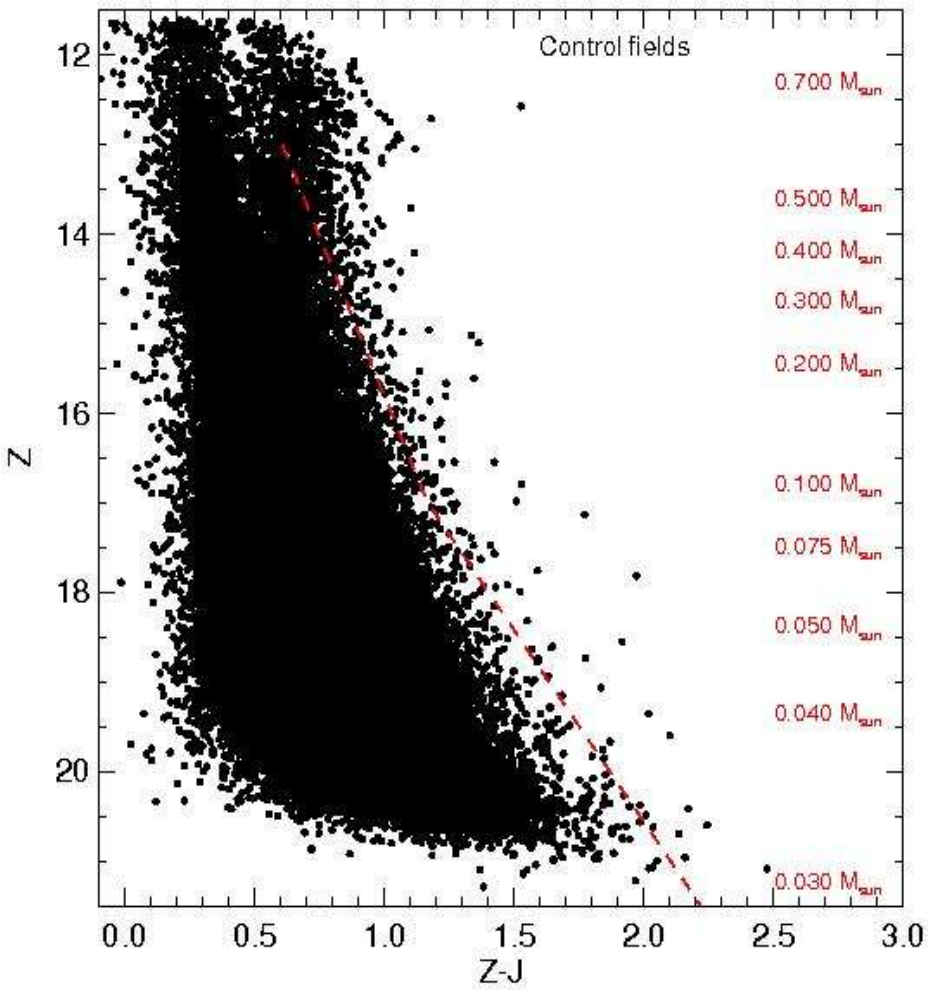
Red boxes: optical coverage (3 deg^2) in *R,I* *(Barrado y Navascues et al. 2002)*

Blue boxes: Infrared coverage (9 deg^2) in *ZYJHK* from GCS *(Lodieu et al. 2006)*



APer: CMDs





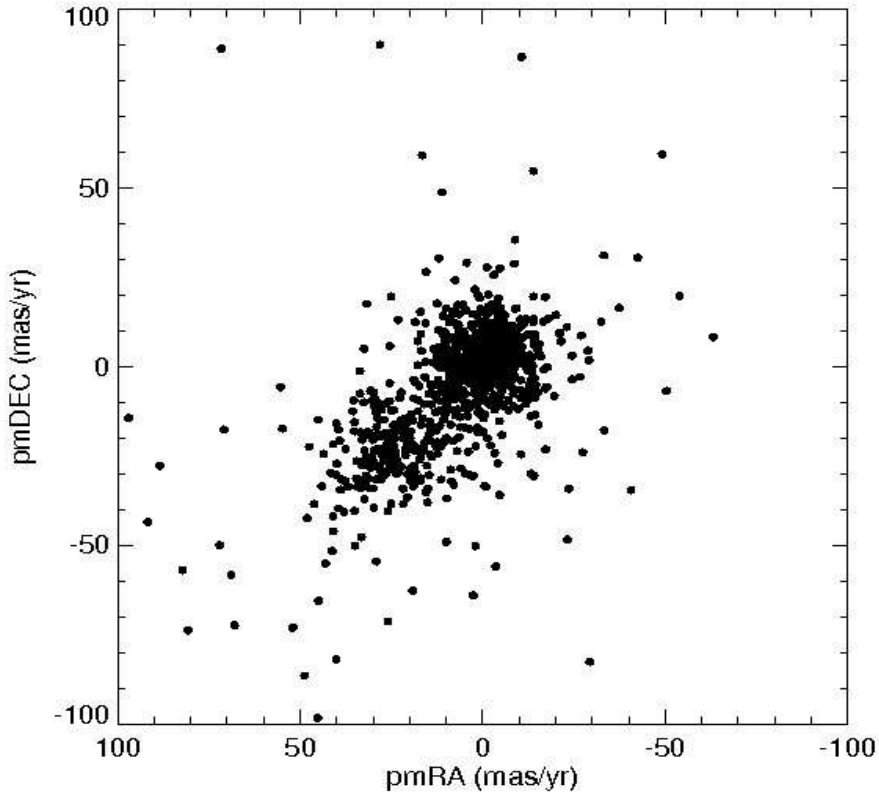
CLUSTER CENTRE

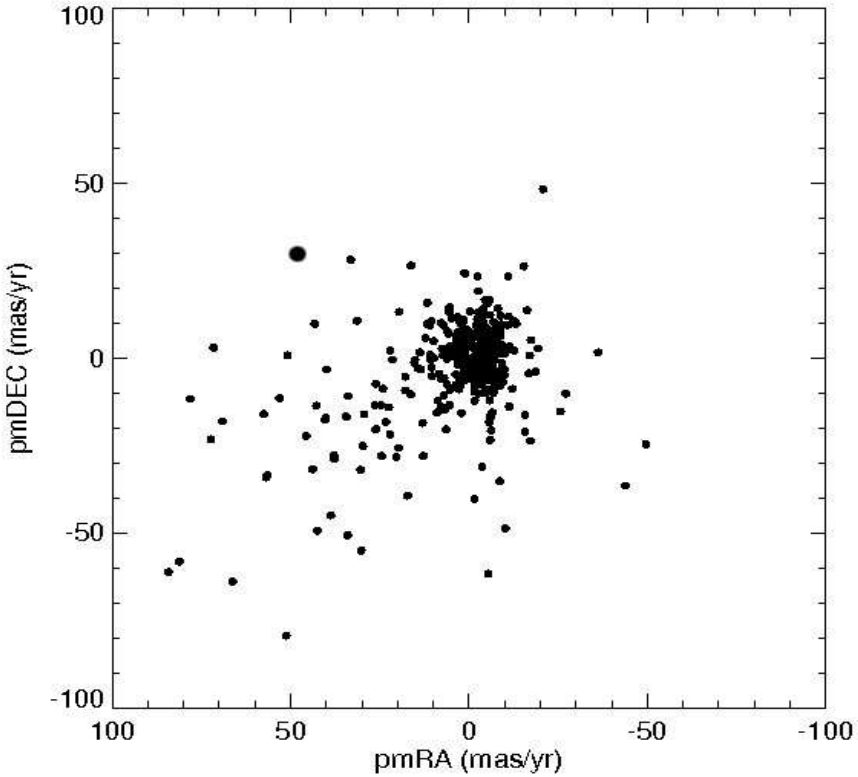
212,396 sources in 6.1 deg^2
963 photometric candidates

CONTROL FIELDS

99,052 sources in 2.9 deg^2
389 photometric candidates

APer: Selection of candidates





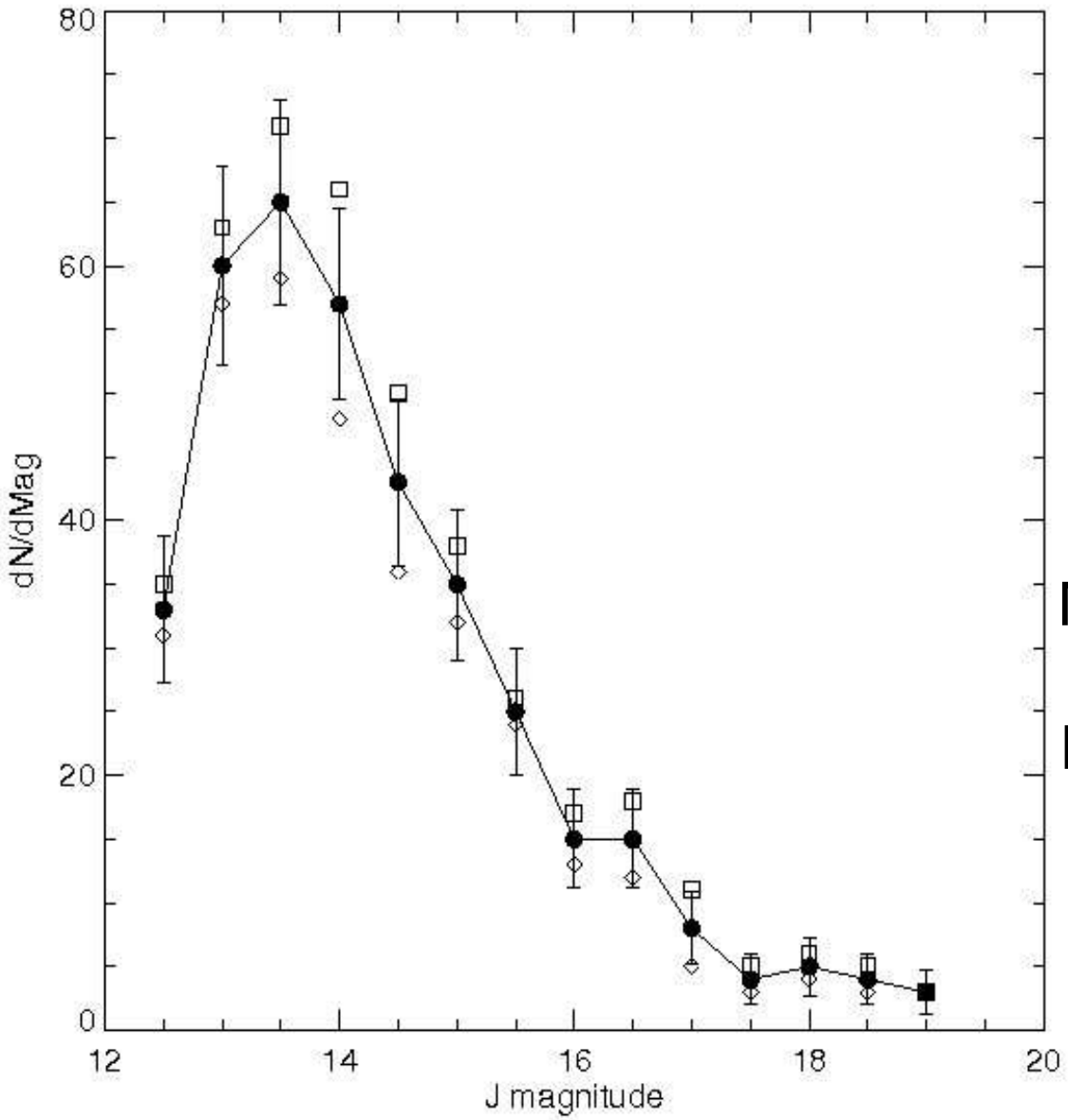
A) Cluster centre

- 963 bright photometric candidates
- 192 bright proper motion members
- 60 (25) faint *ZJ* candidates
- 5 faint *YJ* candidates
- 4 faint *JK* candidates

B) Control fields

- 389 photometric candidates
- 29 bright proper motion members
- 35 (3) faint *ZJ* candidates
- 4 faint *YJ* candidates
- 10 faint *JK* candidates

APer: Luminosity function



● Cluster centre

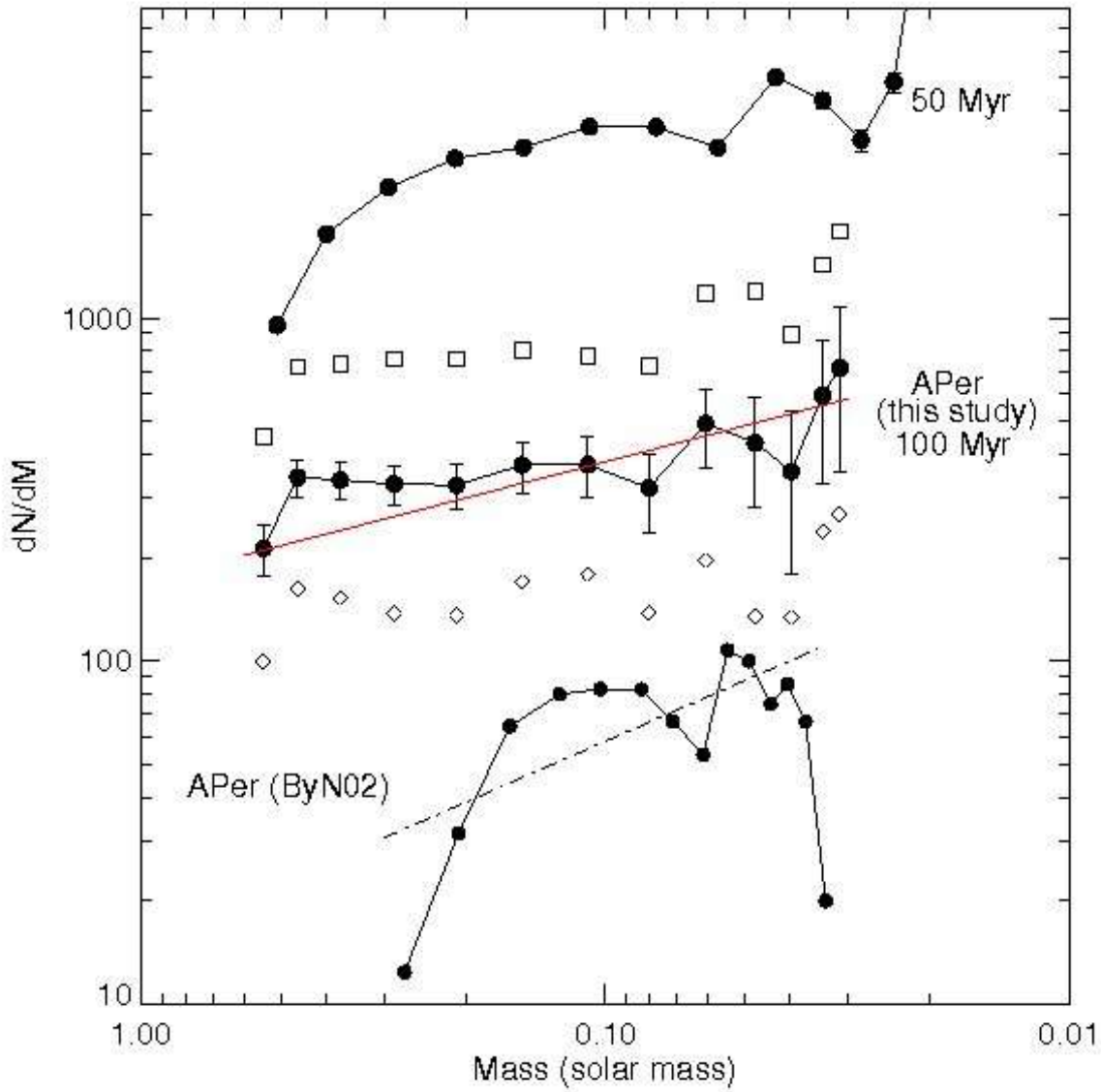
□ Centre + Control fields

◊ Centre – Control fields

M7/M8 gap @ J=16 mag

M/L transition @ J=17.5 mag ?

APer: Mass function



- ● Cluster centre
- □ Centre + Control fields
- ◊ Centre – Control fields

M7/M8 gap @ M~0.08 Msun

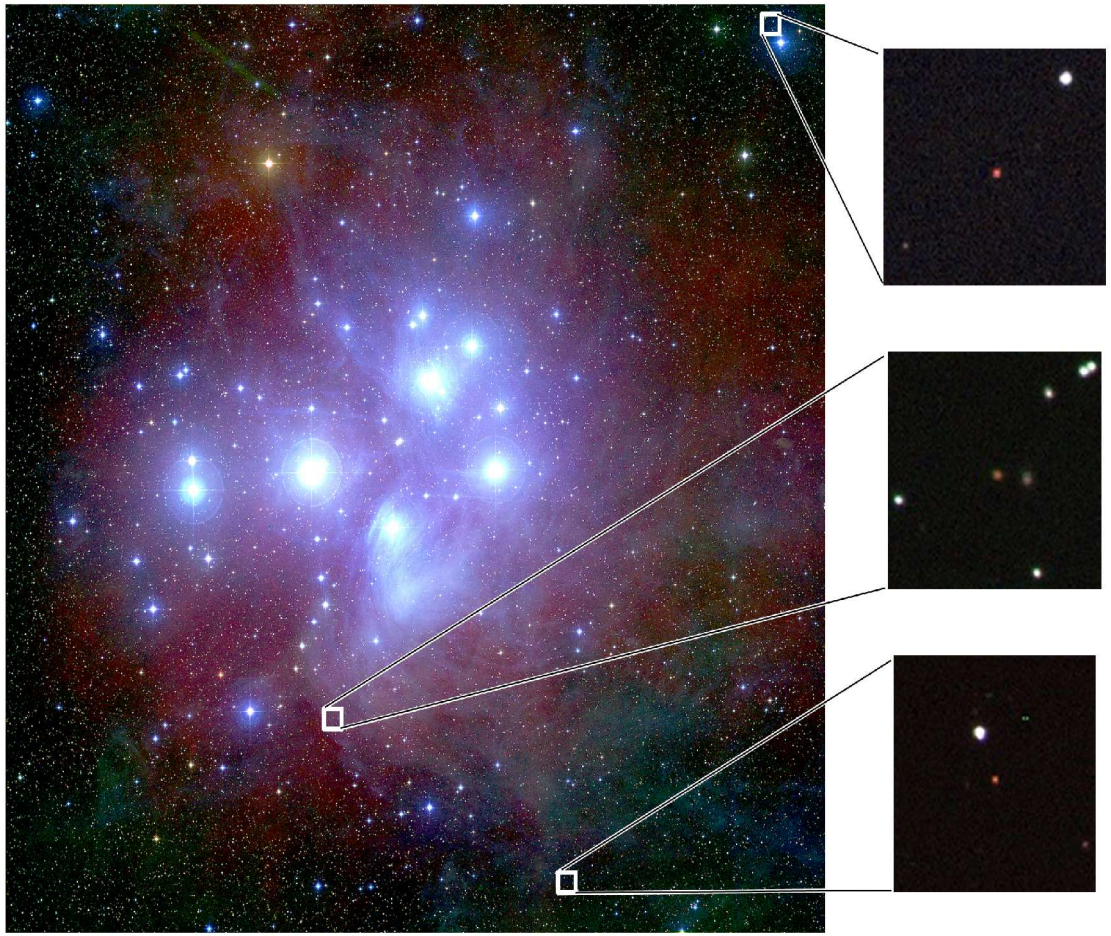
M/L transition @ M~0.04 Msun

=> alpha = 0.35+/-0.20 in the 0.3-0.03 Msun mass range

The Pleiades

Lodieu, Dobbie, Hodgkin, Hambly, Jameson, Moraux, Bouvier

Pleiades: overview



Credit: UKIDSS and Palomar Observatory Sky Survey Schmidt plates

Brown Dwarf Candidates in the Pleiades Cluster (UKIDSS)

ESO Press Photo 26b/06 (21 July 2006)

- ✔ d = 130 pc
- ✔ Age = 125 Myr
- ✔ E(B-V) = 0.03
- ✔ PM = (+19.7,-45.5) mas/yr

Teide+Calar *(Rebolo, Martin, Zapatero Osorio)*

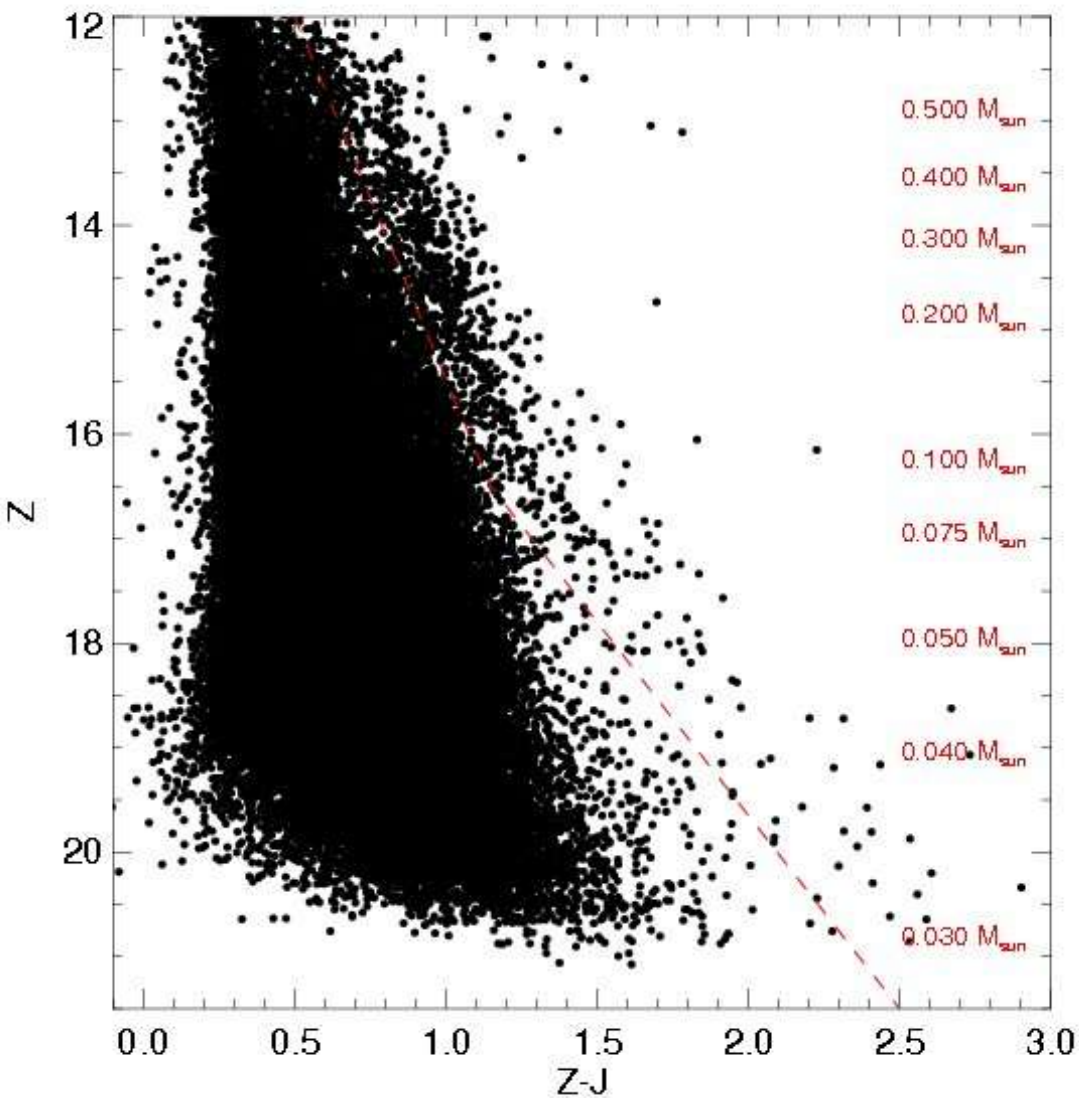
SuperCOSMOS *(Deacon & Hambly 2004)*

CFHT *(Bouvier, Moraux)*

INT *(Dobbie, Pinfield, Jameson)*

and many other surveys...

Pleiades: selection of candidates (I)

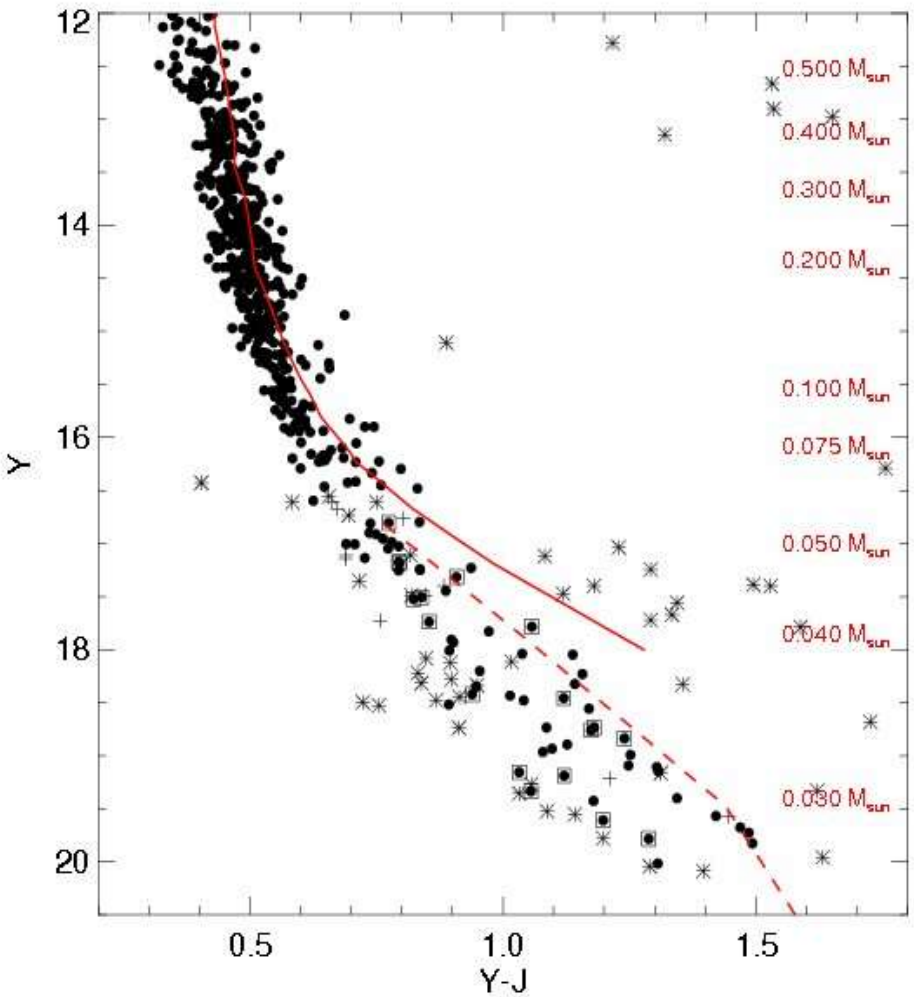


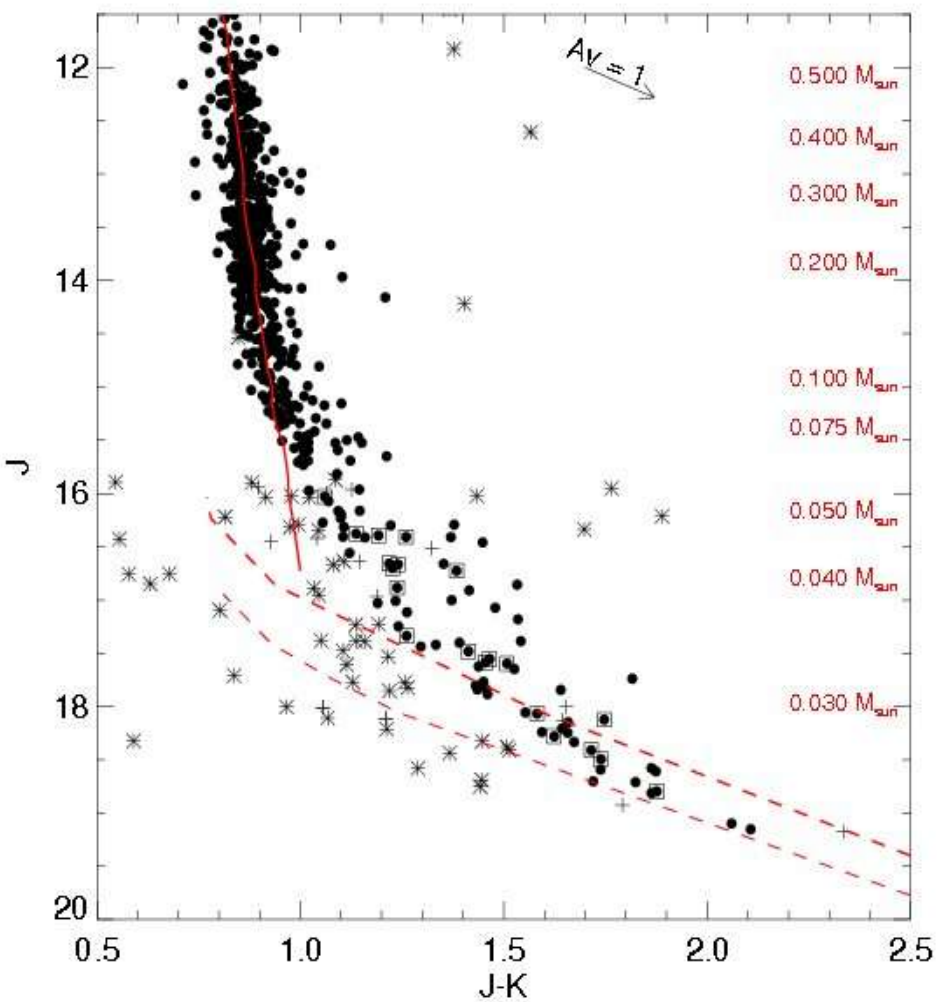
- 97158 sources in 12 sq. deg.
- 0.5-0.03 Msun mass range

✔ 1095 bright photometric cand
- ➔ 518 PM members
- ➔ 31 PM NM
- ➔ 542 photometric NM

✔ 105 faint *ZJ* cand
- ➔ 19 PM members
- ➔ 35 photometric members
- ➔ 8 PM NM
- ➔ 43 photometric NM

Pleiades: selection of candidates (II)

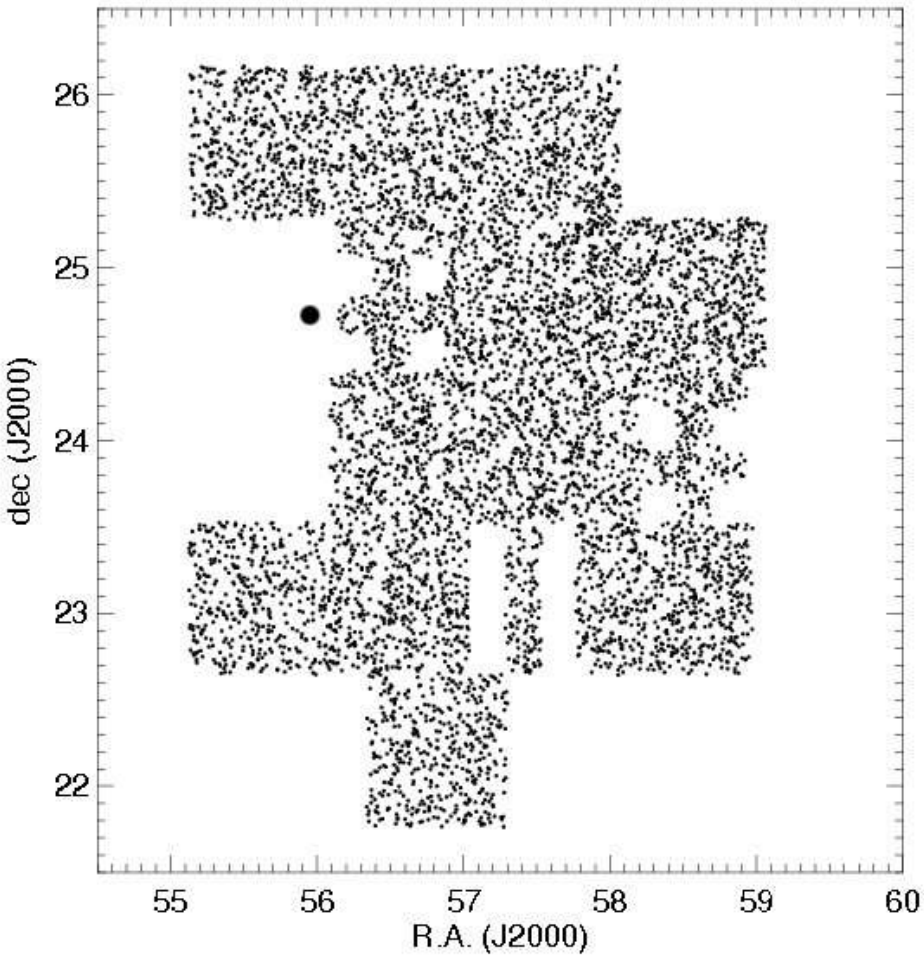


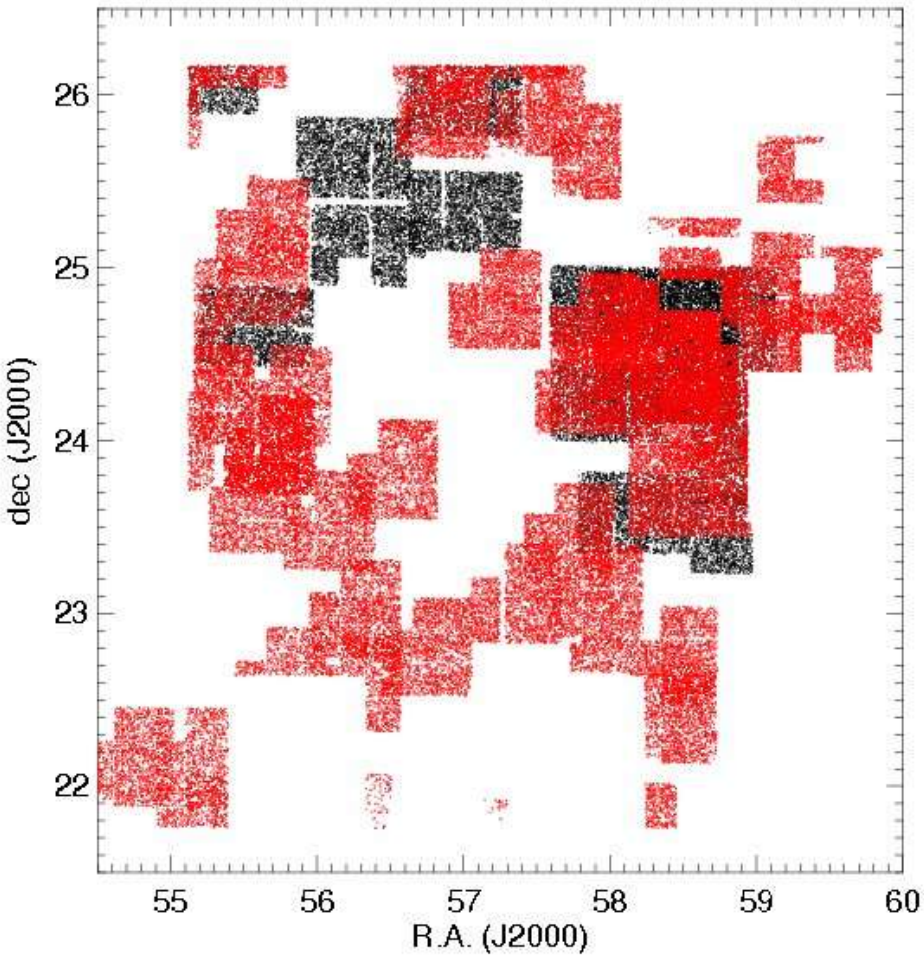


✔ 22 faint *YJ* cand
- ➔ 5 PM members
- ➔ 8 photometric members
- ➔ 2 PM NM
- ➔ 6 photometric NM

✔ 25 faint *JK* cand
- ➔ 1 PM members
- ➔ 7 photometric members
- ➔ 6 PM NM
- ➔ 11 photometric NM

Pleiades: coverage



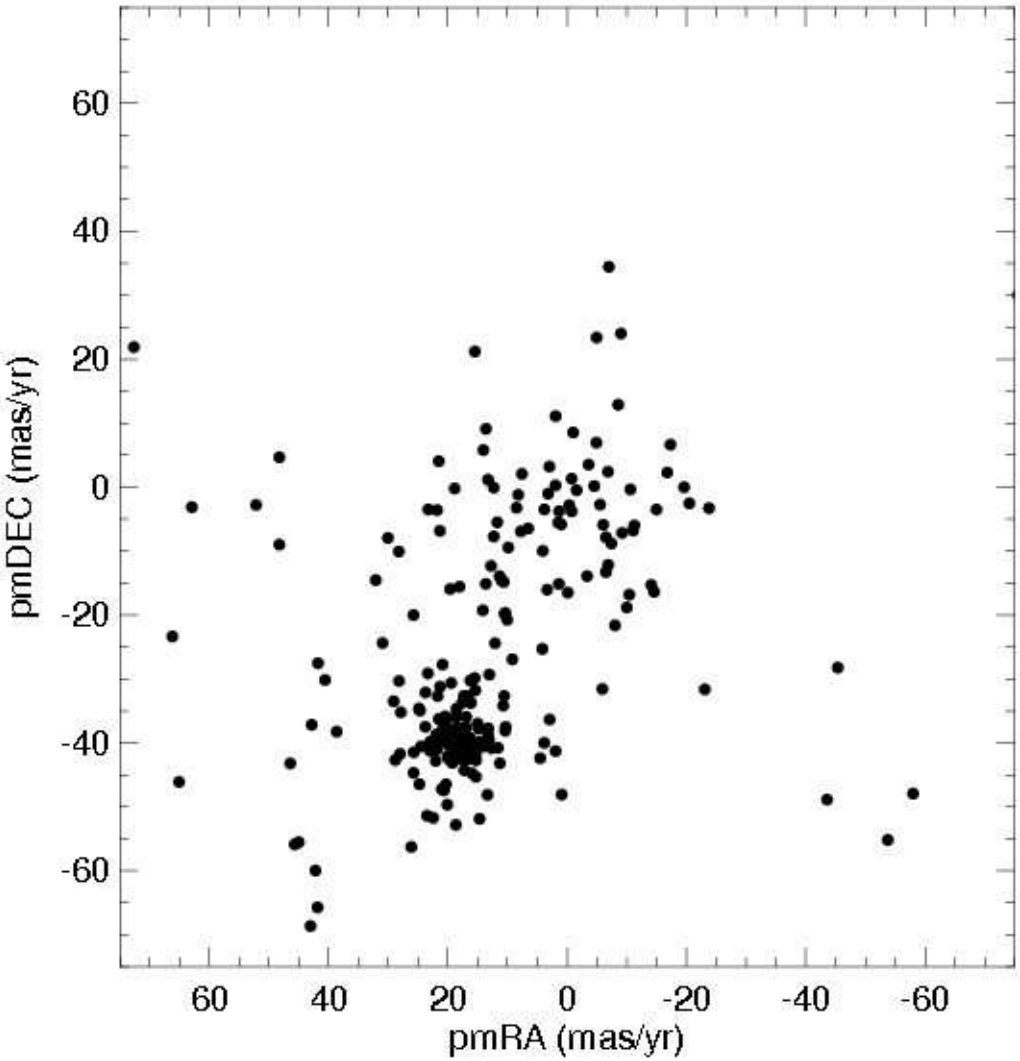


GCS coverage: 12 sq. deg.

CFHT + INT coverage

=> Large number of stellar and substellar with accurate optical-to-infrared proper motions

Pleiades: proper motion

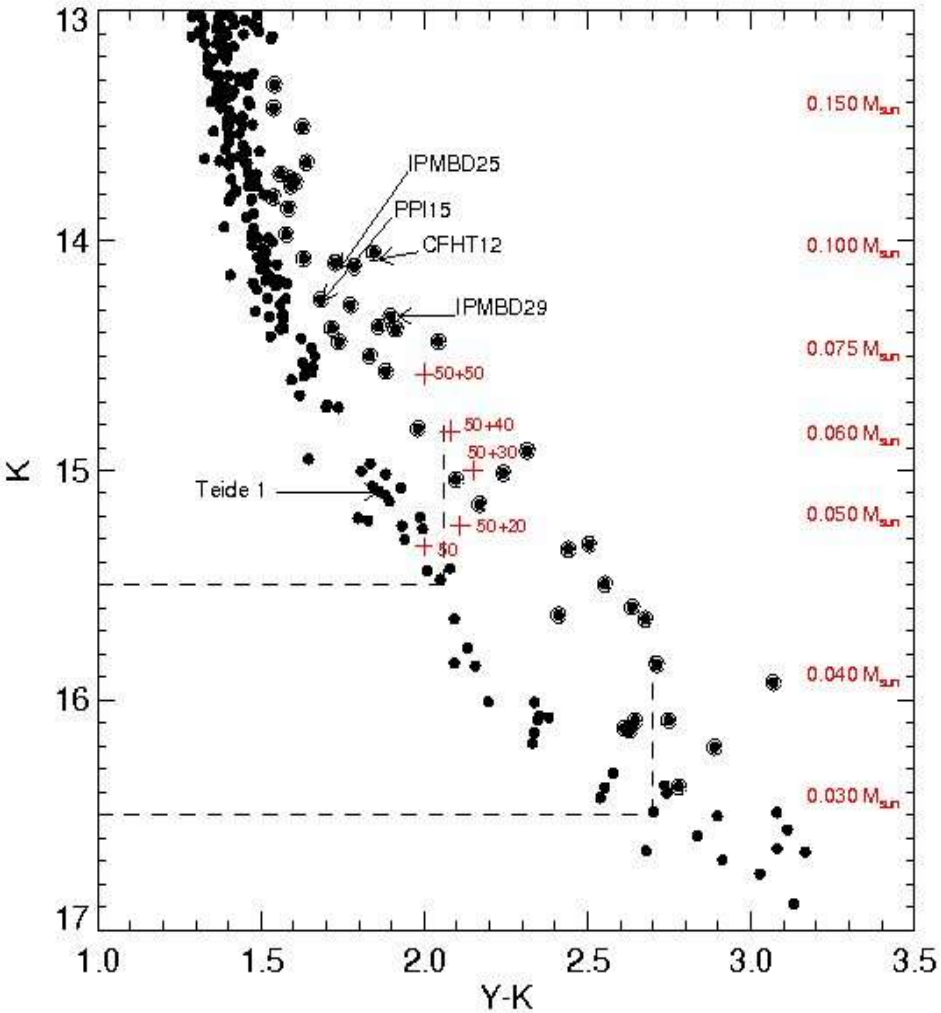


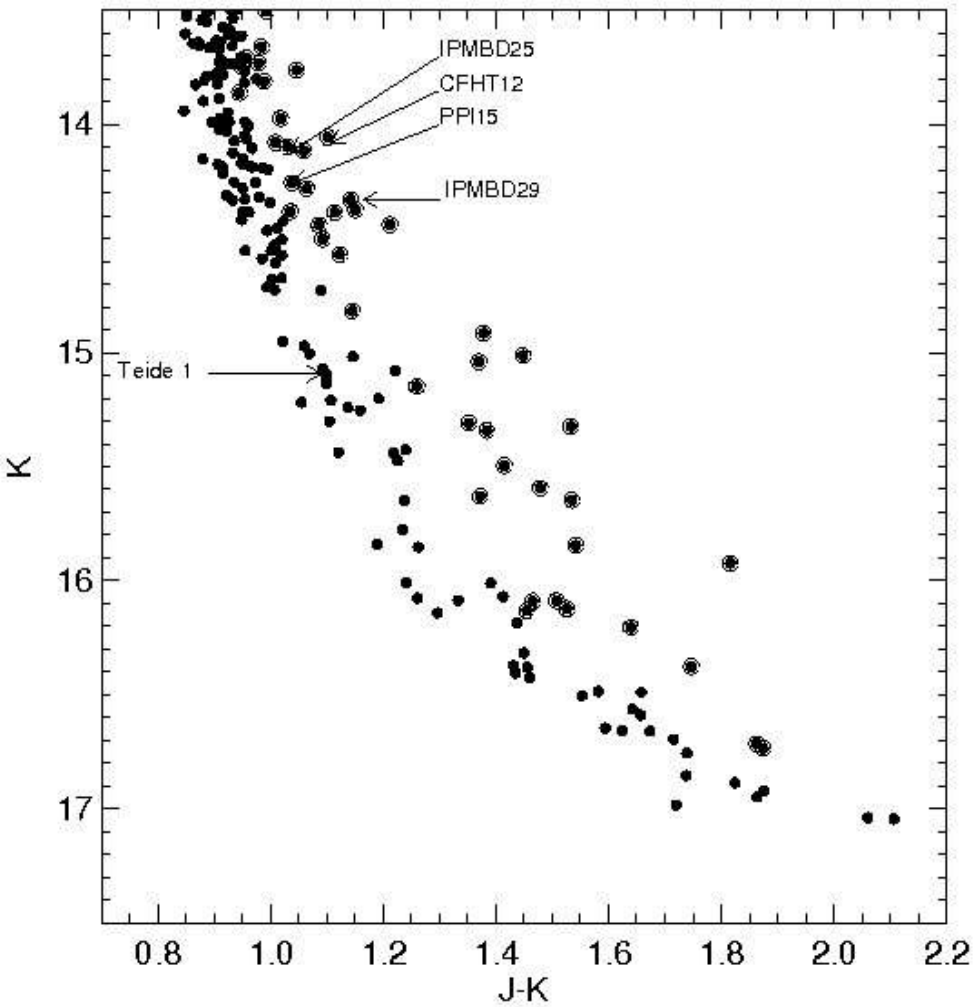
239 out of 1200 photometric candidates are common to the optical (INT+CFHT) and GCS

Pleiades cluster well defined

Proper motions available from the 2MASS/GCS cross-correlation down to *J* = 15.8 mag (60 Mjup)

Pleiades: binary fraction



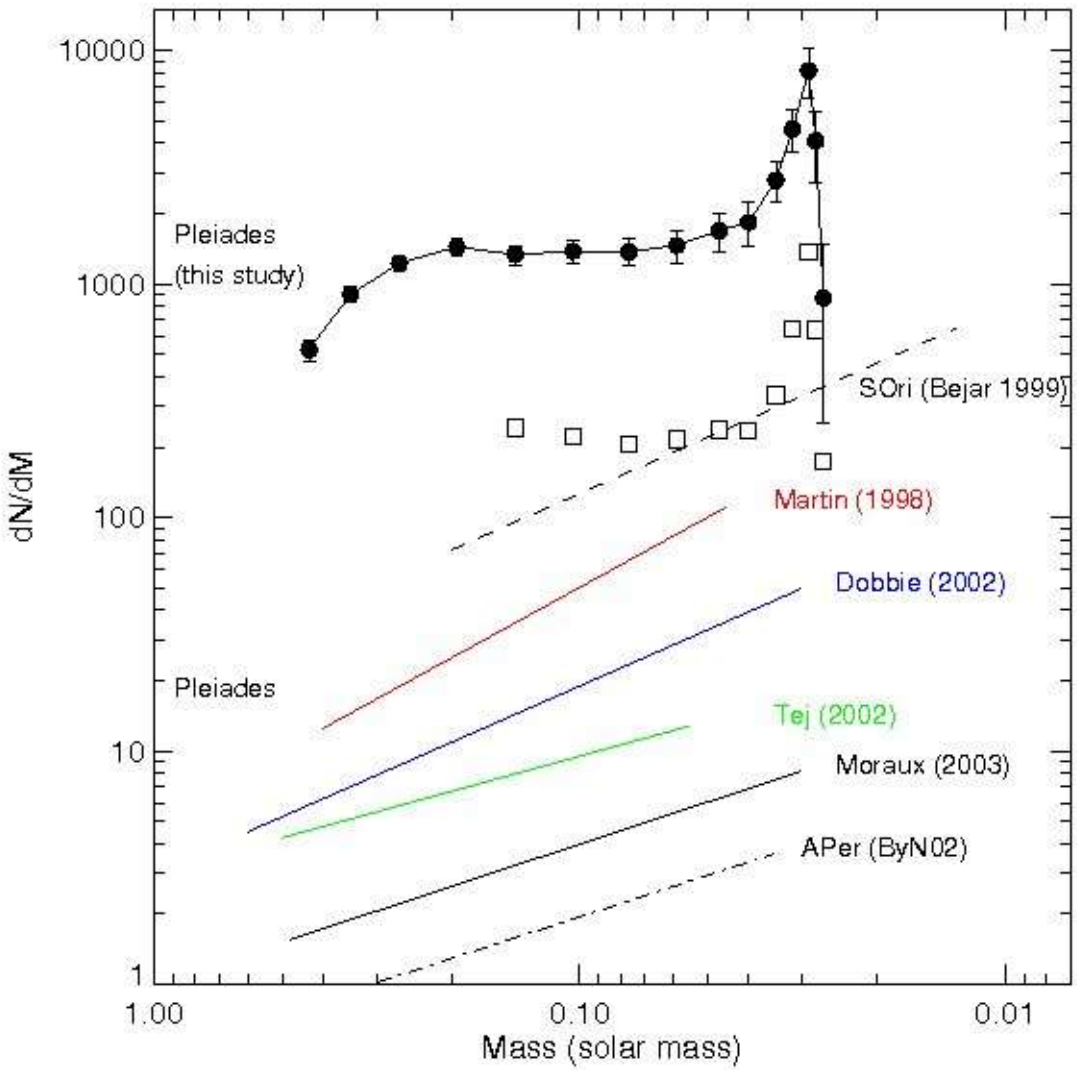


Selection of photometric multiple systems from the (*Y-K*, *Y*) CMD

BF = $N_B/(N_S+N_B)$ = 40/(65+40) = 38%

- 26 single stars with PM
- 24 binary systems with PM

Pleiades: IMF



- ✔ d = 130 pc
- ✔ Age = 125 Myr
- ✔ No reddening correction

- Total number of candidates is 534
- About 100 BDs
- J = 12.0-20.0 mag
- Mass range = 0.52-0.025 Msun
- Lyon group models
- 1 mag bin by steps of 0.5 mag
- Correction for binarity

IMF: all cand (filled circles)
single stars only (squares)

Future plans and outlook

1) The Upper Sco cluster

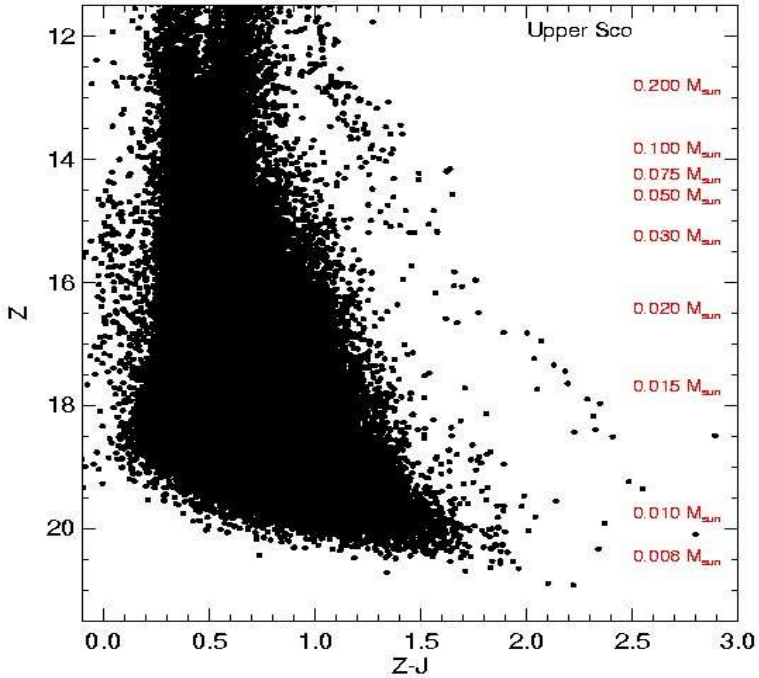
- The full Upper Sco association will be covered by the GCS
- 2nd epoch in *K* to get proper motion for all candidates
- Spectroscopic follow-up with AAT, ESO 3.6-m, and VLT
- Spectroscopic follow-up with Gemini/GNIRS
- Deeper optical *Z* data to find lower-mass brown dwarfs
- VLT NACO LGS for planetary-mass binaries
- Study accretion and variability timescale *(Jayawardhana, Mohanty et al.)*

2) Pleiades and Alpha Per

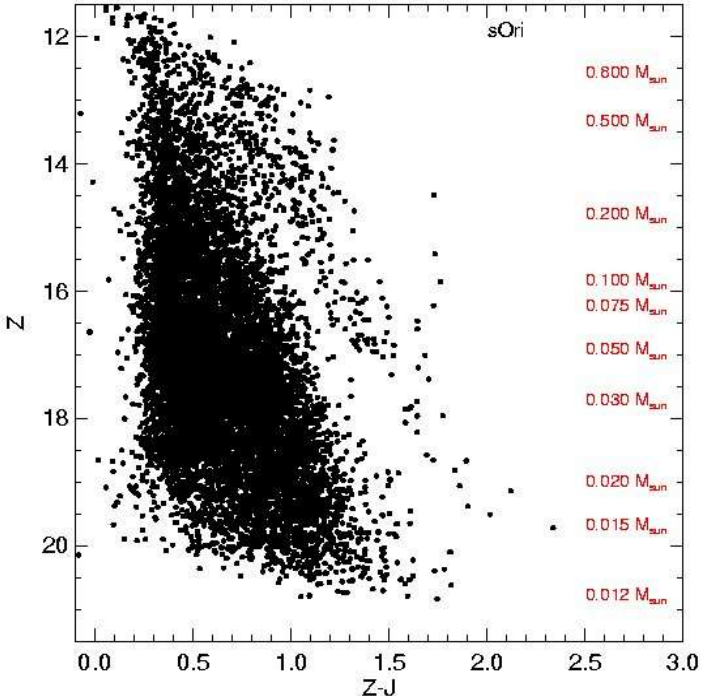
- Full coverage after 7 years by UKIDSS GCS
- Spectroscopic follow-up with Gemini/GNIRS
- Deeper optical *Z* data to find lower-mass brown dwarfs
- VLT NACO LGS for brown dwarf binaries

The power of the GCS

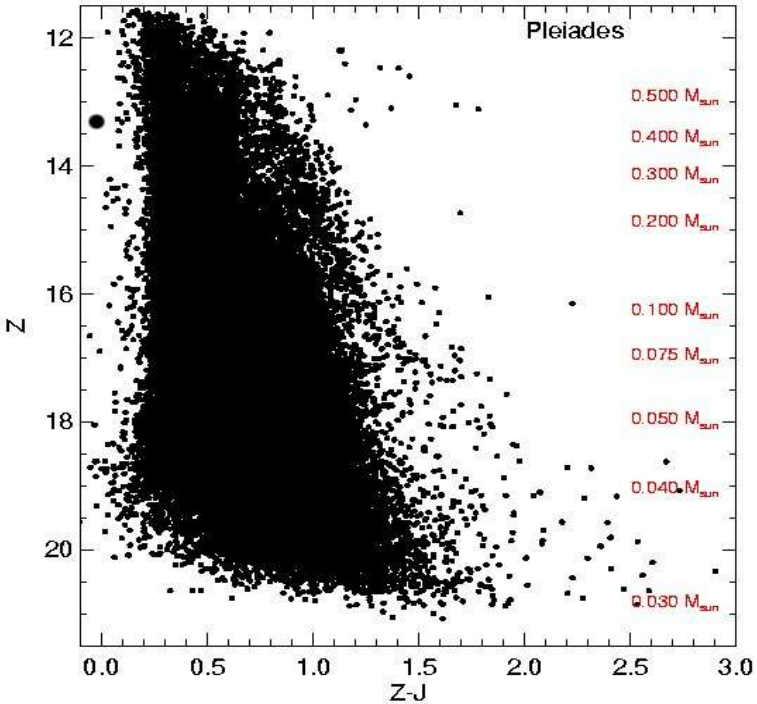
USco



sOri



Pleiades



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