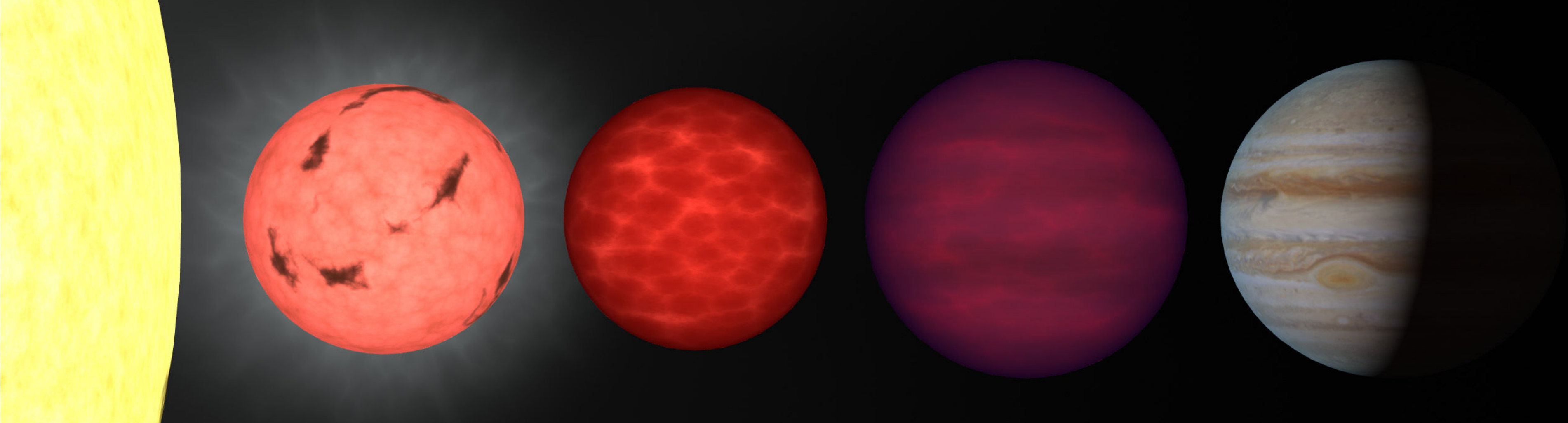
Science & Technology Facilities Council

Cool Stars and Brown Dwarfs



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STFC Astronomy Summer School
University of Hertfordshire

Thursday 4th September 2008

University of Hertfordshire

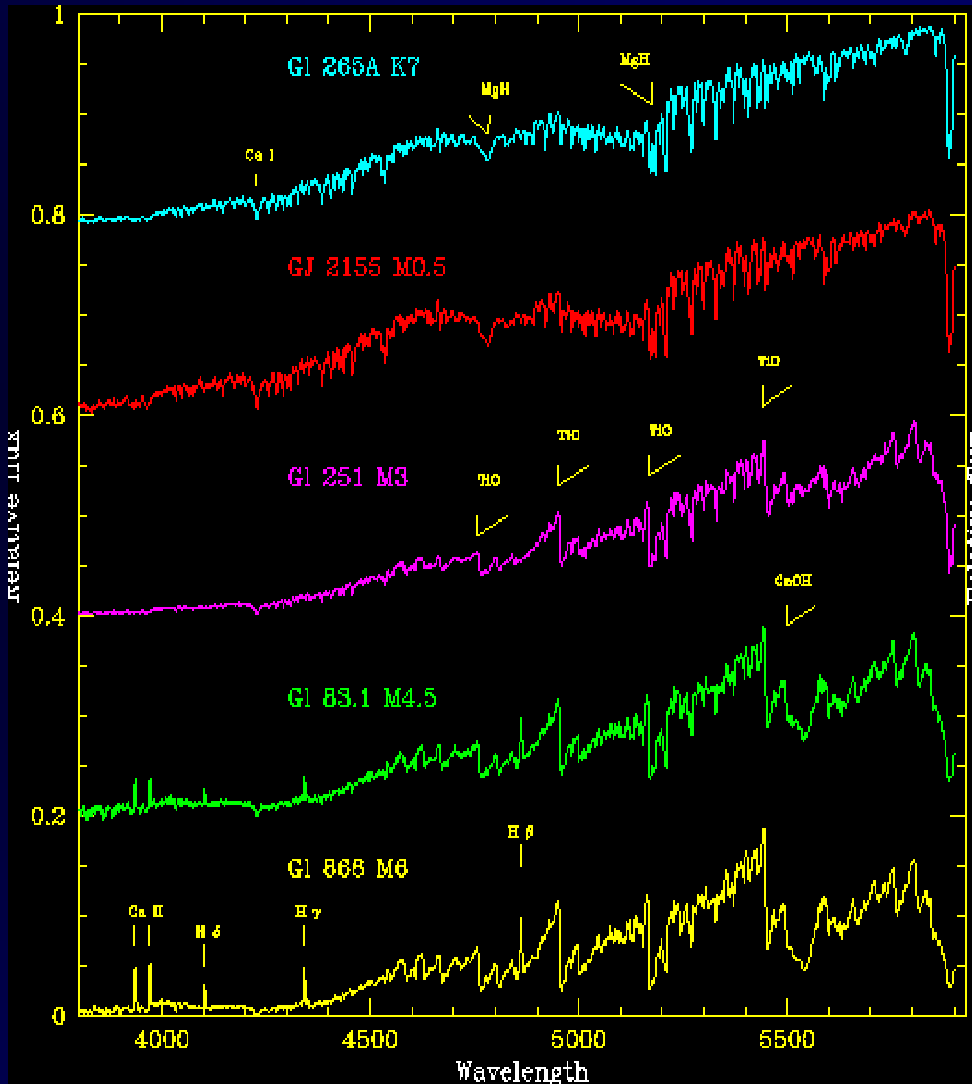
Image credit: Dr. Robert Hurt, IPAC

Some properties of very low-mass stars and brown dwarfs

- We'll consider the 3 latest spectral classes in use:
  - M dwarfs
    - T_{eff} 3500K - 2000K
    - later than M7 – ultracool dwarfs
    - some substellar, some stellar
    - early Ms are substellar at very young ages
  - L dwarfs
    - T_{eff} 2000K – ~1400K
    - early Ls mix of stellar/substellar
  - T dwarfs
    - T_{eff} ~1400K - ?
    - all substellar
    - yet to reach minimum T_{eff} for T dwarf sequence

M dwarfs

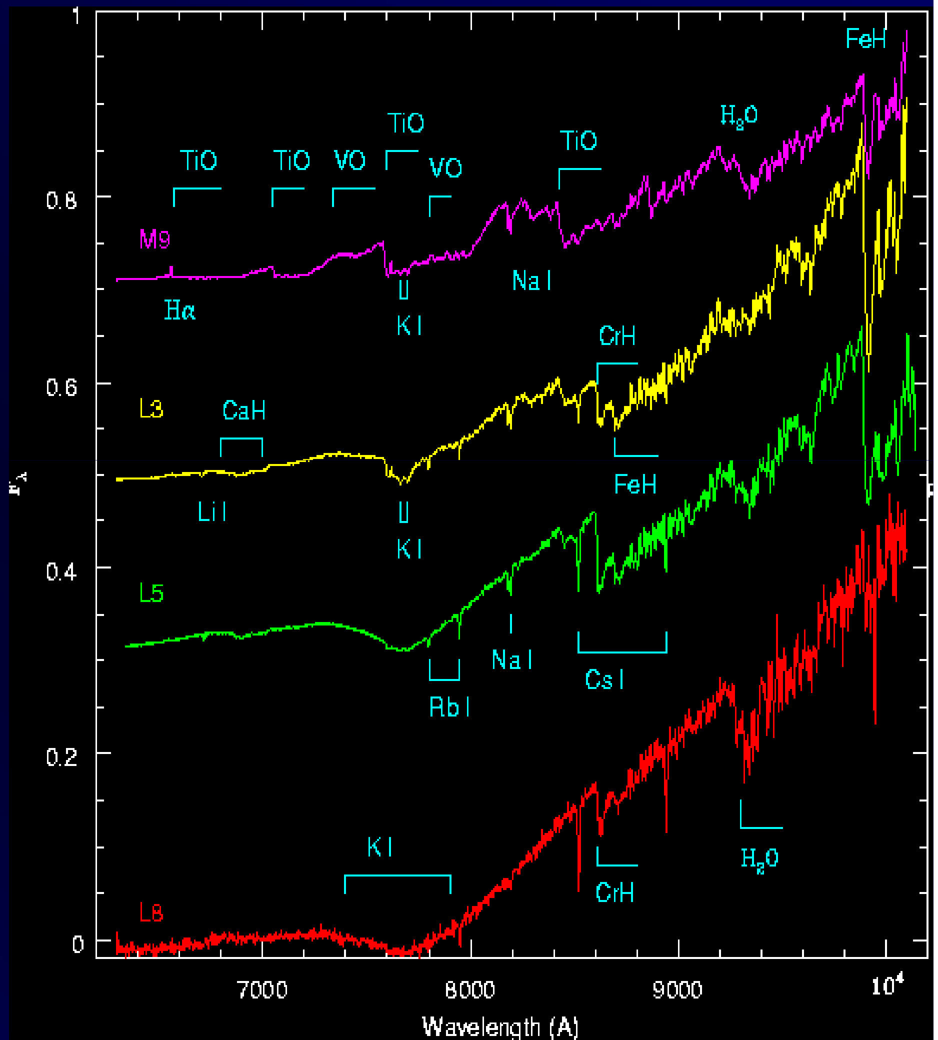
- Relatively red colours, getting redder with type:
  - $i' - z' = 0.4 - 1.8$
  - $z' - J = 1.2 - 2.3$
  - $J - H = 0.6 - 0.8$
  - $J - K = 0.8 - 1.3$
- Spectral sequence defined by development of molecular bands: TiO, VO, CaH and slope of red spectrum
- Convective atmospheres leads to high levels of magnetic activity, e.g flares, star spots



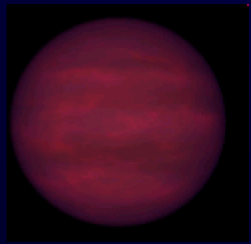
Kirkpatrick et al 1999, 2000

L dwarfs

- At lower T_{eff} we see molecular bands of the M sequence weakening
- TiO, VO condense and dust forms
- L dwarfs have very red, dusty, atmospheres:
  - *i′-z′* > 1.80
  - *z′- J* > 2.50
  - *J- H* > 0.80
  - *J – K* > 1.3
- Many found using 2MASS, DENIS, SDSS

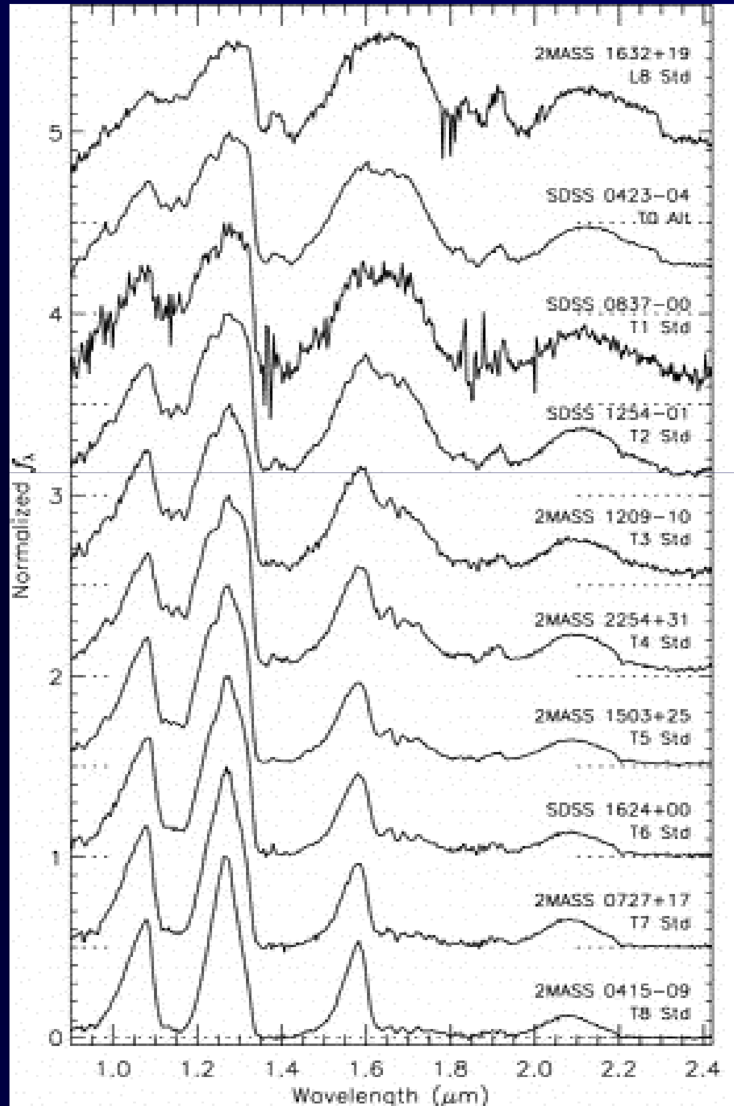


Kirkpatrick et al 1999, 2000



T dwarfs

- dust now absent from photosphere
- near-infrared spectra dominated by methane and water absorption
- very red optical and optical-near IR colours:
  - $i' - z' > 2.2$
  - $z' - J > 3.0$
- blue near-IR colours
  - $J - H < 0.5$
  - $J - H < 0$ for late Ts



Burgasser et al 2006

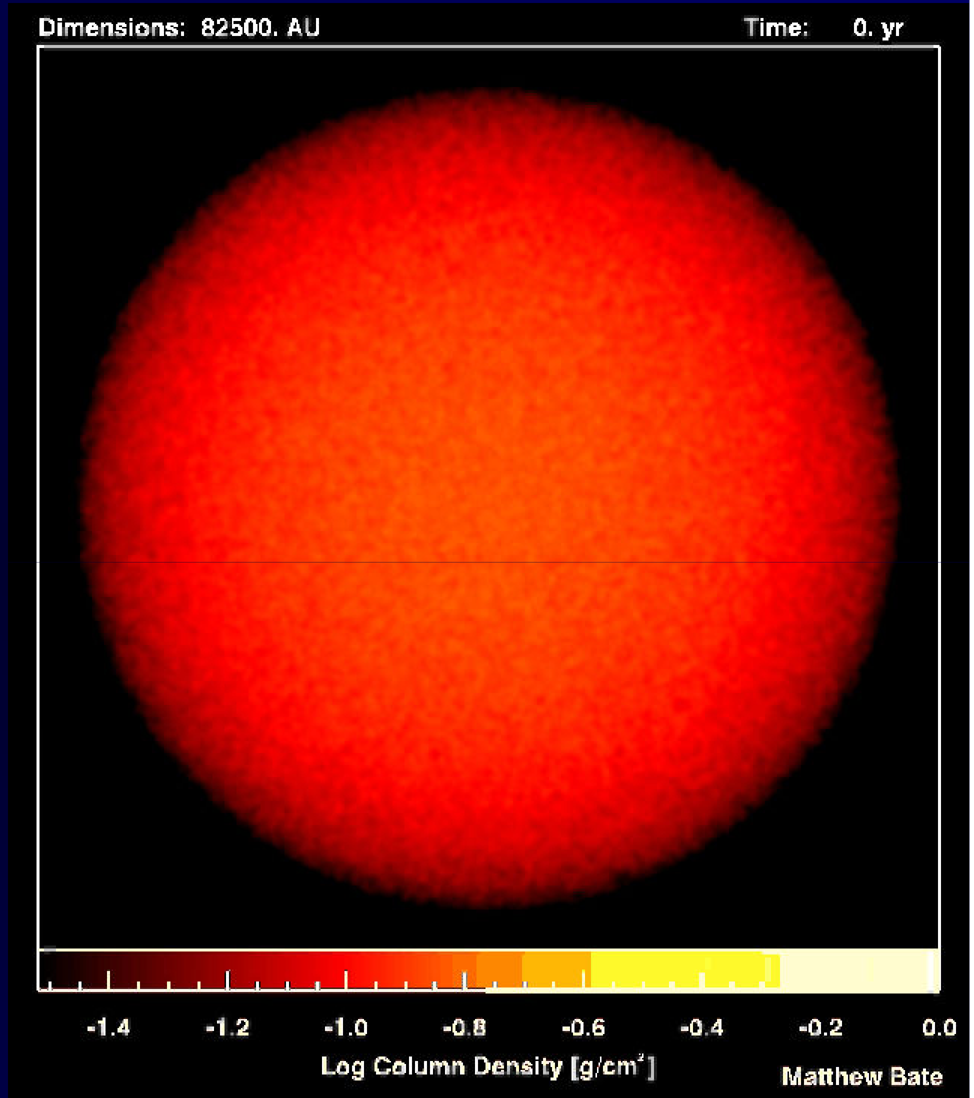
The three most exciting problems in astronomy!

What is the form of the low-mass initial mass function?

What physical processes govern the LT transition?

What happens when brown dwarfs get very cold?

- Studies of low-mass stars and brown dwarfs are fundamental to understanding star formation
- Low mass stars are the most numerous product of star formation
- Low-mass star formation has been accessible for study for a relatively long time
- IMF is the fundamental constraint for theories of star formation – and most can reproduce it



The Low-Mass IMF

- variation in the low-mass IMF between different regions would be a powerful diagnostic
- appears to be universal for M > Msun regardless of environment (!)

EASIER

SAID

THAN

DONE

- most models of SF are capable of reproducing the IMF, within the uncertainties
- low-mass end may prove more diagnostically useful
- need to minimise uncertainties

Let's have a look at some examples...

"Measuring" the IMF

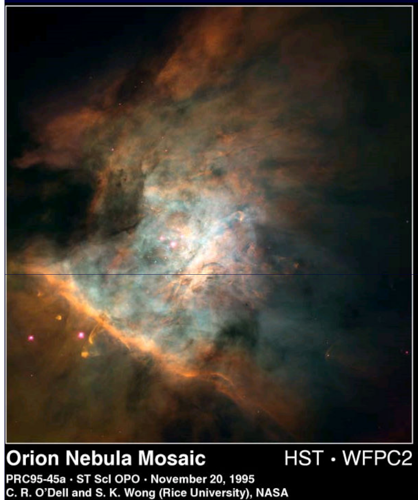
1) In the field:
   - construct luminosity function for spectral type regime of interest
   - apply mass-luminosity relationship to get mass function
   - correct for stellar evolution to get IMF

But substellar M-L relationship evolves with time, so need SF history – we'll come back to this…

2) In clusters:
   - select members and confirm spectral types
   - use spectral types and magnitudes to place on HR diagram
   - PMS evolutionary models give masses and ages

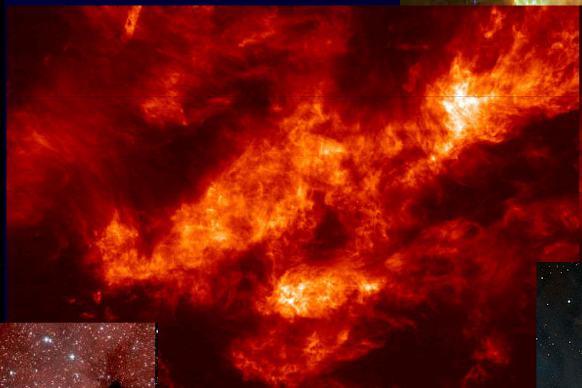
The Usual Suspects

ONC –
Lucas et al,
Muench et al,
Luhman et al,

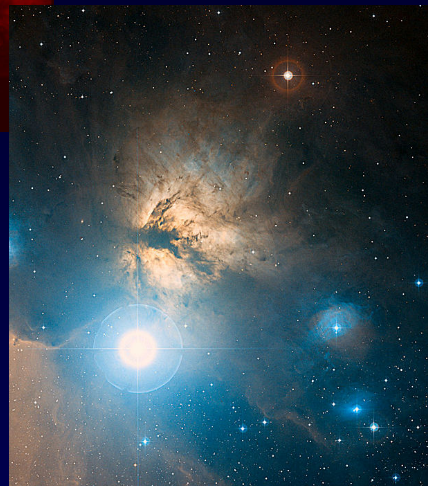


σ Ori – e.g Bejar et al 2001;
Caballero et al 2007;

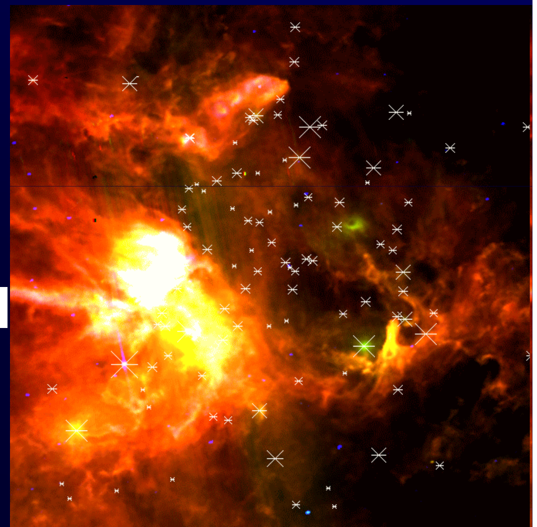
IC348 –
Luhman et al



Taurus –
Luhman et al



NGC2024



Upper Scorpius –
Preibisch et al
Lodieu et al

NGC2264 –
Sung et al

Pros and cons of Young clusters

Pros:

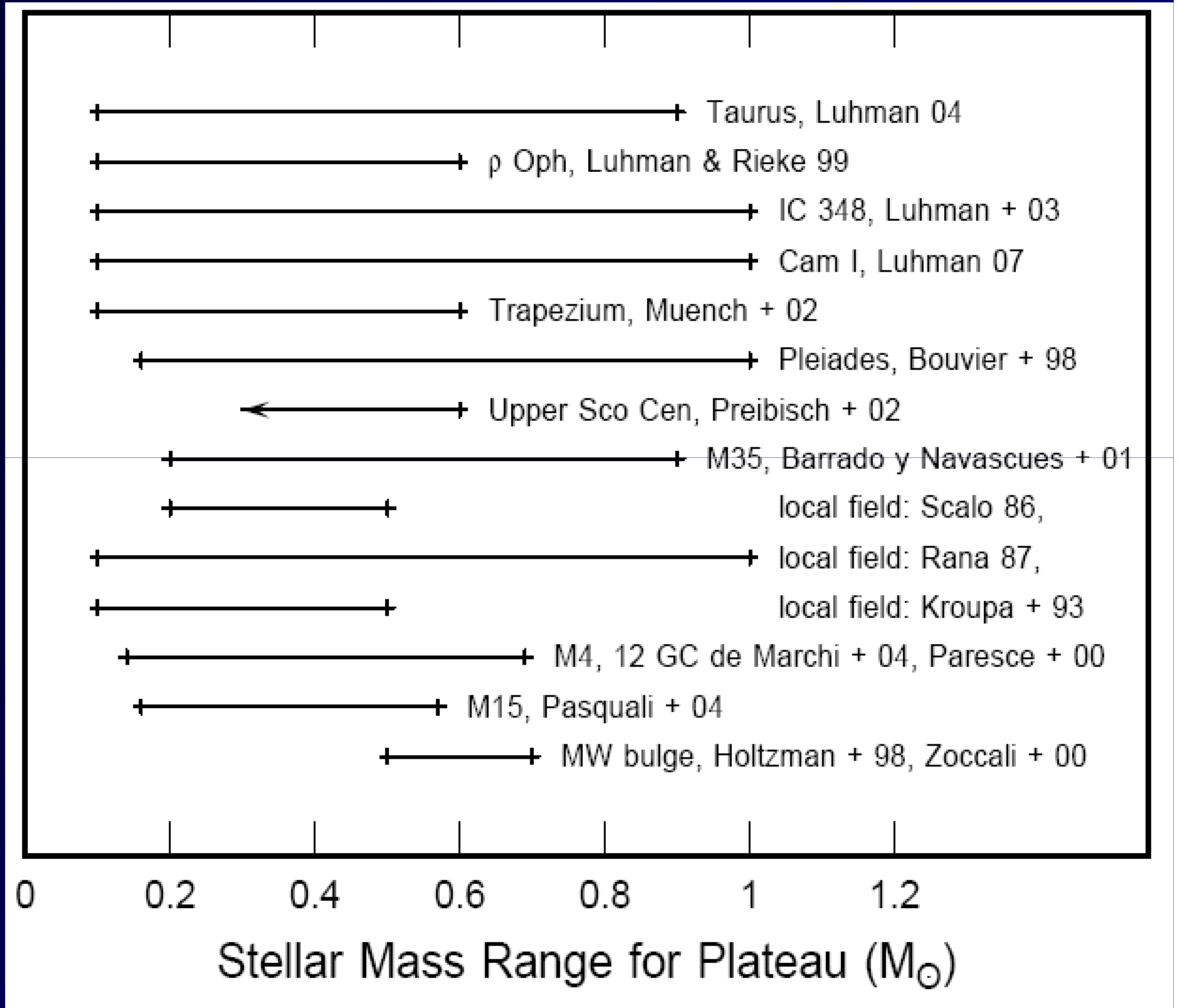
- low-mass stars and substellar objects are brighter when young
- for age < 10 Myrs no need to account for evaporation
- common distances
- similar ages

Caution:

- must be careful about membership
- age spreads?
- large + variable extinction

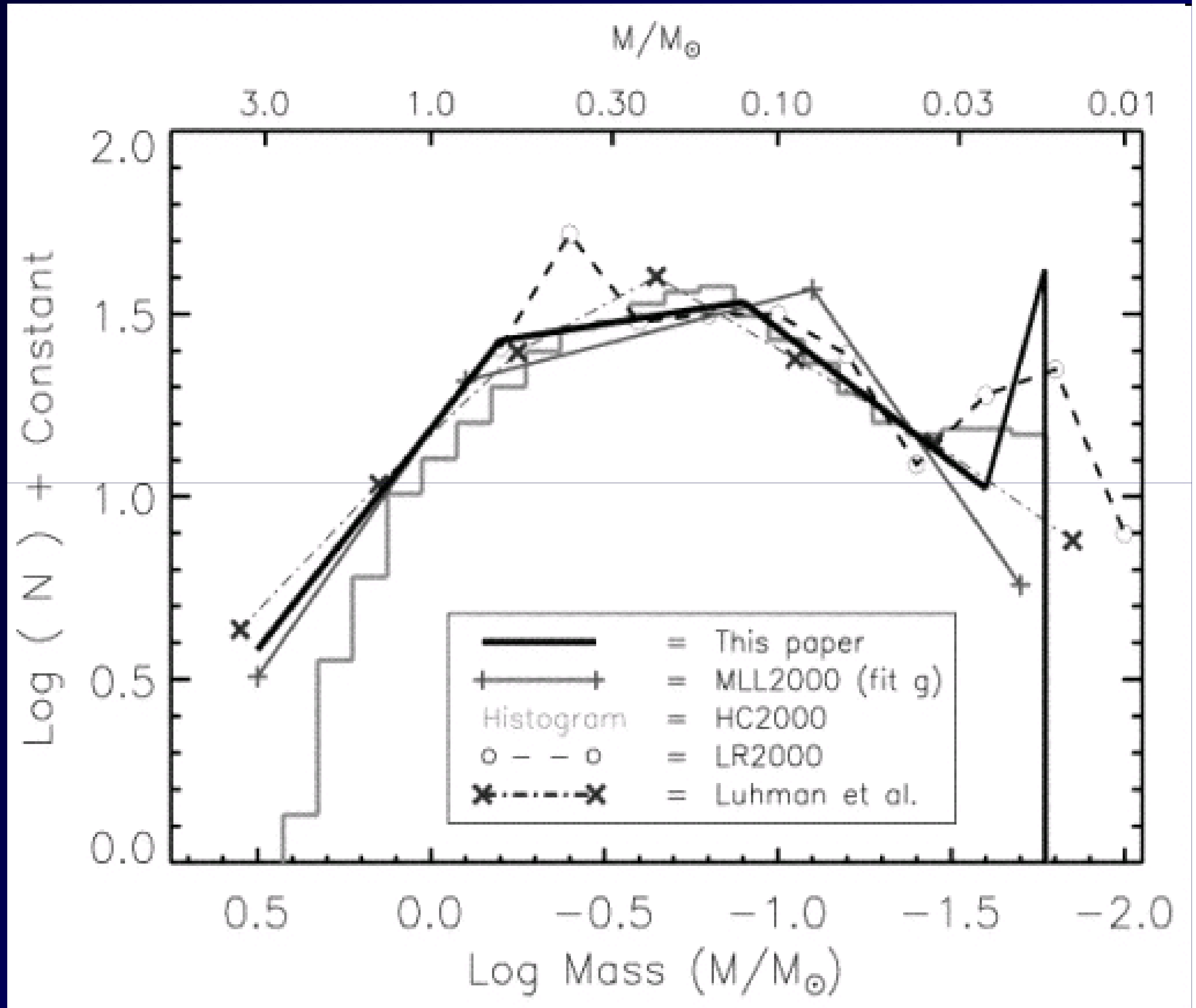
Variations in the IMF

- variations are seen in the characteristic mass
- only marginally significant
- different studies use different models to get mass from observable
- also different samples
- leads to different answers for the same regions



Elmegreen 2008, 4th Spitzer Science Center Conference

- IMFs indistinguishable $M > \sim 1\ M_{solar}$
- characteristic mass varies a little
- lowest masses show greatest differences
  - intrinsic difficulties in measuring the lowest masses
  - small numbers

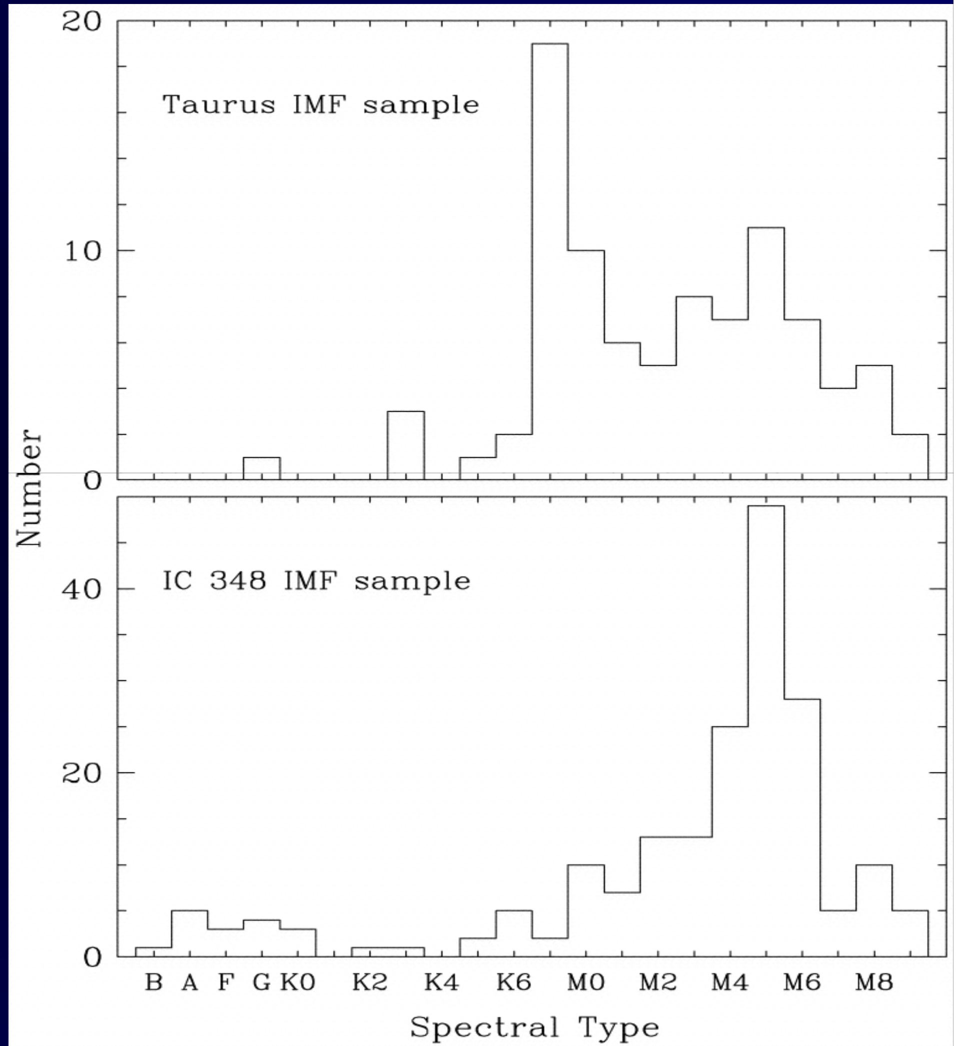


Muench et al 2002 , ApJ, 573, 366

Luhman et al

- Luhman et al have identified possible variations in the IMF
- result is robust wrt choice of models

- IMF turns over at 0.1-0.2 M_{solar} in ONC and IC348
- turnover at 0.8 M_{solar} in Taurus
- BUT: x2 age difference?



Luhman et al 2003, ApJ 593, 1093

Andersen et al 2008

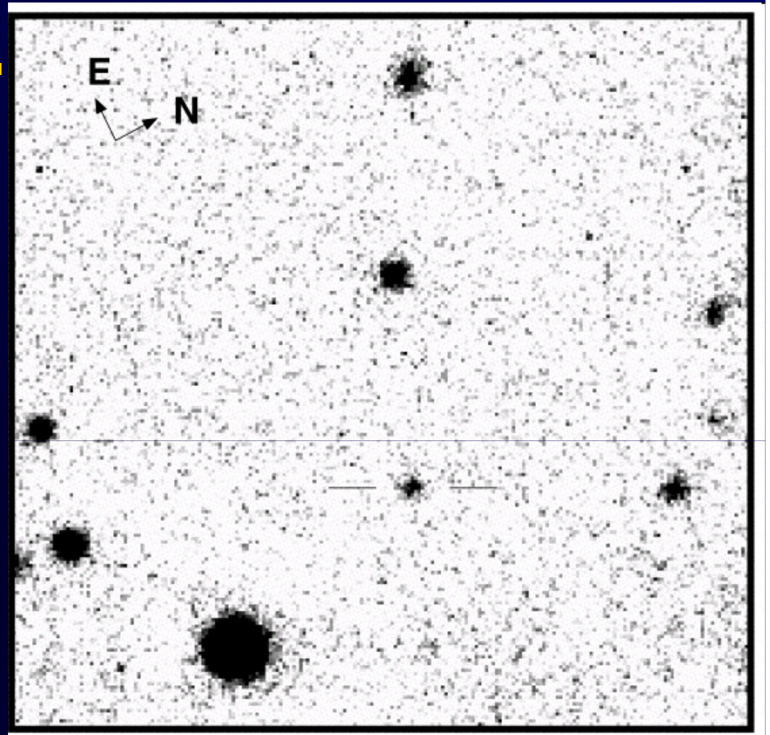
(ApJ, 683, L183)

- Metastudy of data for 7 young clusters
- Find ratio of BDs to stars for all is consistent with a single underlying IMF
- By combining the results for all 7 clusters they confirm that the IMF is falling in the substellar regime
- Later we'll see how this compares to what we're finding in the field…

What happens at even lower masses?

- Is there a low-mass cut-off?
- Does it turn over again as suggested by the Muench et al result in the ONC?
- Are there any other features that may suggest a change in formation mechanism for the lowest mass objects?

S Ori 70: Zapatero Osorio et al (2002) claimed to have identified a $3M_J$ brown dwarf in σ Ori…



Re-analysis by Burgasser et al identified problems with their data:

- saturated flat-field
- observed the wrong comparison star when estimating surface gravity
- S Ori 70 probably a foreground object

Be careful!

The latest lightweights

- Lucas et al (2006) : spectroscopically confirm 6 planetary mass members of the trapezium
- Lodieu et al (2007):
  - using UKIDSS to find brown dwarfs in Upper Scorpius down to $8M_J$, spectral type L2
- Very recent results from Bouy et al (2008) describe $5.5M_J$ member of σ Ori
- Confirms that the IMF extends well into the planetary mass regime, although its form is still uncertain at lowest masses due to small numbers

What about the field?

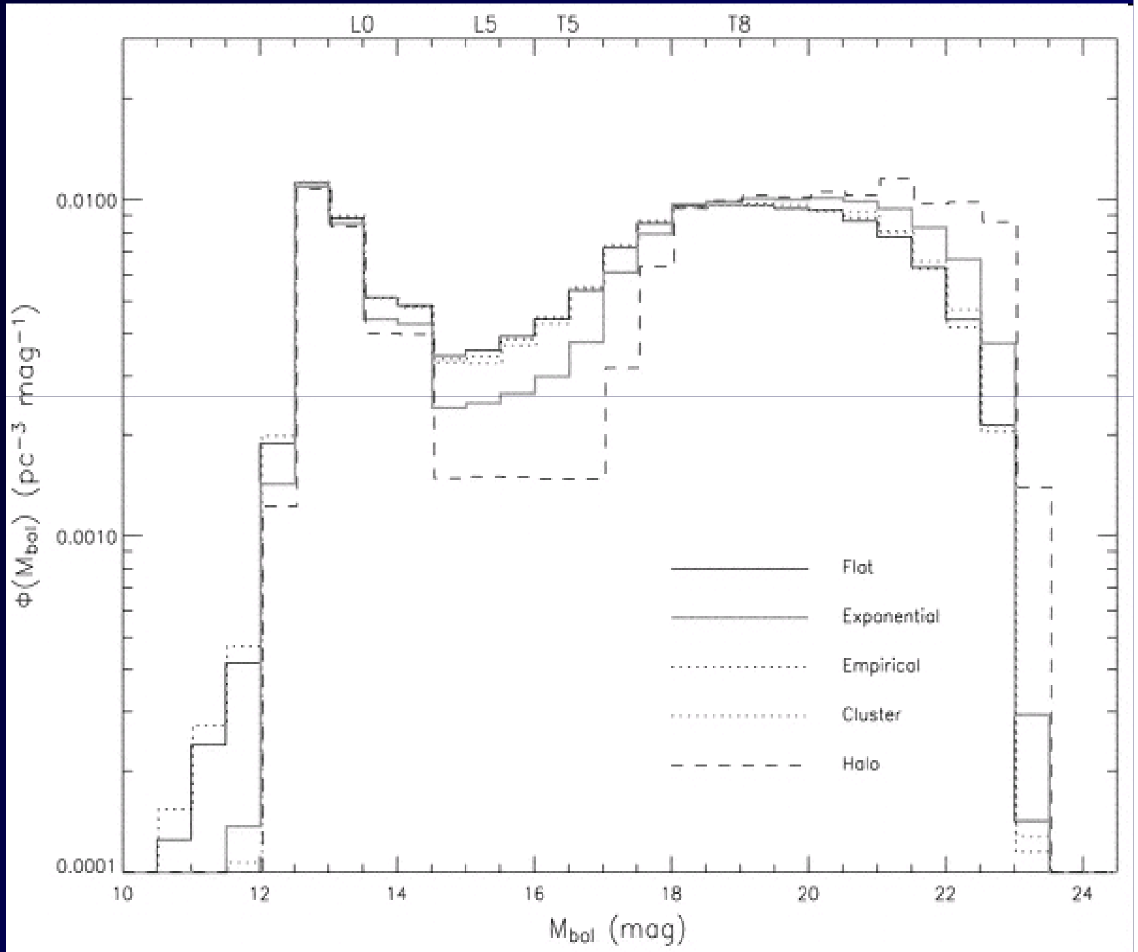
Reid et al 1999 (ApJ, 521, 613):

- used 2MASS to estimate substellar IMF in the solar neighbourhood
- found shallower mass function than Salpeter for L dwarfs (α = 1.0 - 1.5)
- seems at odds with young clusters:
  - » early L dwarfs can be both stars and BDs
  - » small number of late objects
  - » result likely dominated by plateau around peak in IMF

BDs M-L relation is age dependent, so we need to be careful…

Simulating the substellar luminosity function

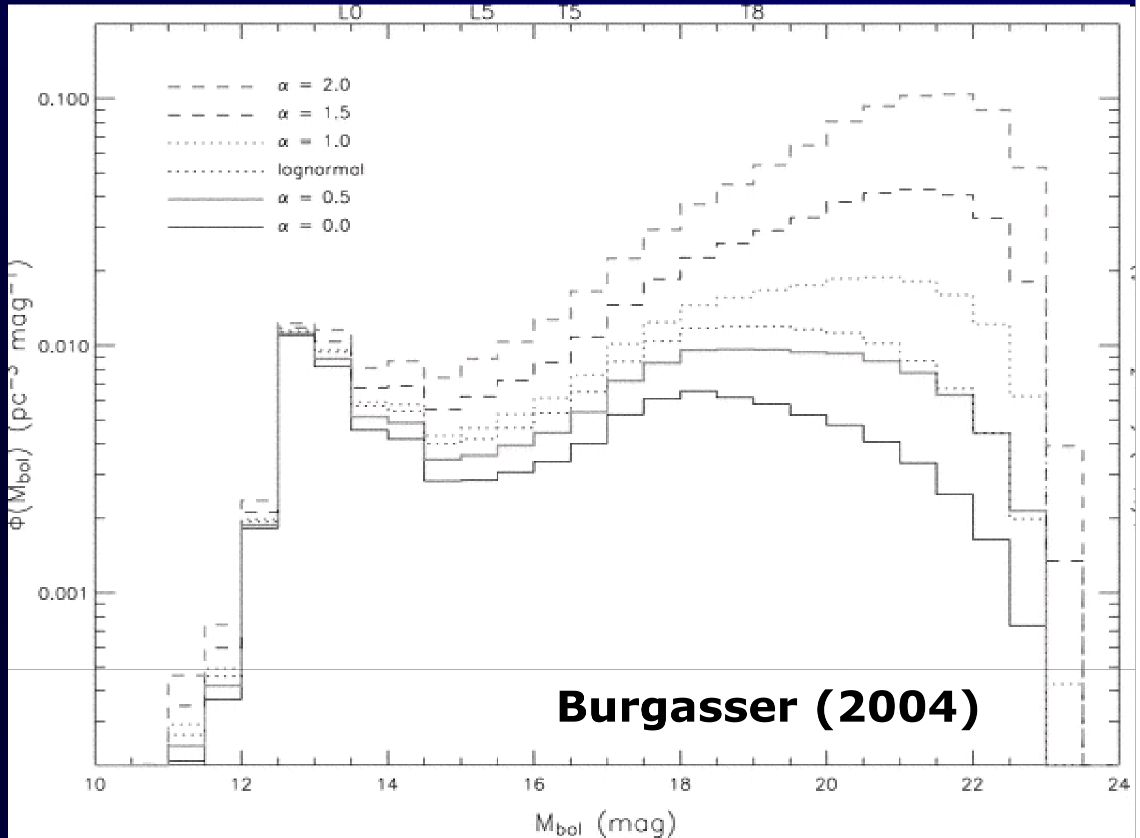
- mid-L – early T regime most sensitive to birthrate
- late-T relatively insensitive to birthrate
- to be able to interpret the field LF must constrain birthrate
- need a large sample of late-Ls to mid-Ts



Burgasser 2004, ApJS, 155, 191

- latest T types most sensitive to IMF
- late T sample has always suffered from small size

So, we need a new large sample of L and T dwarfs that will eclipse what has come before…



Several major surveys are on the boil:

- UKIDSS
- VISTA
- CFBDS
- PanStarrs

UKIRT Infrared Deep Sky Survey (UKIDSS)

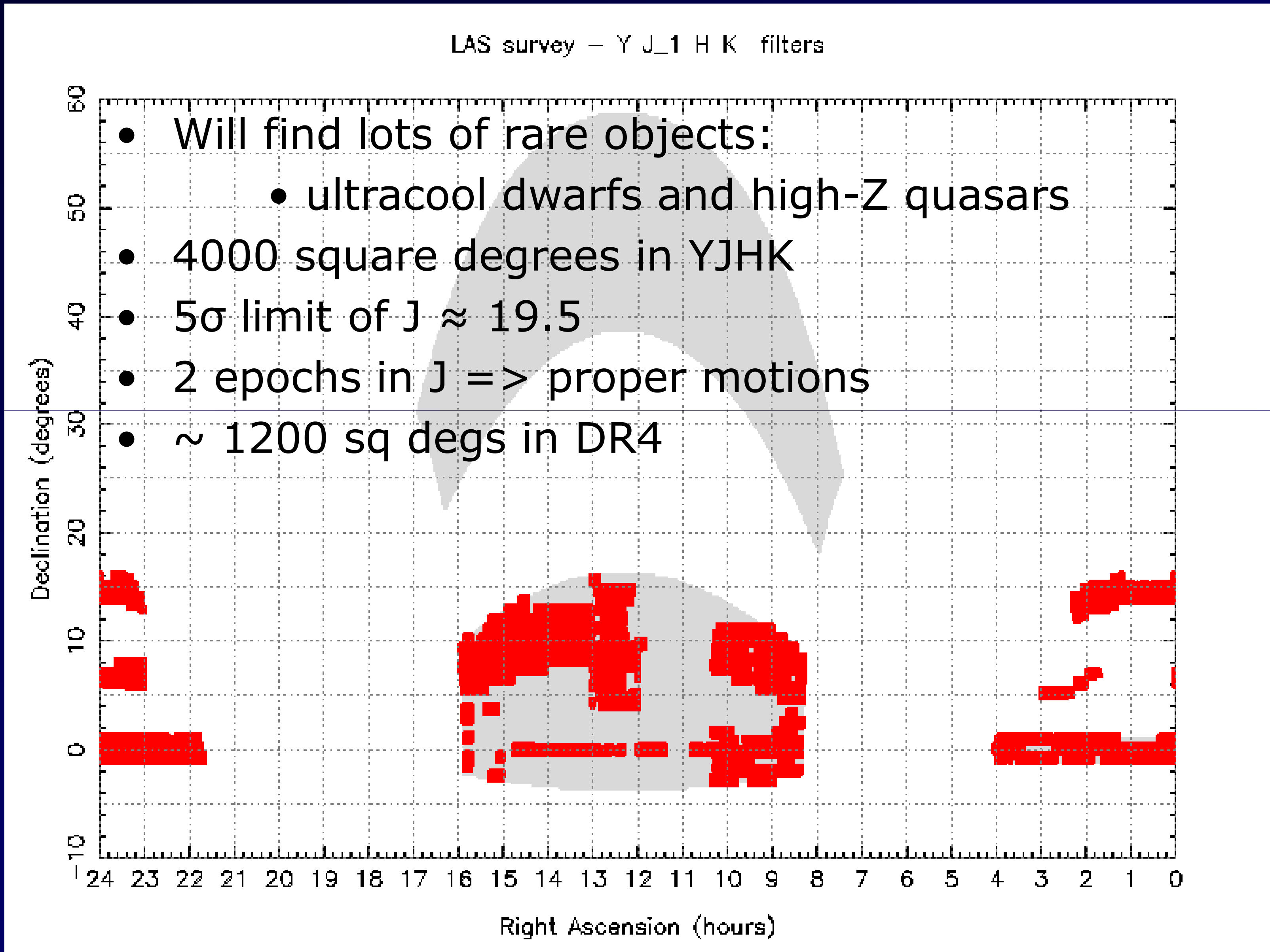
Lawrence et al 2007

Casali et al 2007

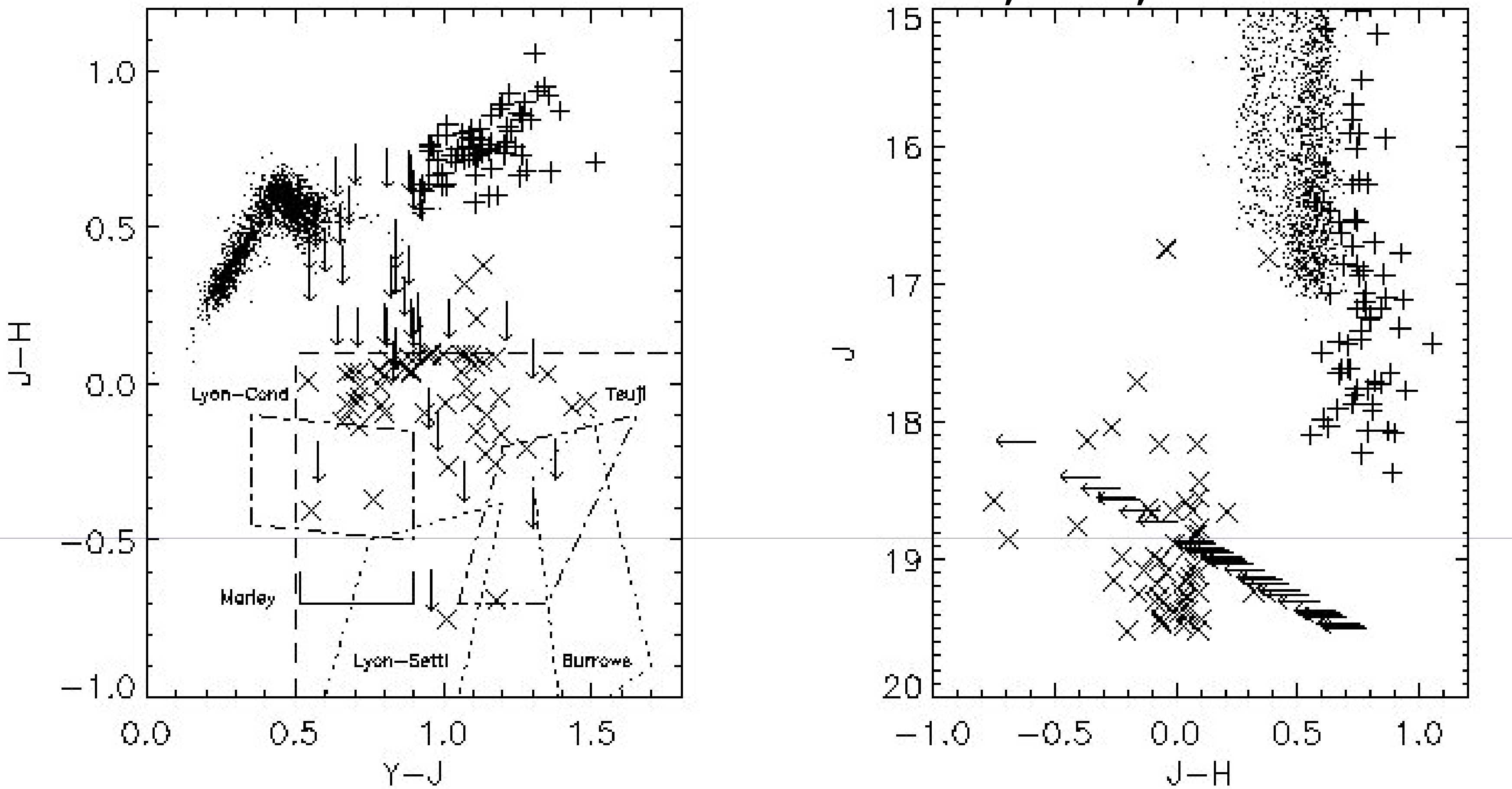
- WFCAM will survey 7500 square degrees
- UKIDSS consists of 5 surveys
- Large Area Survey (LAS)
  - 4000 sq. degs, K=18.4
- Galactic Plane Survey (GPS)
  - 1800 sq. degs, K=19
- Galactic Clusters Survey (GCS)
  - 1400 sq. degs K=18.7
- Deep Extragalactic Survey (DXS)
  - 35 sq. degs, K=21.0
- Ultra Deep Survey (UDS)
  - 0.77 sq. degs, K=23.0

The Large Area Survey (LAS)

- Will find lots of rare objects:
  - ultracool dwarfs and high-Z quasars
- 4000 square degrees in YJHK
- 5σ limit of J ≈ 19.5
- 2 epochs in J => proper motions
- ~ 1200 sq degs in DR4



Pinfield et al, 2008, arxiv:0806.0294



- *Y-J* > 0.5; *J-H <0.1; J-K* < 0.1
- Or Y-J > 0.5 and *H&K* non-detection
- *z′-J* > 2.5 or SDSS non-detection

Contraints on the IMF from DR1+2

- Have now completed the follow up of 280 sq degs of LAS DR2 sky (bar 2)
- Combined results of:
  - Kendall et al (2007)
  - Lodieu et al (2007)
  - Chiu et al (2007)
  - Pinfield et al (2008)

19-21 T4-T8.5 dwarfs with $J \leq 19.0$ and $J-H \leq 0.1$

After applying corrections for:

- scatter from J-H selection
- unresolved binaries
- exclusions due to mis-matches with SDSS
- Malmquist bias (both from intrinsic M_J scatter, and from uncertainties)

…we estimate 17±4 ≥T4 dwarfs in DR2 down to J = 19.0

What can this tell us about the form of the birthrate and the IMF?

Birthrate: $b(t) \propto e^{-\beta t}$	# ≥ T4 dwarfs
$\beta = -0.1$	54±18
$\beta = 0.0$	44±15
$\beta = 0.1$	33±11
$\beta = 0.2$	35±12
$\beta = 1.0$	31±11

IMF with $\alpha = 0.0$

IMF: $dn/dm \propto m^{-\alpha}$	# ≥ T4 dwarfs
$\alpha = -1.0$	15±5
$\alpha = -0.5$	25±9
$\alpha = 0.0$	44±15
$\alpha = 0.5$	57±19
$\alpha = 1.0$	119±40

Constant birthrate

c.f $\alpha = 1.0\text{-}1.5$ for L dwarfs (e.g. Reid et al 1999)

$\alpha \approx -0.5$ from young clusters

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What physical processes govern the LT transition?

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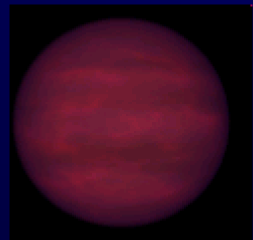
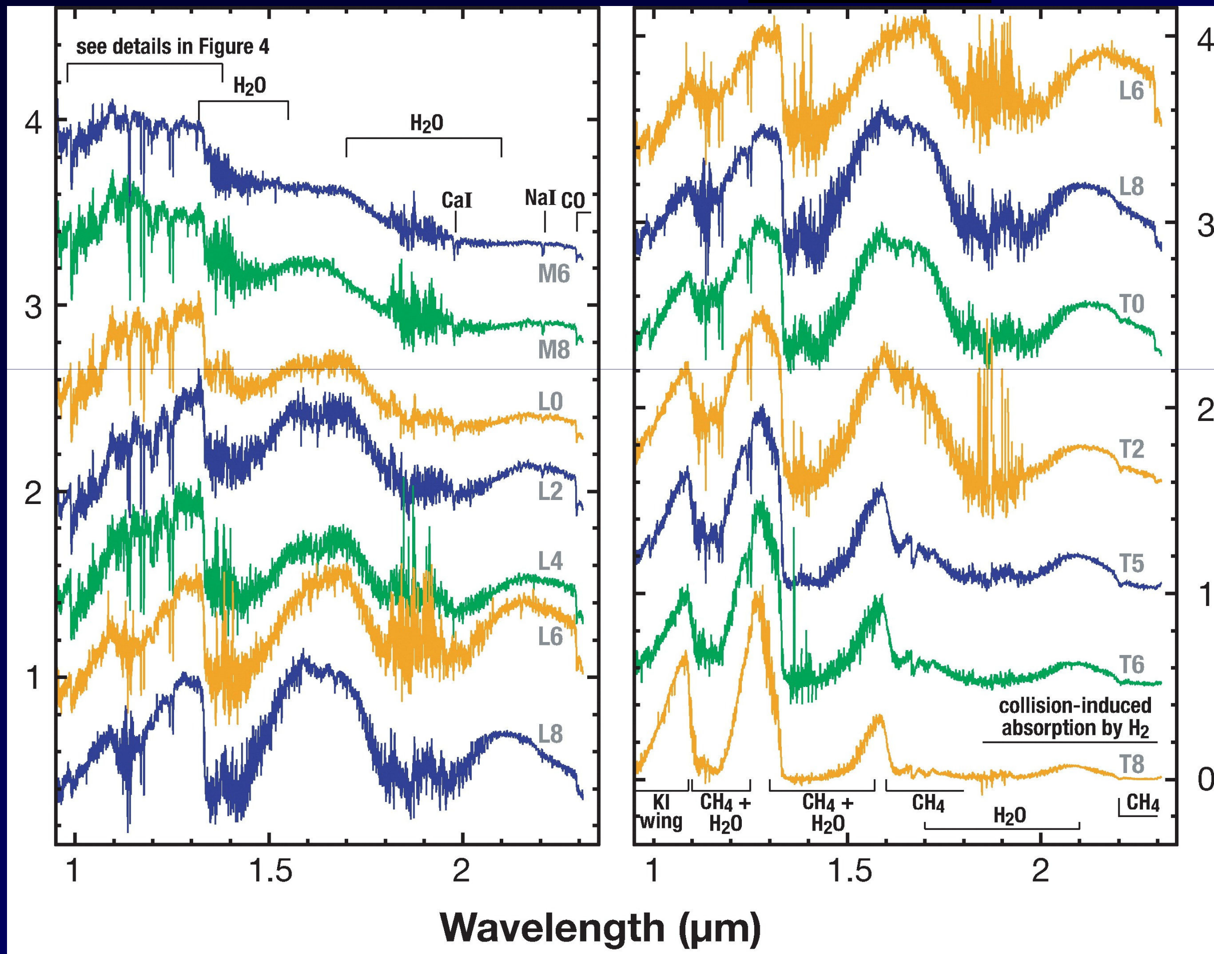
The L and T dwarfs



- dusty
- red NIR colours

NIR opacity:

- FeH
- CrH
- water



Kirkpatrick, JD. 2005
Annu. Rev. Astron. Astrophys. 43: 195–245

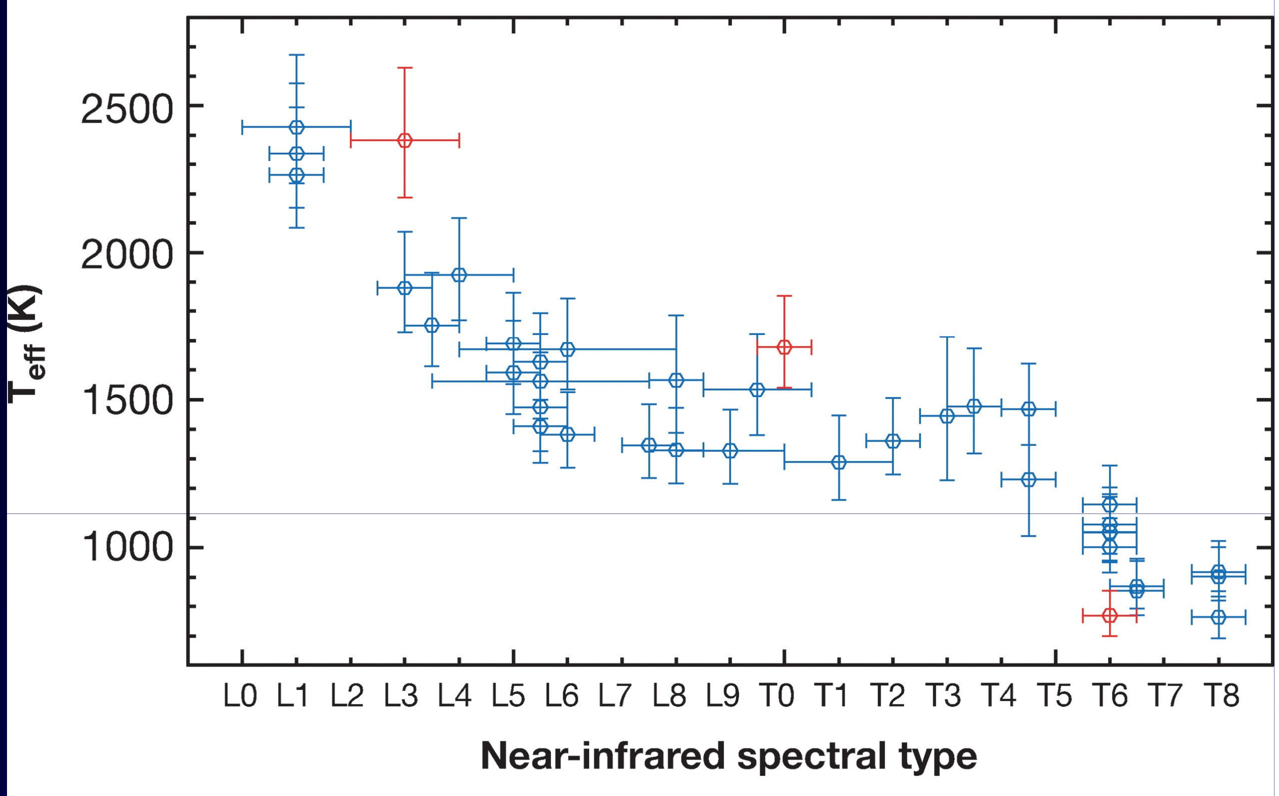
- dust absent
- blue NIR colours

NIR opacity:

- methane
- Water
- CIA H_2

The L-T transition

- large spectral changes over narrow T_{eff} range
- physics of the L-T transition is a hot topic
- clearly the clearing of dust from the visible photosphere is key



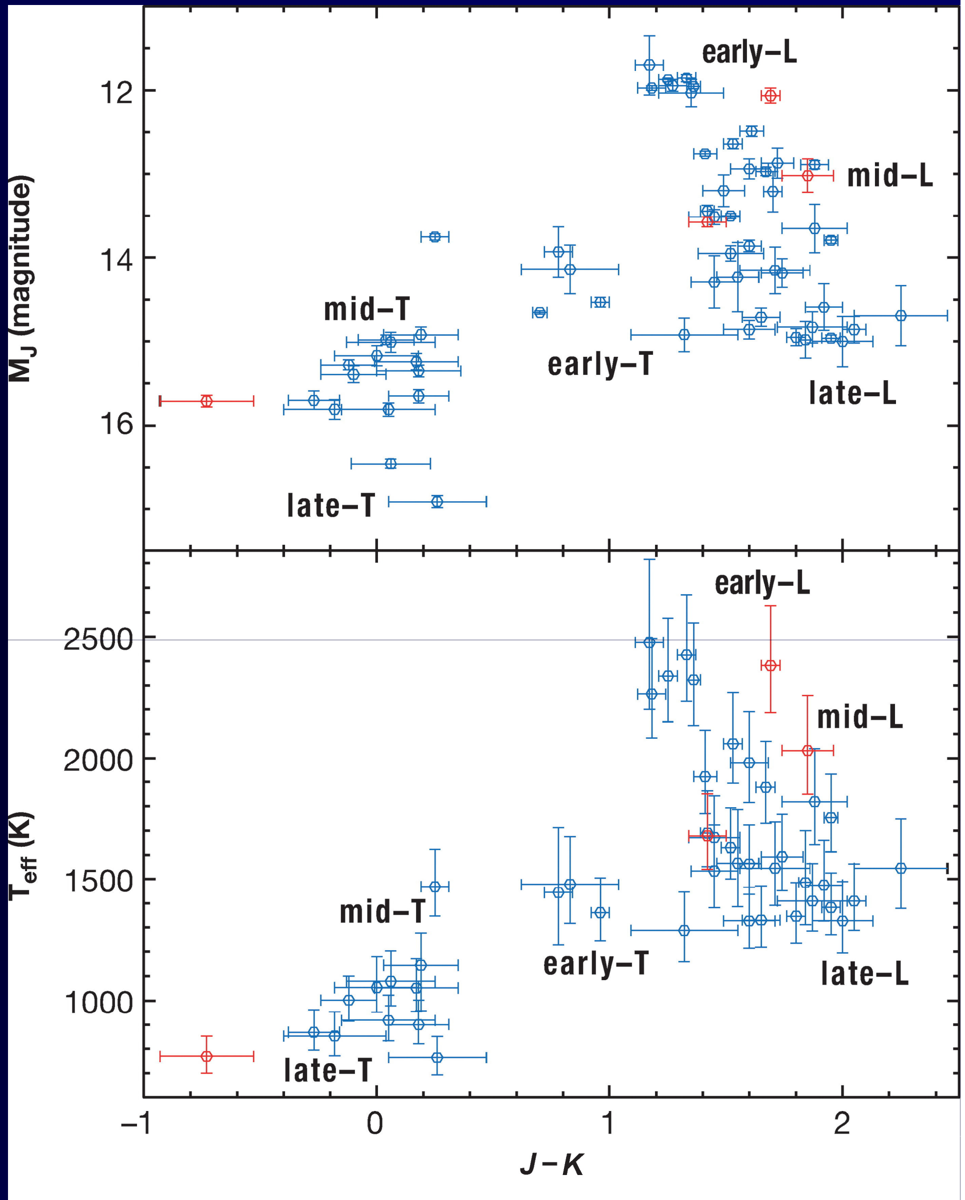
Kirkpatrick, JD. 2005
Annu. Rev. Astron. Astrophys. 43: 195–245

Dusty models (e.g AMES-dusty – Allard et al 2001):

- explain very red colours for L dwarfs
- fail to explain blue colours of T dwarfs

Models with no dust in photosphere (e.g. AMES-cond – Allard et al 2001):

- predict blue colours of mid+late-Ts
- fail to predict colours of early-Ts



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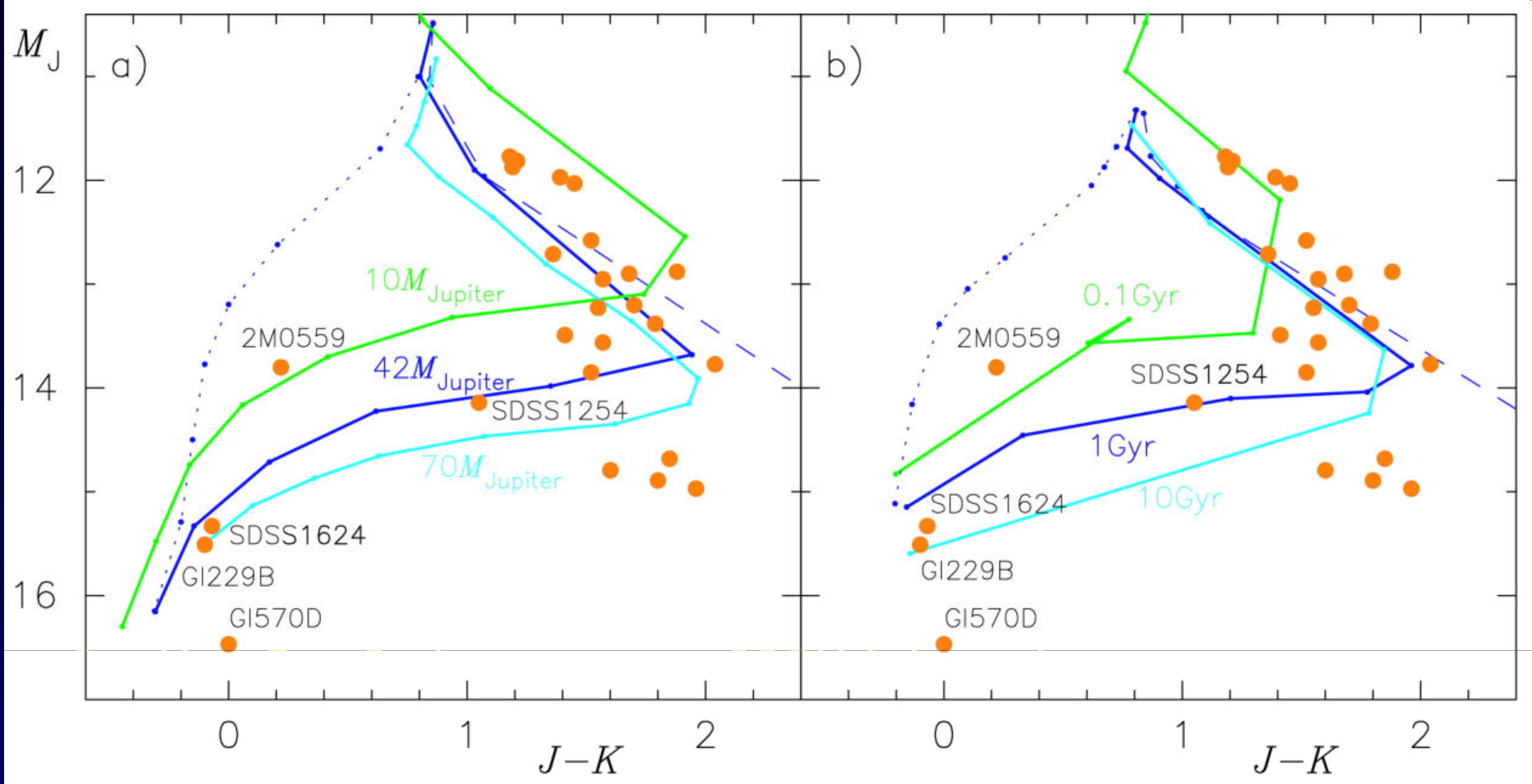


Tsuji & Nakajima (2003) offer solution:

- M_J vs J-K represents a snap shot of objects on different paths depending on gravity
- high-g objects lose dust clouds below photosphere at lower T_{eff} (and M_J) than lower-g objects

Sedimentation II

Marley et al (2002):

- physics of cloud deck governed by f_{sed} – efficiency of sedimentation relative to turbulent mixing

- $f_{sed} = 0$ – well mixed, very dusty, no sedimentation
- $f_{sed} < 3$ explains reddest L dwarfs – optically thick clouds
- $f_{sed} > 3$ explains early T dwarfs – optically thin clouds
- $f_{sed} = \infty$ cloud free model – mid-late T

- also fail to produce rapid J-K change

Burgasser et al (2002) suggest alteration to this model:

- rather than thinning of cloud deck, suggests cloud break-up, analogous to behaviour seen Jupiter and Saturn

- location of object on M_J vs J-K depends on % cloud cover

- raises possibility of observing weather related variability

Sedimentation III

Knapp et al (2004) propose a sudden downpour scenario:

- L dwarfs cool with essentially constant f_{sed} (~3) to about 1300K
- at 1300K f_{sed} starts to rise at roughly constant T_{eff} to ∞
- causes a "torrential rain of condensed iron and silicate grains"
- process would begin at late-L for all masses, T1-T4 represent different stages
- once clouds have rained out cooling continues

LT transition diagnostics I: gravity

Consider the T3.5 dwarf…

Scenario 3:

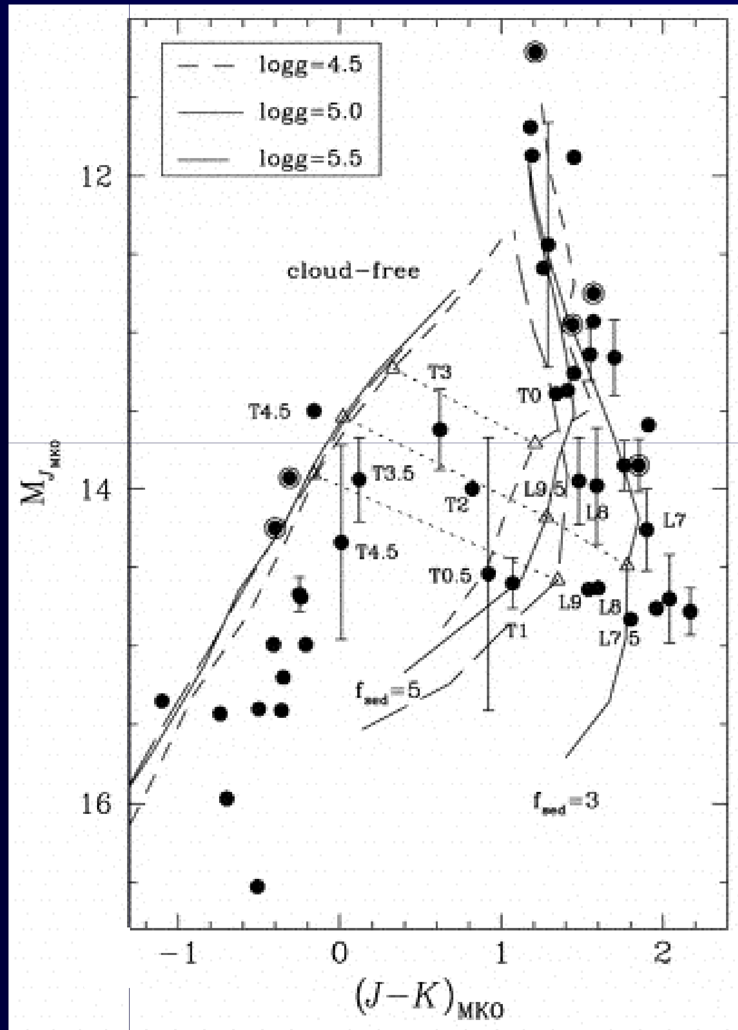
- sudden downpour model predicts log g ~ 5.4

Scenario 2:

- patchy cloud model predicts lower gravity, log g ~ 5.0

Scenario 1:

- it is bright, and has transitioned to blue so must be low-mass => log g ~ 4.



Knapp et al, 2004, AJ, 127, 3553

Understanding gravity indicators

There are a variety of ways to estimate surface gravity in ultracool dwarfs, for example:

- gravity sensitive features e.g. near-IR KI, NaI doublets
- collisionally induced H_2 absorption is dependent on pressure

But all depend on interpretation of model spectra, which must in turn be calibrated against objects with well constrained properties – benchmark objects.

LT transition diagnostics II: weather

Patchy cloud model suggests that variability may be observable due to "weather":

- rotationally modulated variability due to holes in cloud deck $t_{rot} < t_{hole}$
- non-periodic variability if $t_{rot} > t_{hole}$
- also of interest for M-L transition

Spectrophotometry of sensitive features:

- e.g. Bailer-Jones 2002, Clarke et al 2003
- no weather signatures detected

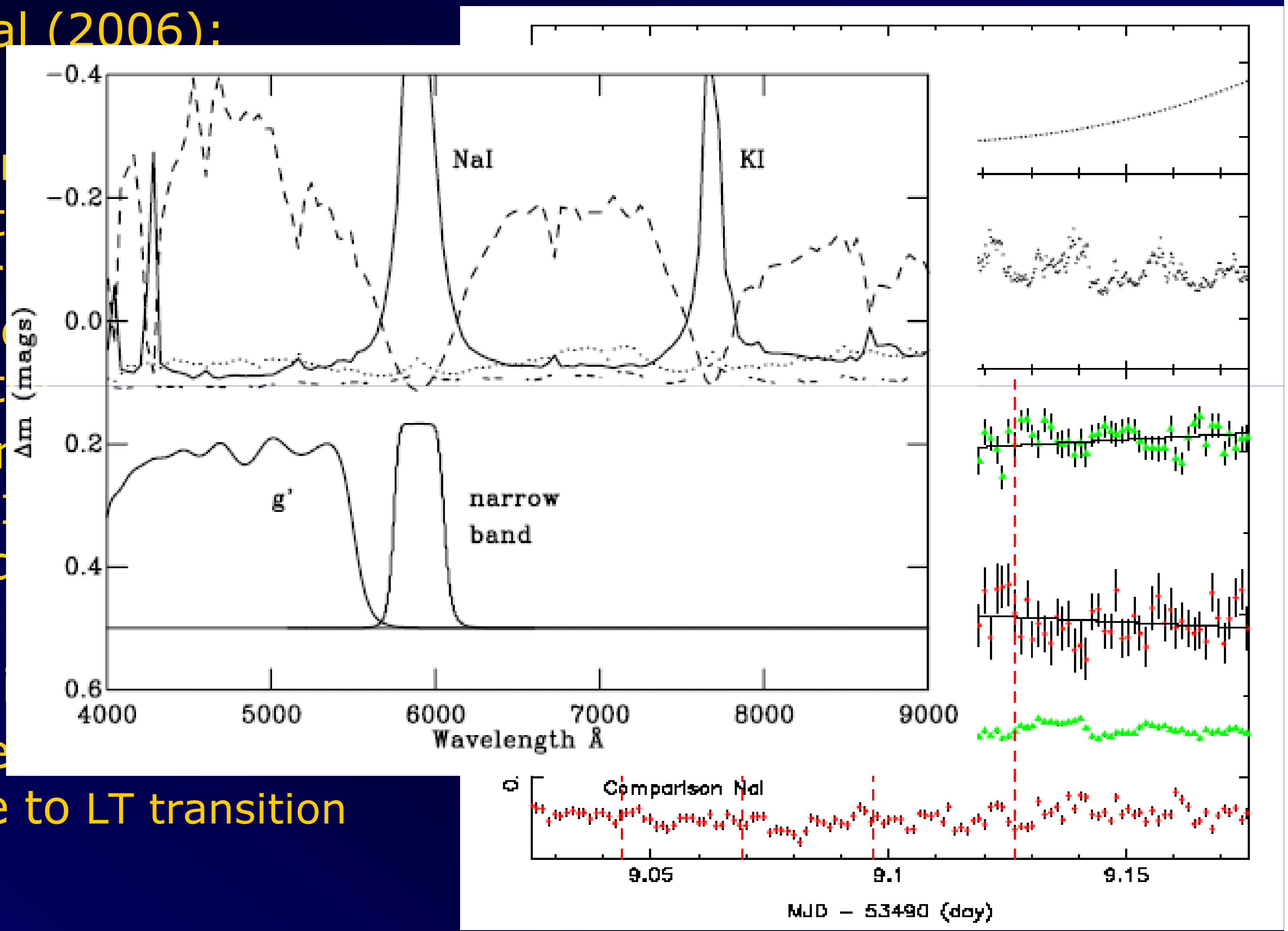
Narrow-band photometry:

- Littlefair et al 2006
- more promising

Brown dwarf weather

Littlefair et al (2006):

- compare r
photomet
with filter
with broad
photomet
- find for or
1300+19
correlated
and NaI
- this case i
- plans to e
technique to LT transition



Littlefair et al, 2006, 370, 1208

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The coldest brown dwarfs

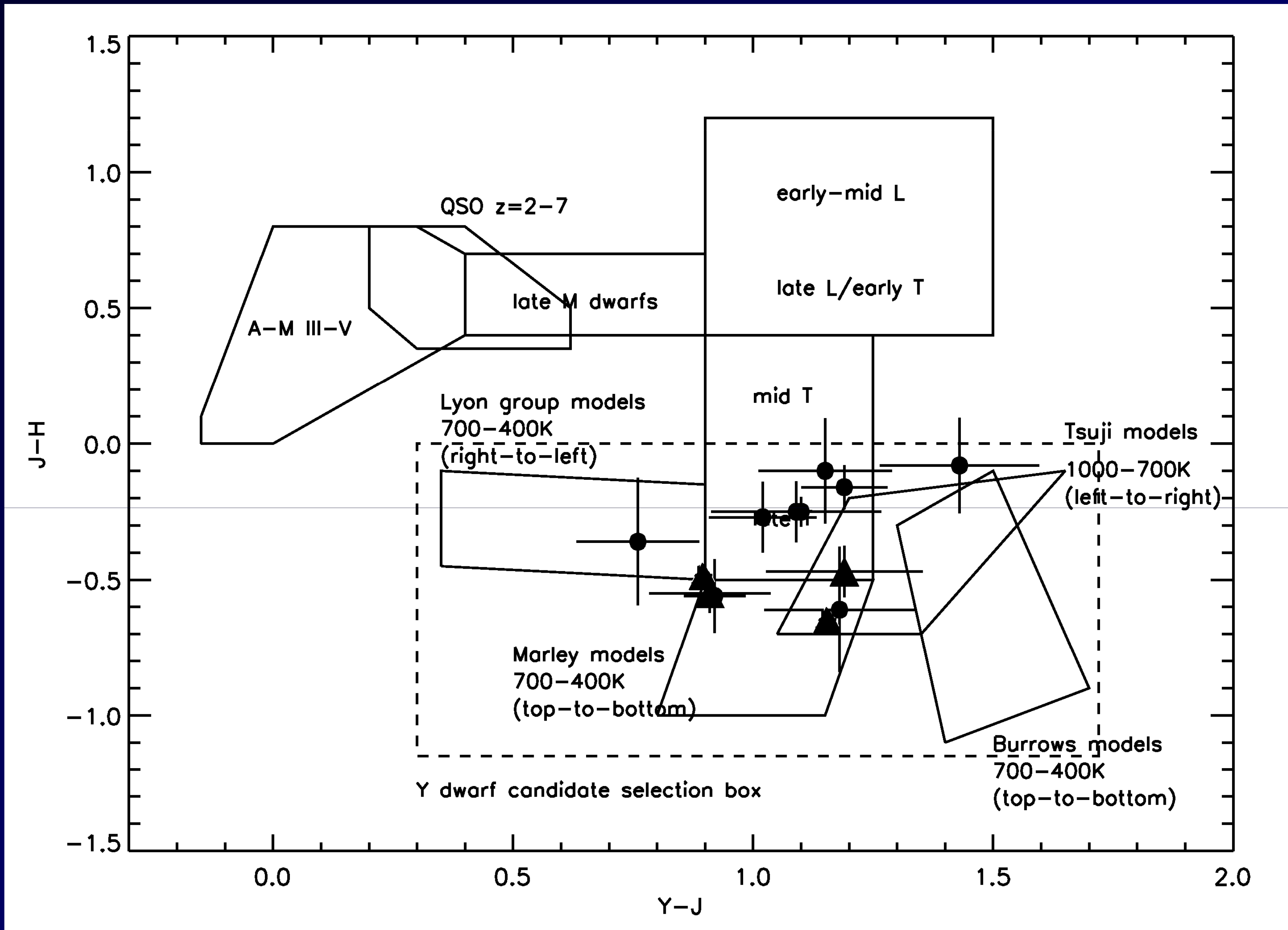
What happens to T dwarf spectra as T_{eff} falls?

- pre-2007 T sequence ended at T8, coldest T8 2MASS0415 (750K)

- expectation was that at lower T_{eff} new opacity sources (e.g. near-infrared NH_3) would become important

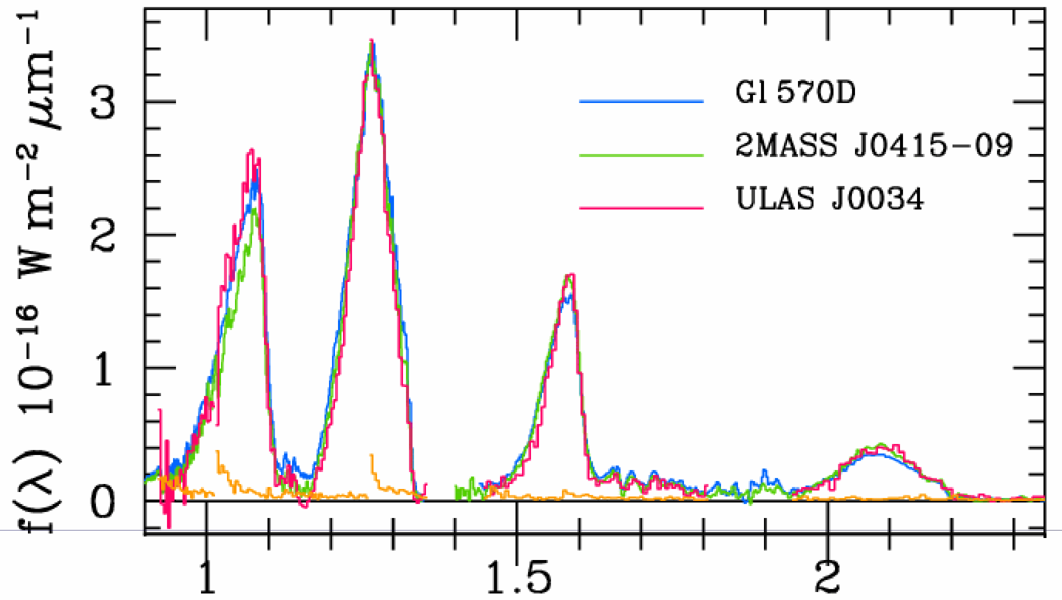
- UKIDSS LAS is aimed at finding the first Y dwarfs

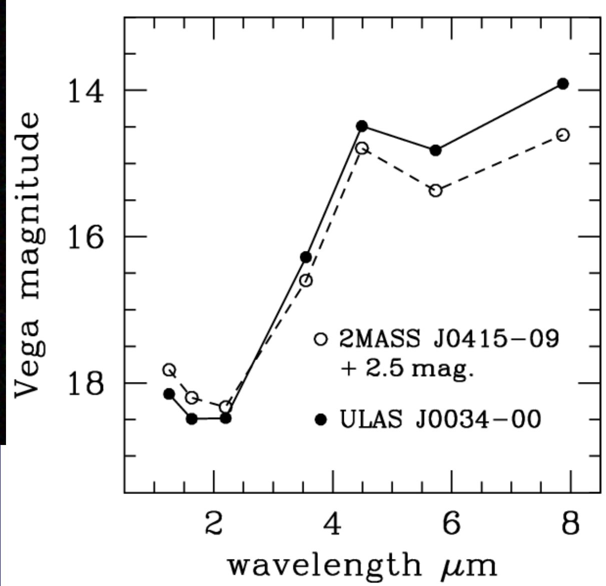
…so, how are we doing?



QSO z=2−7
early−mid L
late L/early T
late M dwarfs
A−M III−V
mid T
Lyon group models
700−400K
(right−to−left)
Tsuji models
1000−700K
(left−to−right)
Marley models
700−400K
(top−to−bottom)
Burrows models
700−400K
(top−to−bottom)
Y dwarf candidate selection box
J−H
Y−J

ULAS0034: the first T8+ dwarf





Warren et al 2007, MNRAS, 381, 1400

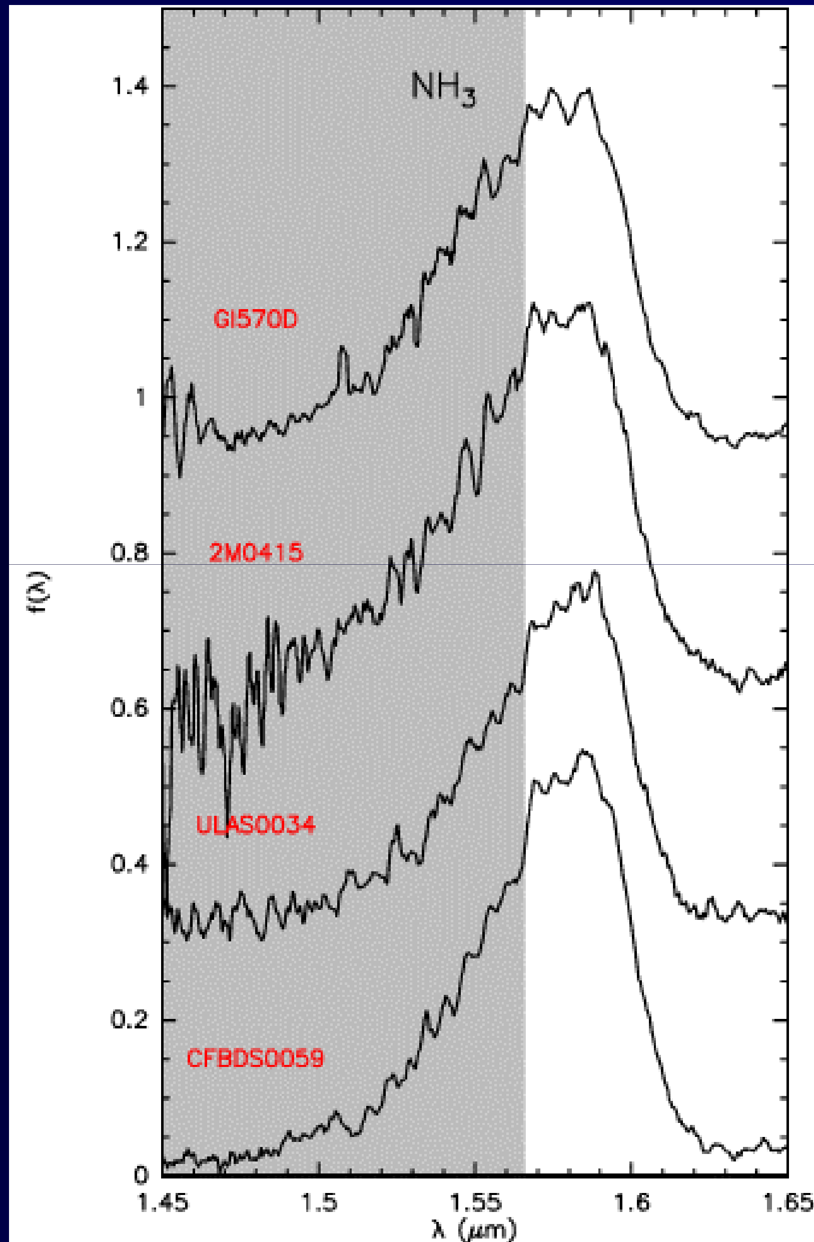
- Tighter J band peak than any previously known T dwarf
- near-IR spectral modelling indicated 50 – 100K cooler than previous record holder
- H-[4.49] colour implies T_{eff} ~ 600K
- 2-8μm SED is significantly redder than 2MASSJ0415-09

Y-J = 0.75
J-H = -0.34
H-K = 0.01
z(AB)-J = 3.76
D ≈14 – 21 pc

The first "Y" dwarfs?

Delorme et al (2008):

- identify a second T8+ dwarf – CFBDS0059
- estimate that CFBDS0059 is ~50K cooler than ULAS0034 based on NIR spectra (may be even cooler)
- claim detection of NH3 in the H-band peak of both CFBDS0059 and ULAS0034
- suggest that if this is seen to develop in cooler objects, then these represent the transition to the Y spectral class

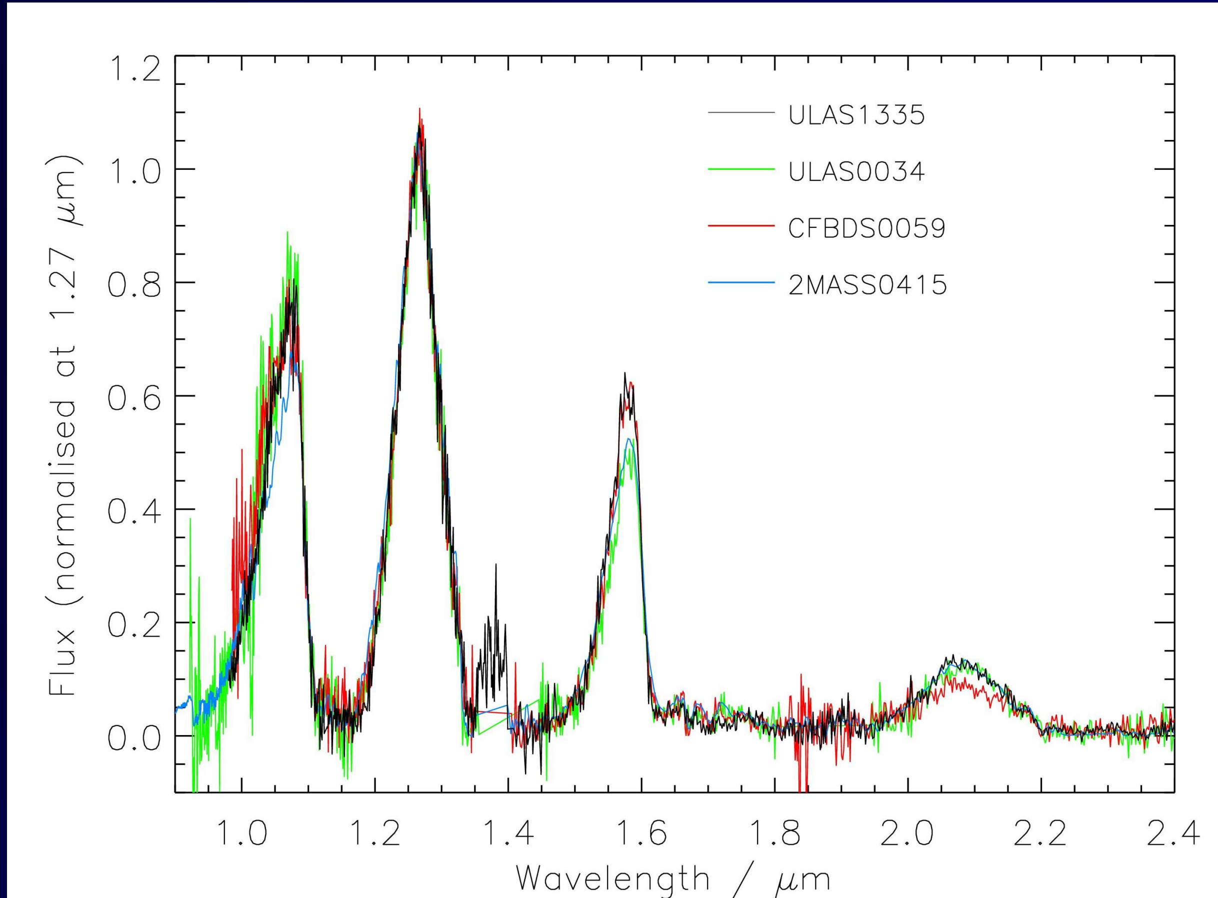


Delorme et al, 2008, A&A, 482, 961

ULAS1335 – a record breaker

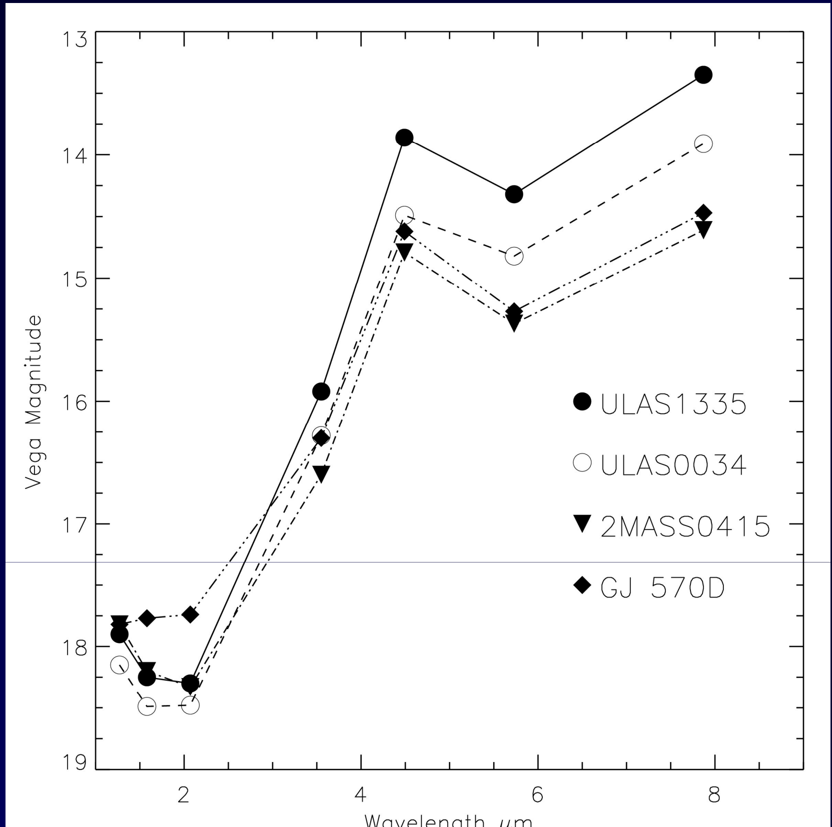
Burningham et al 2008:

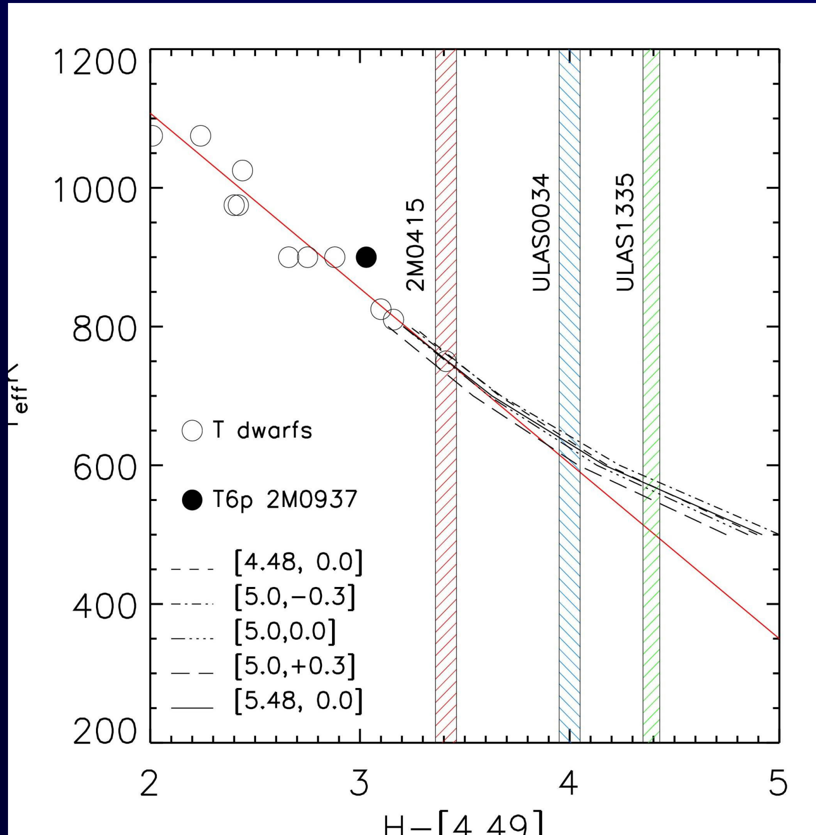
- ULAS1335:
  - very similar to ULAS0034 and CFBDS0059
  - NIR spectral fitting suggests $T_{eff} < 600K$
  - cooler than ULAS0034, but has weaker NH3
  - significance of NH3 band not yet understood



The close resemblance of the T8+ dwarfs to the T8 subtype suggests extension of the T dwarf sequence to T9 is appropriate with ULAS1335 as the spectral type standard.

T dwarfs all the way 550K





- ULAS1335 has the reddest H-[4.49] of any T dwarf yet measured
- linear relation between T_{eff} from hotter T dwarfs not expected to hold to lower T_{eff}
- But latest Marley & Saumon model colours suggest T_{eff} ~ 550 – 600K

NH3 –
Irwin et al (1999)

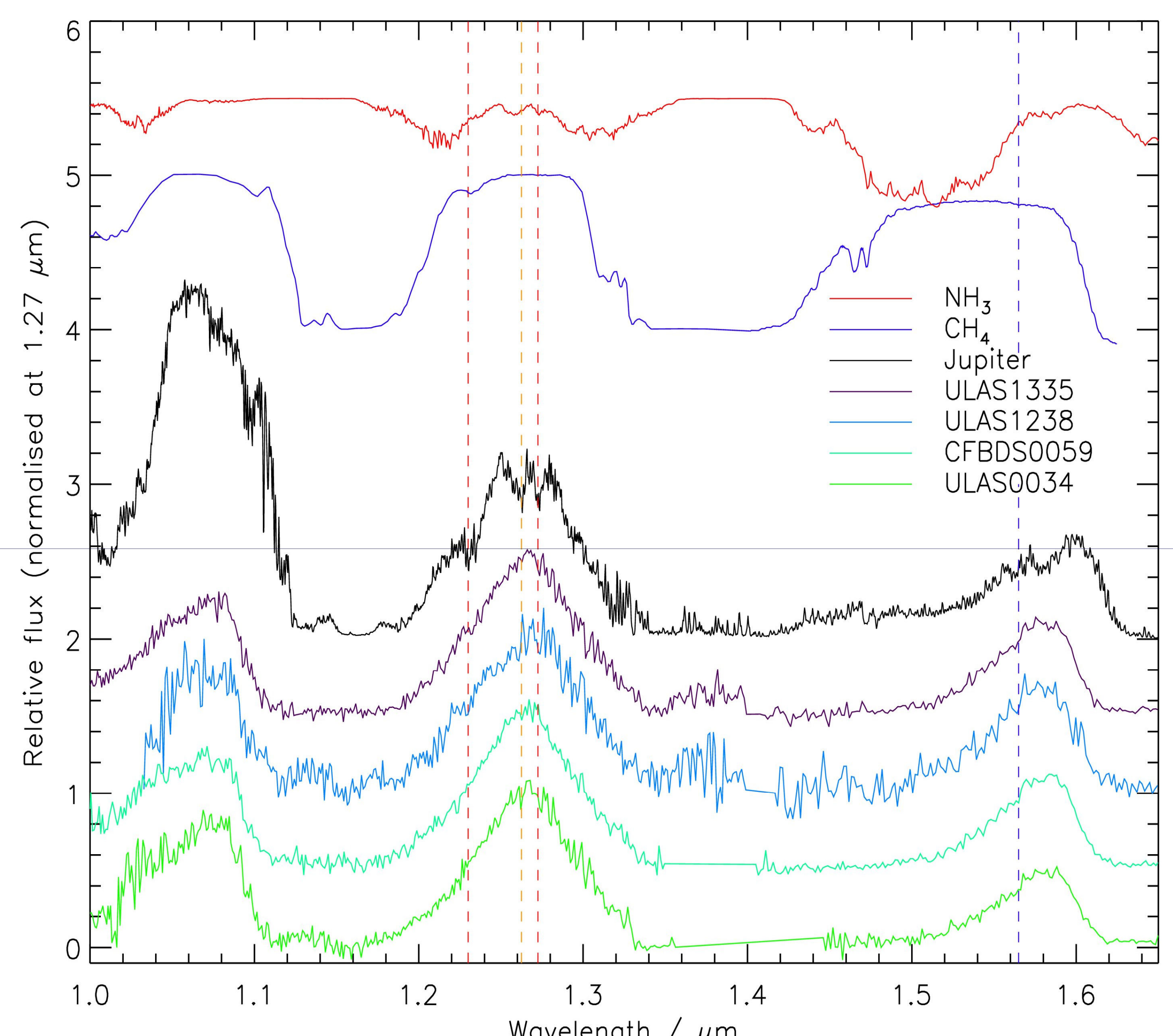
CH4 –
Cruikshank & Binder (1969);

Jupiter –
Rayner, Cushing & Vacca priv comm.

CFBDS0059 –
Delorme et al 2008

ULAS0034 –
Warren et al 2007

ULAS1335 –
Burningham et al 2008



Summary

IMF:

- large NIR surveys will allow us to probe sub-stellar IMF and birthrate as never before
- no lower mass limit yet found for SF process (though IMF appears to be falling in the substellar regime)

LT transition:

- LT transition can be addressed with properly calibrated gravity and metallicity indicators
- current searches for benchmarks are crucial

Coldest Ts:

- current surveys opening up brand new temp. regime
- no Y dwarfs yet, but the development of the T sequence is interesting